Variety of proton whistlers: satellite observation and theoretical analysis

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Abstract

Based on observations from the DEMETER satellite, we present and investigate various types of proton whistlers, including ionospherically reflected proton whistlers, which have not been discussed so far. The observations are complemented by theoretical analysis and numerical simulations. A side result of the analysis consists in that the region in the Earth-ionosphere waveguide illuminated by a lightning stroke, which serves as an effective source of the emission, spreads more than 30 degrees over latitude in meridian plane.

1. Introduction

Spectrograms of lightning-induced emission registered onboard spacecraft are a natural object for numerical modeling. In this case, the source of emission is localized in space and in time, while the observation point on a satellite is situated in the far wave zone, thus the wave field description is the subject of geometrical optics (GO). Expanding the wave field into GO wave packets, and following their ray trajectories, together with the variation of the ray tube cross section and other wave parameters, one can simulate a spectrogram, i.e., frequency-time plots on which non-zero spectral intensity is indicated by darkness or various colors. Computer simulations of this kind [1] suggest that, along with the well-known proton whistlers observed in the same hemisphere as the lightning stroke [2,3] , and trans-equatorial proton whistlers observed in the opposite hemisphere [4,5], ionospherically reflected proton whistlers (IRPW) should also exist, which could be observed in the same hemisphere as the lightning stroke after they have been reflected from the opposite hemisphere [6]. Ionospheric reflection of proton cyclotron waves (PCW), which is the key process in the formation of IRPW, takes place at the ionospheric level where the wave frequency is equal to ion hybrid resonance frequency. This reflection is similar in its physical nature to the well-known lower hybrid resonance reflection of whistler-mode waves [7]. In this report, we present the first observations of IRPW, which have been found in ELF data of the DEMETER satellite. The main difficulty in identifying IRPW consists in distinguishing them from trans-equatorial proton whistlers. We present experimental example where this identification is unambiguous.

A recent trend in spectral analysis of various wave events consists in displaying, along with the electric and magnetic field intensities, the wave characteristics such as the polarization, the index of refraction, the wave normal angle, and the Poynting flux [8, 9]. We follow up this trend and include these characteristics into consideration, which makes the the arguments much more conclusive.

2. Some features of ion cyclotron wave propagation in the near-Earth space

To understand the formation of ionospherically reflected proton whistlers, we should know how ion cyclotron waves that form this emission propagate in the upper ionosphere and magnetosphere. We will recall here the main features of this propagation, referring the reader to [9] for details.

The wave refractive index $N \equiv kc/\omega$ in cold magnetized plasma is determined by the well-known dispersion relation (see, e.g.,[10]):

$$AN^4 + BN^2 + C = 0 \,, \tag{1}$$

where the coefficients A, B, and C are expressed through the wave normal angle θ and the components of the dielectric tensor ε_{ij}, which in a cold plasma with a constant magnetic field directed along the z-axis has the form:

$$\varepsilon_{ij}(\omega) = \begin{pmatrix} \varepsilon_1 & i\varepsilon_2 & 0 \\ -i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} \tag{2}$$

The expressions for the coefficients A, B, and C, as well as the components ε_1, ε_2, and ε_3 may be found in textbooks (see, e.g.,[10]). Here we will only write the expressions for the quantities A and ε_1 (in standard notation):

$$A = \varepsilon_1 \sin^2\theta + \varepsilon_3 \cos^2\theta \; ; \quad \varepsilon_1 = 1 - \sum_s \frac{\omega_{\rm ps}^2}{\omega^2 - \omega_{\rm cs}^2} \; , \tag{3}$$

with the summation over all plasma species: electrons and all types of ions.

As the analysis shows, the waves belonging to the mode that forms proton whistlers propagate nearly along the ambient magnetic field for almost all wave normal angles θ except a small vicinity of $\pi/2$ where the group velocity changes its sign. Since this change occurs abruptly and takes place in a small spatial domain, they speak about ray reflection at this point. The wave reflection occurs at large values of refractive index, $N \gg \omega_{\rm pH^+}/\omega$. As follows from (1) and is generally known, for $N \to \infty$, the dispersion relation is reduced to

$$A \equiv \varepsilon_1 \sin^2\theta + \varepsilon_3 \cos^2\theta = 0 \; . \tag{4}$$

As was mentioned above, the wave reflection corresponds to $\theta = \pi/2$, thus the wave reflects at

$$\varepsilon_1 = 0 \; .$$

In plasma containing three types of ions, H^+, He^+, and O^+, and for wave frequencies $\omega_{\rm cHe^+}^2 \ll \omega^2 < \omega_{\rm cH^+}^2$, the expression for ε_1 takes the form [see (3)]

$$\varepsilon_1 \simeq \frac{\omega_{\rm pH^+}^2}{\omega_{\rm cH^+}^2 - \omega^2} - \frac{\omega_{\rm pHe^+}^2}{\omega^2} - \frac{\omega_{\rm pO^+}^2}{\omega^2} \; .$$

Equating ε_1 to zero, we find the frequency at which the wave is reflected:

$$\omega_{\rm ih} = \frac{\omega_{\rm cH^+}^2 (\omega_{\rm pHe^+}^2 + \omega_{\rm pO^+}^2)}{\omega_{\rm pH^+}^2 + \omega_{\rm pHe^+}^2 + \omega_{\rm pO^+}^2} \; , \tag{5}$$

which by the analogy with the lower hybrid resonance frequency could by called the ion hybrid resonance frequency. It is easy to see that the waves having frequencies below the proton gyrofrequency at the equator, while propagating to higher latitudes can reach the height where their frequency is equal to ion hybrid resonance frequency and, thus, be reflected.

3. Examples of proton whistlers registered by the DEMETER satellite

Similar to electron whistlers [11-13], proton whistlers originate from the emission of lightning strokes. According to the generally accepted knowledge, this emission, while propagating in the Earth-ionosphere waveguide, partly leaks into the ionosphere and magnetosphere and, due to the dispersion of group velocity, forms various wave events that depend on the observation site. Whereas the frequency of electron whistlers is below the electron gyrofrequency on the propagation path, the maximum frequency of proton whistlers is equal to proton gyrofrequency. Two examples (left and right panels) of proton whistlers registered onboard the DEMETER satellite [14], along with the results of the wave analysis, are shown in Figure 1. Orbital data for the satellite pass include universal time (UT), altitude (Alt), McIlwain parameter (L), and geomagnetic latitude (λ_m). The first panel is the frequency-time spectrograms for the total (i.e., the sum over three components) power spectral density of the electric field fluctuations. Results for the wave polarization, the wave normal angle (to the direction), the parallel components of the Poynting vector, and the index of refraction are shown in the remaining four panels, each of which represents the frequency-time dependence of one of these wave properties.

Four proton whistlers with upper cutoff frequency close to the local proton gyrofrequency can be seen in the left panel around 16:14:20 UT, followed by other four traces with much lower cutoff frequency. No doubt that these events were caused by the same sequence of lightning strokes, however, the formation of the second group is not obvious. According to the sign of parallel component of the Poynting flux (fourth panel), the signals of the first group came to the satellite from the Northern hemisphere along "direct" paths, while the signals of the second group came to the satellite from the Southern hemisphere along magnetospheric paths. Ray tracing analysis of the propagation time shows that the latter could hardly be ionospherically reflected proton whistlers, but most probably came to the satellite starting directly from the opposite hemisphere. Since the PCW that form these events propagate almost along

the geomagnetic field, we must conclude that the region illuminated by a lightning stroke in the Earth-ionosphere waveguide, which then serves as a source of the wave events under discussion, spreads more than 30 degrees over latitude, assuming a lightning stroke near the equator.

An example that we rate as the registration of ionospherically reflected proton whistler (IRPW) is shown in the right panels of Figure 1. The first, most intense, trace is a regular proton whistler observed in the same hemisphere as the source lightning. The second trace is the trans-equatorial proton whistler due to the illuminated region spread over both hemispheres, and the third trace is the IRPW. Few arguments support this conclusion. First, the time delay of the third trace is about twice the time delay of the second trace. In applying this argument one should keep in mind that, due to almost longitudinal propagation of PCW, the signal can reach the satellite only from two conjugate regions situated around the field line of observation, no matter how wide the illuminated region is. Second, the wave normal angles of the IRPW are closer to 90° and, third, the index of refraction of IRPW is larger than for trans-equatorial whistlers. Both of these features are consistent with the propagation properties of PCW in the magnetosphere, and prove in fact that the waves which form the third trace have propagated along a more extensive trajectory.

4. References

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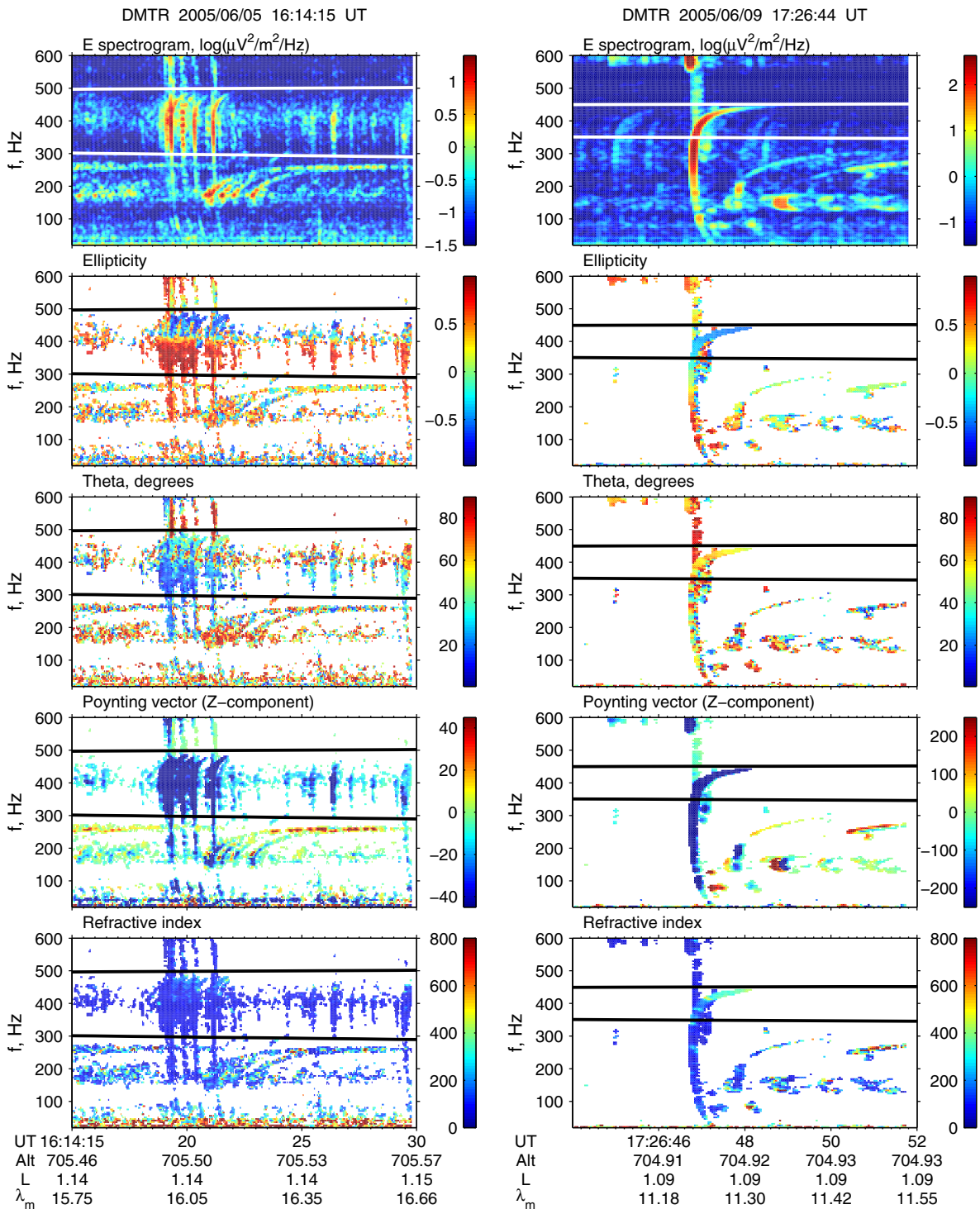

Figure 1: Examples of proton whistlers (see the text for details).