GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L15106, doi:10.1029/2009GL039803, 2009

MHD nature of night-time MSTIDs excited by the solar terminator

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Received 30 June 2009; accepted 9 July 2009; published 6 August 2009.

[1] We have obtained first experimental evidence in favour of the magnetohydrodynamic (MHD) nature of night-time medium-scale travelling ionospheric disturbances (MSTIDs). We used total electron content (TEC) measurement data from the dense GPS networks in California and in Japan for 2008–2009. It was found that the spectral MSTID characteristics are determined by the solar terminator (ST) dynamics. In summer, MSTIDs are detected 1.5–3 hours before the evening ST at 100 km above the point of observations, but at the moment of the evening ST passage through the magnetoconjugate point. At the equinox MSTIDs are registered at once after ST appearance. In winter, MSTIDs are observed 1.5–3 hours after the evening ST occurrence at the point of observations, but at the moment of the evening ST passage in the magnetoconjugate point. The MSTID occurring synchronously with the ST passage through the magnetoconjugate area suggest that the ST-excited MSTIDs are of MHD nature. **Citation:** Afraimovich, E. L., I. K. Edemskiy, A. S. Leonovich, L. A. Leonovich, S. V. Voeykov, and Y. V. Yasyukevich (2009), MHD nature of night-time MSTIDs excited by the solar terminator, *Geophys. Res. Lett.*, *36*, L15106, doi:10.1029/2009GL039803.

> Solar terminator is like a bow that elicits divine sounds from the vibrating geomagnetic field line.
>
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1. Introduction

[2] Earlier investigations have shown that the passage of the solar terminator (ST) generates acoustic-gravity waves (AGW), turbulence and instabilities in the ionospheric plasma [*Beer*, 1973; *Cot and Teitelbaum*, 1980; *Somsikov*, 1995]. The above-cited papers used different methods of ionospheric radio sounding marked the beginning of numerous experimental observations of the "terminator" waves [e.g., *Drobzhev et al.*, 1992; *Dominici et al.*, 1997; *Galushko et al.*, 1998].

[3] The large-scale solar terminator waves were first discovered in neutral thermospheric densities [*Forbes et al.*, 2008]. The data originated from the accelerometric experiment onboard the CHAMP satellite between 2001 and 2007. During the solar minimum, the phase fronts of the dusk terminator wave during the Northern Hemispheric summer extend from about 60°S to almost +30°N latitude, at an angle of about 30° to the terminator.

[4] Recently a considerable progress has been made in the study of terminator waves using the new technology of GPS radio sounding and high spatial and temporal resolution determination of the total electron content (TEC). *Afraimovich* [2008] has obtained the first GPS-TEC evidence for the wave structure excited by the morning ST. Using TEC measurements from the dense network of GPS sites, GEONET, *Afraimovich et al.* [2009] have obtained the first GPS-TEC image of the space structure of high-frequency MSTIDs excited by the morning ST on 13 June 2008.

[5] The goal of this paper is to present detailed information regarding the spectral characteristics of the high-frequency MSTIDs excited by the ST as deduced from the dense GPS networks in Japan and California. We also provide a physical model conforming with observational data.

2. MSTID Dynamic Spectra and Solar Terminator Passing Over Observational and Magnetoconjugate Points

[6] We use RINEX data for 2008–2009 from the SOPAC and CORS networks in California, USA, (30–50°N; 230–250°E; about 900 sites in total) (http://sopac.ucsd.edu/other/services.html) and (ftp://www.ngs.noaa.gov/cors/rinex), respectively. We also employ data from the Japanese GPS network GEONET (30–50°N; 120–150°E; about 1225 sites in total) (ftp://terras.gsi.go.jp/data/GPS_products/). The geomagnetic situation during these days of 2008–2009 can be characterized as quiet: the Kp index varied from 1.0 to 3.0.

[7] The standard GPS technology provides a means of detection of wave disturbances based on phase measurements of slant TEC $I_0(t)$ at each of two-frequency spaced GPS receivers [*Hernández-Pajares et al.*, 2006]. The primary data include series of TEC slant values $I_0(t)$, as well as the corresponding series of elevations $\theta(t)$ and azimuths $\alpha(t)$ of the line of sight (LOS) to the satellite. Series of LOS elevations $\theta(t)$ and azimuths $\alpha(t)$ were used to determine coordinates of subionospheric points for selected height h_{max} of the F_2-layer maximum and to convert the slant TEC $I_o(t)$ to the corresponding value of the vertical TEC $I(t)$. All results in this study were obtained for elevation θ larger than 50°.

[8] To eliminate variations in the regular ionosphere, as well as trends introduced by orbital motion of the satellite, we remove TEC variations $dI(t)$ with a time period of more than 30 min. Then we smooth the $dI(t)$ with time window of 5 min. So we select the TEC variations in high-frequency part of MSTID spectrum [*Hocke and Schlegel*, 1996].

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0094-8276/09/2009GL039803$05.00

[9] The main characteristic of wave processes is their temporal spectrum. Calculating a single spectrum of TEC variations involves continuous series of $dI(t)$ lasting no less than 2.3 hours, thus enabling us to obtain a number of counts equal to 256 that is convenient for the algorithm of the fast Fourier transform used in this study. To improve the statistical validity of the data, we use a method involving a regional spatial averaging of TEC disturbance spectrum for all the GPS sites and PRNs (up to several millions spectra) [*Afraimovich et al.*, 2001].

[10] The hypothesis about a connection between MSTID generation and the ST appearance can be tested in the terminator local time (*TLT*) system: $dT = t_{obs} - t_{st}$, where t_{obs} is the data point time, and t_{st} is the time of the ST appearance at the altitude of H above this point [*Afraimovich et al.*, 2009]. By convention, we selected a value of H = 100 km for all our estimations.

[11] Figure 1 displays the dynamic spectra of MSTIDs versus the terminator local time (TLT) dT for the sunset (SS) ST passing over the points of observation: Figure 1a - summer in Japan, days 155–166, 182–187, 191–206, 2008; Figure 1b - summer in California, days 123–125, 131–147, 159–162, 165, 2008; Figure 1c - equinox in Japan, days 245–265, 2008; Figure 1d - winter in Japan, days 1–31, 2009.

[12] The dynamic spectra are calculated using m individual spectra: m = 3687173 for Figure 1a; m = 2381885 for Figure 1b; m = 2059177 for Figure 1c; m = 2811748 for Figure 1d. The TLT dT and variation frequency F steps are 0.5 h and 0.13 mHz, respectively. The amplitude of spectral components is about 0.02–0.1 TECU (scales for dI are plotted to the right). Vertical lines SS and MCSS mark the moments of SS ST passage over the observational point and the magnetoconjugate point (for conventional central points of the observational fields in Japan, 35°N, 135°E and in California, 35°N, 245°E).

[13] The most important discovery is that summer nighttime MSTIDs are registered in Japan 1.5–2.0 hours before the SS ST appearance over the observational point, when the evening ST passes over the magnetoconjugate (MCSS) point (Figure 1a). At the equinox, these moments (SS and MCSS) close coincide (Figure 1c), and MSTIDs are registered at once after ST appearance. Winter MSTIDs are recorded 1.5–3.0 hours after the evening SS ST occurrence at the point of observations, but when the evening ST passes over the magnetoconjugate point (Figure 1d).

[14] For comparison, Figure 1b shows the MSTID dynamic spectra for the summer California. There are certain distinctions in MSTID spectra between Japan and California. But similarly to Japan, summer MSTIDs in California are also registered 1.5–3.0 hours before the SS ST appearance over the observational point, when the evening ST passes over the magnetoconjugate point.

[15] Figure 2 presents the dynamic spectra of MSTIDs versus the universal time UT, argumentative about synchronism of MSTIDs appearance in selected region in Japan (30–50°N; 130–136°E) and near the magnetoconjugate field for this region, GPS site CEDU (−31.7°N; 131.8°E): Figure 2a - winter in Japan, days 1–26, 31, 2009; Figure 2b - winter in Australia, days 330–364, 2009; Figure 2c - summer in Japan, days 155–166, 182–187, 191–206, 2008; Figure 2d - summer in Australia, days 150–210, 2008. The dynamic spectra are calculated using m individual spectrum: m = 961548 for Figure 2a; m = 3959 for Figure 2b; m = 1277796 for Figure 2c; m = 7115 for Figure 2d. Vertical lines SS mark the moments of SS ST passage over the observational points. Unfortunately we can only used the data from a single GPS site CEDU. However even incomplete statistics show a complete symmetry of the seasonal dependence of the spectra at magnetoconjugate points (compare Figures 2a and 2d; Figures 2b and 2c). Our data support a result that MSTID occurrence rate becomes high simultaneously in Japan and Australia [*Kotake et al.*, 2006].

3. Slow Magnetosonic Eigen-Oscillations of the Magnetosphere

[16] Since the observed TEC oscillations are associated with the terminator passage through the magnetoconjugate ionosphere, it is only natural to assume that there is a mechanism for transferring the disturbances along magnetic field lines. Such a mechanism may be represented by an MHD wave sensitive to the geomagnetic field. In magnetospheric plasma, there are two kinds of MHD waves propagating along the geomagnetic field lines. They are the Alfven and the slow magnetosonic (SMS) waves. The typical characteristic periods of Alfven eigen oscillations in the magnetosphere at the latitudes under study (T_A < 10s) are several orders of magnitude less than the periods of the registered TEC disturbances (~20–30 min). This does not allow us to treat the Alfven waves as a mechanism for transferring the disturbances. A more probable mechanism is the SMS waves. A detailed analytical study of the structure of SMS eigen oscillations in a dipole model of the Earth's magnetosphere was presented by *Leonovich et al.* [2006].

[17] To make sure the above suggested model is realistic, we have carried out numerical computations of the periods of SMS eigen oscillations on the geomagnetic field lines whose intersection points with the ionosphere are located above the territory of Japan. To compute the medium parameters, we used the numerical Krinberg-Taschilin model, describing the plasma distribution in the ionosphere-plasmasphere system, detailed by *Krinberg and Taschilin* [1984]. This model served to calculate the daily dynamics of the magnetospheric plasma temperature and plasma density along the geomagnetic field lines. Since the most intriguing feature of the TEC variation spectrum has been obtained for summer, we chose the day of June 14, 2008.

[18] The results of computations for the point 36°N; 138°E are presented in Figure 3. The daily dynamics of the basic period t_S and frequencies of the first three harmonics of the SMS eigen oscillations $f_N = \Omega_{SN}/2\pi$ are shown. The LT scale is displaced 9.2 hours relative to UT.

[19] The computations imply that the frequency of the observed TEC oscillations corresponds to SMS eigen oscillations of the magnetosphere at the 2nd – 3rd harmonic (Ω_{SN}, N = 2, 3) during the terminator passage (Figure 3b). Closeness of the recorded oscillation frequencies to one of the first harmonics of the eigen oscillations is especially important, since the SMS waves decay strongly. If such a closeness involved the higher harmonics of the eigen oscillations, we would be justified to doubt if the SMS

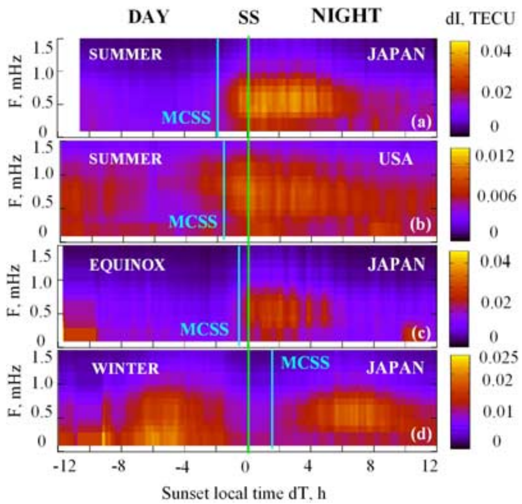

Figure 1. The dynamic spectra of MSTIDs versus the local terminator time $dT = t_{obs} - t_{st}$ between the time of observation t_{obs} and the time t_{st} of sunset (SS) ST passing over the observational points at the altitude 100 km: (a) summer in Japan; (b) summer in California; (c) equinox in Japan; (d) winter in Japan.

waves could reach the conjugate ionosphere with a noticeable amplitude (the smaller the scale of the SMS wave, the higher its dissipation). If the frequency of the recorded oscillations were much smaller than the frequency of the fundamental harmonic it would be impossible to construct a wave packet with the corresponding set of harmonics of the magnetospheric SMS eigen oscillations.

[20] The horizontal straight dashed line in Figure 3b marks the conventional upper boundary of the time window used for trend removal in TEC variations. The time intervals *TSS* and *TSR* (marked by filled ellipses) qualitatively correspond to the time intervals of MSTID observations in Figure 1.

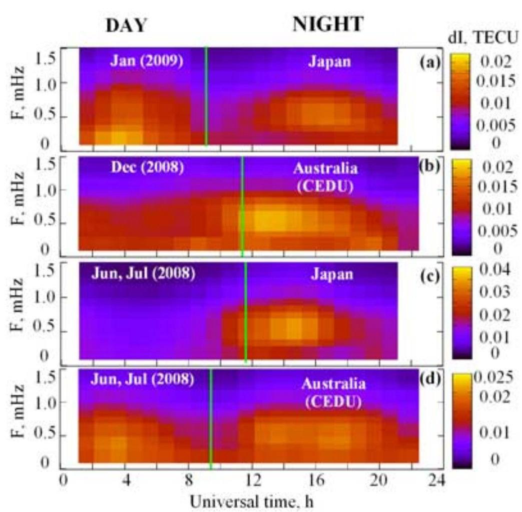

Figure 2. The dynamic spectra of MSTIDs versus the universal time UT, argumentative about synchronism of MSTIDs appearance in the magnetoconjugate fields in Japan (30–50°N; 130–136°E) and near GPS site CEDU (−31.7°N; 131.8°E): (a) winter in Japan; (b) winter in Australia; (c) summer in Japan; (d) summer in Australia.

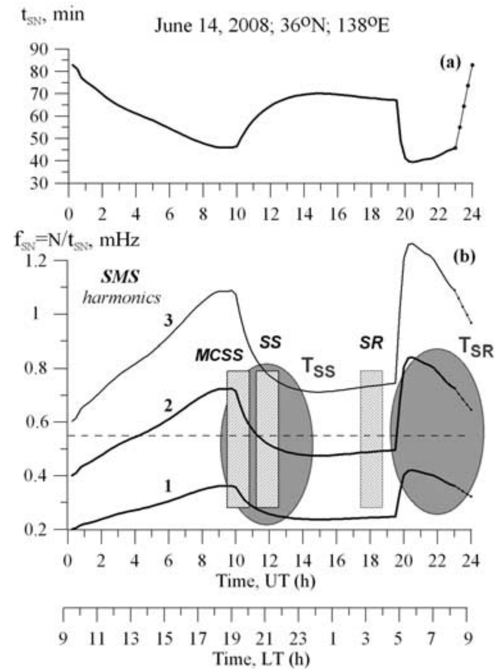

Figure 3. (a) Numerical computation of diurnal dynamics of the basic period of SMS eigen oscillations t_S on the field lines crossing the upper boundary of the ionospheric conductive layer over Japan at point 36°N, 138°E (June 14, 2008). (b) Diurnal dynamics of the SMS eigen frequencies $f_N = N/t_S$ of 1-st, 2-nd and 3-rd harmonics; filled bands corresponds to the time interval when the solar terminator passes over the observational point (SS and SR) and over the magnetoconjugate point (MCSS) at heights from 100 to 300 km.

[21] Figure 3 might make one conclude that the SMS oscillations can last 24 hours. It should be noted, however, that the mere presence of a magnetospheric resonator for SMS waves does not necessarily mean that the oscillations always exist in the resonator. As was noted above, these oscillations decay strongly. Consequently, in order for them to appear, the presence of a powerful source of the SMS oscillations is necessary, in addition to the resonator. The vertical motions of plasma due to the solar terminator passage are such a source.

[22] As was shown by *Leonovich et al.* [2006], the amplitudes of all the electromagnetic components of SMS wave field and components of the oscillation velocity across the field lines tend to zero when approaching the ionosphere. The only oscillation field component whose amplitude does not decrease near the ionospheres is the parallel component of velocity. Thus, near the ionosphere the SMS wave looks like the parallel plasma oscillations, which almost does not disturb the electromagnetic field. The vertical motions of plasma due to its heating and cooling after the terminator passage can be the driver of such oscillations.

[23] The filled bands in Figure 3b correspond to the time intervals of the solar terminator passing 100 to 300 km high above the observation point. It is possible to ascertain that the considerable variations in the fundamental period of the SMS eigen oscillations are synchronous with these inter-

vals. The sharpest increase of the frequencies f_{SN} occurs about 2 hours after the morning terminator passage (TSR). On the other hand, the high-frequency SMS oscillations, appear earlier than the evening terminator is seen at the observation point (SS) and are most likely to be synchronised with the evening terminator passage (MCSS) through the magnetoconjugate point. Thus, the main properties of the observed TIDs are close to the expected parameters of the magnetospheric SMS eigen oscillations.

4. Discussion and Conclusion

[24] We have obtained first experimental evidence in favour of the MHD nature of night-time MSTIDs. It was found that the diurnal, seasonal and spectral MSTID characteristics are determined by the solar terminator (ST) dynamics. In summer, MSTIDs are detected 1.5–3 hours before the evening ST at 100 km above the point of observations, but at the moment of the evening ST passage through the magnetoconjugate point. At the equinox MSTIDs are registered at once after ST appearance. In winter, MSTIDs are observed 1.5–3 hours after the evening ST occurrence at the point of observations, but at the moment of the evening ST passage in the magnetoconjugate point. The MSTID occurring synchronously with the ST passage through the magnetoconjugate area suggest that the ST-excited MSTIDs are of MHD nature.

[25] The results are in agreement with experimental data on the MSTID occurrence and spectrum [*Drobzhev et al.*, 1992; *Dominici et al.*, 1997; *Galushko et al.*, 1998; *Afraimovich et al.*, 2003; *Hernández-Pajares et al.*, 2006; *Kotake et al.*, 2006, 2007; *Tsugawa et al.*, 2007], which are based on limited statistical material.

[26] MSTIDs (including the terminator MSTIDs) are traditionally related to modulation of the electron density by AGWs generated in the lower atmosphere as the terminator passes over the observation point. However, this hypothesis does not agree with the night-time terminator wave characteristics we have found. The strongest argument against the AGW model of MSTIDs, at least for the summer night conditions, is our observations of MSTIDs 1.5–2 hour before the terminator passes over an observation point and the explicit dependence on the instant of the terminator passage through a magnetoconjugate point. This implies that the night-time MSTID formation depends on a number of phenomena at magnetoconjugate points and in the magnetic field line joining these points. Data from simultaneous optical observations of periodic structures in Japan and Australia also confirm this connection [*Otsuka et al.*, 2004; *Shiokawa et al.*, 2005].

[27] To explain the MSTID characteristics we have obtained, we used a model of standing slow magnetosonic waves developed by *Leonovich et al.* [2006]. The diurnal dependence of the SMS eigen oscillation period is in a qualitative agreement with the observed effects in high-frequency MSTIDs prior to and/or after the ST passage at observation and magnetoconjugate points. In summer SMS generation starts after the passage of the evening terminator at the magnetoconjugate point in the Southern Hemisphere (magnetoconjugate solar terminator, MST). A while (about one SMS period t_S) later, TEC modulation is registered in the magnetoconjugate area in the Northern Hemisphere. When the ST affects the magnetic field lines, this excites induced oscillations that decay over one period t_S.

[28] Thus, our results may be treated as the first experimental evidence for the existence of standing slow magnetosonic waves, which have been studied analytically by *Leonovich et al.* [2006]. Our model of slow magnetosonic waves is in agreement with modelling by *Huba et al.* [2000]. Those authors found that ion sound waves can be generated in the topside low-latitude ionosphere at sunrise and sunset.

[29] Both our experimenting and modelling and the model of ion sound waves [*Huba et al.*, 2000] agree with data of simultaneous GPS-TEC and DEMETER observations of daytime MSTIDs over North America by *Onishi et al.* [2009]. They found that the ion velocity along magnetic field lines at the satellite's altitude (660–710 km) correspond to the MSTID structures in the TEC map at 300 km altitude.

[30] In fact, we discovered a NEW PHENOMENON and have provided experimental proof for a possible detection of ST-generated ion sound waves using modern methods of ionospheric diagnostics.

[31] **Acknowledgments.** The authors thank V.A. Mazur and V.M. Somsikov for their interest to the work and fruitful discussion, Zhivetiev I.V. for data preparation. We acknowledge the SOPAC, CORS and GEONET for providing GPS data used in this study. The work was supported by the Interdisciplinary integral project of SB RAS N 56 and RFBR grants 07-05-00127 and 09-02-00082. The authors wish to thank the referees for their useful suggestions.

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