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ON THE SPACE-TIME LOCALIZATION OF INCIPIENT EARTHQUAKES BY DIAGNOSTICS OF DISTURBANCES IN THE IONOSPHERIC PLASMA USING A SPACE PROBE

This paper reports the results of in-situ probe diagnostics of local disturbances in the ionospheric plasma. The results are presented as the space–time distributions of the charged particle temperatures and densities measured by the electric probes onboard the DEMETER (France) and the distributions of the electron and neutral particle temperatures and densities measured by the Langmuir probe and the two-channel pressure probe onboard the Sich-2 (Ukraine). By the example of interpreting the output signals of the electric probes onboard the DEMETER (France), the Sich-2 (Ukraine), and the CSES (China), it is found that maxima in the electron and neutral particle temperature and density distributions along the spacecraft orbit in the ionospheric plasma correspond to the location of the epicenters of earthquakes incipient on the ground track. An additional parameter that improves the epicenter localization accuracy is the electron energy gain rate in the ionospheric plasma. It is shown that the relaxation times of maxima in the electron and neutral particle temperatures in the ionospheric plasma determine the time to the first shock of an earthquake incipient on the ground track.

Keywords: *earthquake, ionospheric plasma, ground track, electric probe, temperature relaxation time.*

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1. INTRODUCTION

The worldwide network of ground seismic stations and observatories allows one to detect earthquakes nearly at any point on the Earth's surface and in the oceans; however, they cannot detect incipient earthquakes. A substantial complement to the ground network of seismic stations may be a space segment: seismic activity monitoring with diagnostic instrumentation onboard spacecraft.

The ionospheric plasma is a sensitive indicator of the processes accompanying earthquake incipience. Based on the results of numerous observations of variations in the ionospheric plasma parameters, the basic ionospheric plasma disturbances induced by seismic activity were identified.

Disturbances in the charged particle parameters — the electron and ion temperature and density — were found to be earthquake precursors [1, 8, 9, 14, 16, 23].

The ionospheric plasma is a weakly ionized gas. At altitudes ≤1,000 km, the neural particle density is far (more than an order of magnitude) greater than the ion and the electron density. The state of the ionospheric plasma is largely governed by the processes of collisions and energy exchange between electrons, ions, and neutral particles. Information on collisions and energy exchange between charged and neutral particles may be used to analyze the ionospheric plasma response to inputs from below and increase the accuracy of data on seismic activity.

Satellite monitoring of variations in the ionospheric plasma parameters in the spacecraft orbit gives information on processes on the ground track. Measurements using onboard diagnostic instruments give space-time distributions of local values of the ionospheric plasma parameters along the spacecraft orbit.

In most cases, incipient earthquakes are identified by the total electron content (GPS signals received by ground stations) and by the electron density corresponding to the critical ionospheric frequency f_0F2 (measurements by ground vertical sounding stations). This gives information on the electron density averaged over the sounding path. Onboard probe systems give information on local disturbances in the ionospheric plasma parameters.

Electric probes have long been successfully used onboard spacecraft to diagnose the rarefied ionospheric plasma [2, 3, 7, 8, 9, 11, 20, 22]. The current-voltage characteristics of single Langmuir probes and multielectrode retarding-potential analyzers give local values of the electron and ion temperature and density in the ionospheric plasma. For example, in [8, 9, 18, 20], the maxima in the space-time distributions of the electron and ion temperature and density along the spacecraft orbit were used to localize the epicenters of earthquakes incipient on the ground track. As to the neutral particle parameters, little use has been made of them in localizing incipient earthquake epicenters.

The goal of this work is to show that the use of space-time distributions of the electron and neutral particle temperature and density along the spacecraft orbit measured with specially designed probes (a cylindrical Langmuir probe and a two-channel electric pressure probe) allows one to localize the epicenter of an earthquake incipient on the ground track and predict the time to its first shock.

2. ELECTRIC PROBES ONBOARD THE DEMETER AND THE SICH-2

2.1. DEMETER satellite (France). The DEMETER satellite (125 kg) was launched on June 29, 2004, to study ionospheric disturbances associated with earthquakes. The DEMETER orbit: a perigee of 685 km, an apogee of 712 km, and an inclination of 98.2°. In December 2005, the orbit lowered to 660 km. The satellite was operable for about six years. To diagnose and monitor the ionospheric plasma, three probe systems were used: two identical cylindrical Langmuir probes (ISL, Instrument Sonde de Langmuir, a measuring electrode of radius r_p = 0.15 cm and length l_p = 5.0 cm with a guard electrode of length ~2.5 cm); a segmented Langmuir probe (SLP, a sphere of diameter 4.0 cm made up of six measuring electrodes); and a multielectrode thermal plasma ion analyzer (IAP, Instrument d'Analise du Plasma). The electron density N_e and temperature T_e were calculated from the ISL current-voltage characteristics. The ion density N_i and temperature T_i were determined from the IAP output signals. The neutral component of the ionospheric plasma was not diagnosed onboard the DEMETER [8].

2.2. Sich-2 satellite (Ukraine). The Sich-2 satellite (145 kg) was put into a heliosynchronous circular orbit of altitude ~700 km and inclination ~98.1° on August 17, 2011. The satellite was equipped with two probe systems: a charged particle detector (DE, a cylindrical Langmuir probe of radius $r_p = 0.05$ cm and length $l_p = 12.0$ cm with a guard electrode of radius $r_g = 0.2$ cm and length $l_g = 12.5$ cm) and a neutral particle detector (DN, a two-channel electric pressure probe).

The probes were developed by the authors and made at the Institute of Technical Mechanics, National Academy of Sciences of Ukraine. The Langmuir probe serves to determine the electron density N_e and temperature T_e from its current-voltage characteristic.

The electric pressure probe serves to determine the neutral particle density N_n and temperature T_n in a partially ionized rarefied plasma flow from its output signals (the measuring channel currents). The outer diameter of the case $D_n = 70$ mm, the height $h_n = 100$ mm, the measuring channel inlet diameter $d_{ch} = 8.5$ mm, and the tube length $l_{ch} = 50$ mm. The measuring channels of the probe are orthogonal. The normal $\mathbf{n}_1$ to the inlet aperture of channel 1 is parallel to the neutral particle velocity $\mathbf{U}_n$ ($\mathbf{n}_1 \parallel \mathbf{U}_n$), i. e., to the spacecraft velocity $\mathbf{U}_\infty$ in the ionosphere. The normal $\mathbf{n}_2$ to the inlet aperture of channel 2 is perpendicular to the neutral particle velocity ($\mathbf{n}_1 \perp \mathbf{U}_n$).

Before installing the DE and DN probes on the Sich-2, comprehensive studies were conducted to simulate their interaction with rarefied hypersonic plasma flows on the ITM plasmaelectrodynamic setup: physical and numerical simulation (the solution of the Vlasov — Poisson equations) [19, 21, 22]. The probes were tested in an atomic-molecular nitrogen plasma at ion velocities 8.3...10.5 km/s, electron densities $N_e = 10^6...10^{10}$ cm^{-3}, electron temperatures $T_e = 0.8...2.5$ eV, ion dissociation degree $\xi_{d_i} = 0.7...0.79$, plasma ionization degree $\varepsilon_i = 0.001...0.1$, and ion-to-electron temperature ratio $T_i/T_e = 0.2...0.4$. The measurement accuracy provided by the DE and DN probes was determined by comparing the plasma parameter values measured with them with those registered using the ITM setup diagnostic system: cylindrical, spherical, and plane Langmuir probes, a Faraday cup, and a multielectrode retarding-potential analyzer. The dissociation degree was measured with an MKh 7303 mass-spectrometer. In addition to the probe diagnostics system, the electron density was measured using 3 to 9.8 GHz interferometers.

The error in plasma probe diagnostics is governed by two components: the probe current measurement error and the error of analytical and approximate mathematical relationships that describe the collection of plasma particles by a probe.

The Sich-2's scientific information acquisition system developed and made at the Lviv Center of the Institute for Space Research of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine measured the currents to the working electrodes of the DE and DN probes with an error less than 1.0 % in the range from 10^{-7} to 10^{-4} A. The physical and numerical simulation of the interaction of the DE and DN probes with a hypersonic flow of the ionospheric plasma made it possible to get analytical and approximate relationships for the current to the DE cylindrical probe and the pressure (the output signal of the DN probe). The accuracy of those relationships for the ionospheric conditions was checked by comparing the measured values of the probe output signals with the calculated ones; for the DE probe, use was made of the current-voltage characteristics measured with the cylindrical probes onboard the Intercosmos-10 [11], DEMETER [8], and Explorer-17 [2].

It was found that the calculated current-voltage characteristics of the DF cylindrical probe in the electron saturation current mode approximated the measured ones with an error less than 2 %. The total error for the DE probe does not exceed 3 % [21]. In estimating the error introduced by the computed current-voltage characteristics of the DE probe, the reference data were the angular pressure cyclograms measured by the magnetron-type probe and the cold-anode probe onboard the Explorer-32 [13]. It was found that the calculated output signals of the DN pressure probe agreed with the measured values in the angle θ range from –90° to +90° with an error not greater than 5 % where θ is the angle between the spacecraft velocity and the normal to the inlet opening plane of the probe's measuring channel. The total error in measuring the DN probe output signal does not exceed 6...7 % [13, 19, 22].

The neutral particle temperature in a plasma flow is proportional to the squared ratio of the currents in the two mutually orthogonal probe channels: $T_n \propto (I_2/I_1)^2$. The neutral particle density is proportional to the output signal (current) of channel 2: $N_n \propto I_2$.

The symmetry axis of the Langmuir probe onboard the Sich-2 was parallel to the Earth's surface and orthogonal to the spacecraft's velocity and the Earth's magnetic field. The electron current saturation portion of the current-voltage characteristic was measured and processed at a probe potential from 0 to +6.95 V [21]. The combined use of the cylindrical Langmuir probe and the pressure probe allows one to determine not only the electron density N_e and temperature T_e but also the neutral particle density N_n and temperature T_n in the ionospheric plasma. The ion component of the ionospheric plasma was not diagnosed onboard the Sich-2.

The output signals from the two-channel pressure probe are measured within a time of $\Delta\tau_n \le 0.1$ s, which corresponds to a distance of $\Delta z_n \sim 750$ m on the ground track. The electron saturation current is measured within a time of $\Delta\tau_e \le 0.3$ s, which corresponds to a distance of $\Delta z_e \sim 2{,}300$ m on the ground track.

3. ELECTRON ENERGY BALANCE IN THE IONOSPHERIC PLASMA

According to the concept of a global electric circuit and the penetration of a vertical electric field into the ionosphere over a seismic activity zone [14, 15], it is Joule heating that increases the temperatures and particle densities in the plasma. In a steady state, the energy imparted by Joule heating to a unit volume of the electron gas in a unit time is equal to the energy it loses due to electron-ion and electron-neutral collisions, and this energy balance may be represented as [4, 5, 10]

$$Q_e = \frac{3}{2}kT_eN_e\left[\left(1-\frac{T_n}{T_e}\right)\delta_{en}\nu_{en} + \left(1-\frac{T_i}{T_e}\right)\delta_{ei}\nu_{ei}\right], \quad [\mathrm{W/m^3}], \tag{1}$$

where Q_e is the electron energy gain rate, k is the Boltzmann constant, δ_{en}, δ_{ei} are the fractions of the electron energy loss by electron-neutral and electron-ion collisions, and ν_{en}, ν_{ei} are the electron-neutral and electron-ion collision rates. For Joule heating $Q_e = \mathbf{J_e}\cdot\mathbf{E}_\mathrm{p} = \sigma_e E_p^2 \big/ \left(1+\beta_e^2\right)$ [10]

$$E_p^2 = \frac{3}{2}\frac{kT_e}{e}\left(\frac{m_e}{e}\right)\times$$
$$\times\left[\left(1-\frac{T_n}{T_e}\right)\delta_{en}\nu_{en} + \left(1-\frac{T_i}{T_e}\right)\delta_{ei}\nu_{ei}\right](\omega_{eB}^2+\nu_{e\Sigma}^2)\big/\nu_{e\Sigma},$$

or

$$E_p = 2.92\times10^{-6}\left\{\frac{kT_e}{e}\left[\left(1-\frac{T_n}{T_e}\right)\delta_{en}\nu_{en} + \left(1-\frac{T_i}{T_e}\right)\delta_{ei}\nu_{ei}\right]\left(\omega_{eB}^2+\nu_{e\Sigma}^2\right)\big/\nu_{e\Sigma}\right\}^{1/2}, \ [\mathrm{V/m}]$$

where $\mathbf{J_e}$ is the electron current density, $\mathbf{E_p}$ is the electric field; σ_e is the plasma conductivity, $\beta_e = \omega_{eB}/\nu_{e\Sigma}$, $\nu_{e\Sigma} = \nu_{ei}+\nu_{en}$, and ω_{eB} is the electron cyclotron frequency.

The magnetic field does not affect the electron velocity component parallel to $\mathbf{B}_\infty$; it only affects the electron motion in a direction perpendicular to $\mathbf{B}_\infty$. The transfer coefficients along the magnetic filed lines are equal to those in the absence of a magnetic field ($\mathbf{B}_\infty = 0$) [5].

The electric field component parallel to $\mathbf{B}_\infty$ is

$$E_{\|p} = 2.92\times10^{-6}\left\{\frac{kT_e}{e}\left[\left(1-\frac{T_n}{T_e}\right)\delta_{en}\nu_{en} + \left(1-\frac{T_i}{T_e}\right)\delta_{ei}\nu_{ei}\right](\nu_{en}+\nu_{ei})\right\}^{1/2} \ [\mathrm{V/m}]. \tag{2}$$

For electrons of the ionospheric plasma at altitudes of 200...700 km, inelastic collisions with neutral particles are predominant. The electron energy loss factor $\delta_{e\mathrm{O}}$ in collisions with atomic oxygen (AO) is [5]

$$\delta_{e\mathrm{O}} = \frac{6.6\times10^{-5}}{T_n\cdot T_e^{1/2}}, \tag{3}$$

where T_n and T_e are in eV.

With consideration of the data from [5], for e — O inelastic collisions, it follows

$$\delta_{e\mathrm{O}}^*\nu_{e\mathrm{O}}^* = 2\times10^{-12}\,N_\mathrm{O}\big/T_n, \tag{4}$$

where T_n is in eV, and N_O is the AO density (in cm^{-3}).

The ion temperature T_i appearing in Eqs. (1) and (2) is determined from the equation

$$T_i = T_n + \frac{T_e - T_n}{1+\delta_{in}\nu_{in}/\delta_{ei}\nu_{ei}}, \tag{5}$$

where δ_{ia} is the fraction of the ion energy loss by ion-electron ($\alpha = e$) and ion-neutral ($\alpha = n$) collisions, and ν_{ia} is the ion-electron and ion-neutral collision rate, $\nu_{ei} = 3.64\times10^{-6} N_i \ln\Lambda / T_e^{3/2}$, $\Lambda = 1.24\times10^7 \left(T_e^3/N_e\right)^{1/2}$, $N_i \approx N_e$, $N_{e,i}$ in cm^{-3} and T_e in K [10].

The O$^+$ and He$^+$ ion temperature T_i is found from Eq. (5) using iterative procedures because the ion-neutral collision rate for the resonant charge exchange $\mathrm{O^+ + O \to O + O^+}$ and $\mathrm{He^+ + He \to He + He^+}$ depends on T_i

$$\nu_{in} \sim \nu_{\mathrm{O^+ + O}} \sim 1.8\times10^{-9}(T_i + T_n)^{1/2} N_{\mathrm{O}},$$

$$\nu_{in} \sim \nu_{\mathrm{He^+ + He}} \sim 3.3\times10^{-9}(T_i + T_n)^{1/2} N_{\mathrm{He}},$$

and the resonant charge exchange cross-section is a function of T_i and T_n.

As a first approximation, in Eqs. (1), (2), and (5) the equality $T_i \approx T_n$ is used for altitudes $h = 200\ldots700$ km at night and 200...500 km in the daytime, and $T_i \approx (T_e + T_n)/2$ is used for altitudes of 600...700 km. For the AO charge exchange reaction, it is adopted $\delta_{in} = \delta_{\mathrm{O^+ + O}} \approx 1/2$ [5].

For elastic collisions

$$\left(\delta_{e\mathrm{O}}\nu_{e\mathrm{O}}\right)_{ela} / \delta^*_{e\mathrm{O}}\nu^*_{e\mathrm{O}} \approx T_e^{1/2} T_n << 1$$

in Eqs (2), (4), and (5) the factor $\delta_{en}\nu_{en}$ for the "e — O" system is put equal to $\delta^*_{e\mathrm{O}}\nu^*_{e\mathrm{O}}$. For "$e$ — He" collisions at $T_e = 0.1\ldots0.3$ eV, it follows that

$$\delta_{e\mathrm{He}} \approx \delta_{ela} \approx 2.8\times10^{-4}$$

and

$$\delta_{e\mathrm{He}}\nu_{e\mathrm{He}} \approx 1.4\times10^{11} N_{\mathrm{He}} T_e^{1/2}$$

where N_{He} is in cm^{-3} and T_e is in eV.

4. RELAXATION TIME OF THE PLASMA ELECTRON AND NEUTRAL PARTICLE TEMPERATURES

A shock relieves the stresses accumulated in the Earth's crust and the electric field that heats the ionospheric plasma. The disturbed plasma parameters relax to their undisturbed values by particle collisions, diffusion, and recombination. At first, the electron temperature relaxes by electron-neutral collisions [4, 17], and the relaxation times may be represented as

$$t_{r_1} = \frac{2.8\times10^{-4}}{\delta_{en}\nu_{en}} \left| \ln\frac{T_{0e} - T_{0n}}{T_e^{\max} - T_n^{\max}} \right|, \text{ [h]}, \qquad (6)$$

and if δ_{en} and ν_{en} depend on the temperatures, then at $\delta_n\nu_n \propto T_e^{0.5}$ and $T_e > T_n$, the time dependence of the electron temperature $T_e(t)$ in the ionospheric plasma for O, He, and H may be determined as

$$t_{r_2} = \frac{5.6\times10^{-4}}{\delta_{en}\nu_{en}} \left[\left(T_e^{\max}/T_{0e}\right)^{0.5} - 1 \right], \text{ [h]} \qquad (7)$$

where $t_{r_{1,2}}$ is the temperature relaxation time by Eqs. (6) and (7), respectively.

5. SPACE-TIME LOCALIZATION OF EARTHQUAKES ON THE GROUND TRACK

5.1. DEMETER. Figure 1 shows the space-time distributions of the ionospheric plasma parameters calculated from the output signals of the DEMETER electric probes [8]. The maxima in the space-time distributions of the electron and ion density and temperature were detected at satellite flyover time UT$_1$ ≈ 15:50:37, and they correspond to the intersection of the magnetic equator and the ground track. The measurements were made at night (local time LT ≈ 22.30 h). The most probable source of the local disturbances in the ionospheric plasma parameters over Sumatra at night was an M 8.6 earthquake at a depth of h_d~14 km. The earthquake struck at UT$_2$ ≈ 16:09:36, i. e., ΔUT ≈ UT$_2$ – UT$_1$ ≈ +18 min after the DEMETER flew over the epicenter [8]. The DEMETER electric probes detected the local disturbance in the ionospheric plasma parameters ΔUT ≈ ≈ 0.3 h in advance of the shock. Thus, the effect of an earthquake as a source of ionospheric plasma disturbances manifests itself as maxima in the space-time distributions of N_e, T_e, and T_i along the spacecraft orbit detected over the earthquake epicenter on the ground track.

Figure 2 shows the space-time distributions of the electron density N_e and temperature T_e found from the output signals of the DEMETER cylindrical Langmuir probe (ISL) in the daytime before and after the Haiti earthquake [18], which struck on January 12, 2010 at LT$_2$ = 16:53 (UT$_2$ = 21:53) at the point Lat = 18.44°N, Long = 72.57°W (Leogan, Haiti) on the ground track (Fig. 2, *a*). The maxima $T_e^{\max}$ and $N_e^{\max}$ were detected on January 11, 2010 over the epicenter in the daytime (LT = 10:00) and at night (LT = 21:00) in geomagnetically quiet conditions: 3-hour planetary index of geomagnetic activity $Kp \approx 1$ and equivalent planetary amplitude index $Ap = 9\ldots4$, i.e., nearly 24 hours before the M 7.0 first

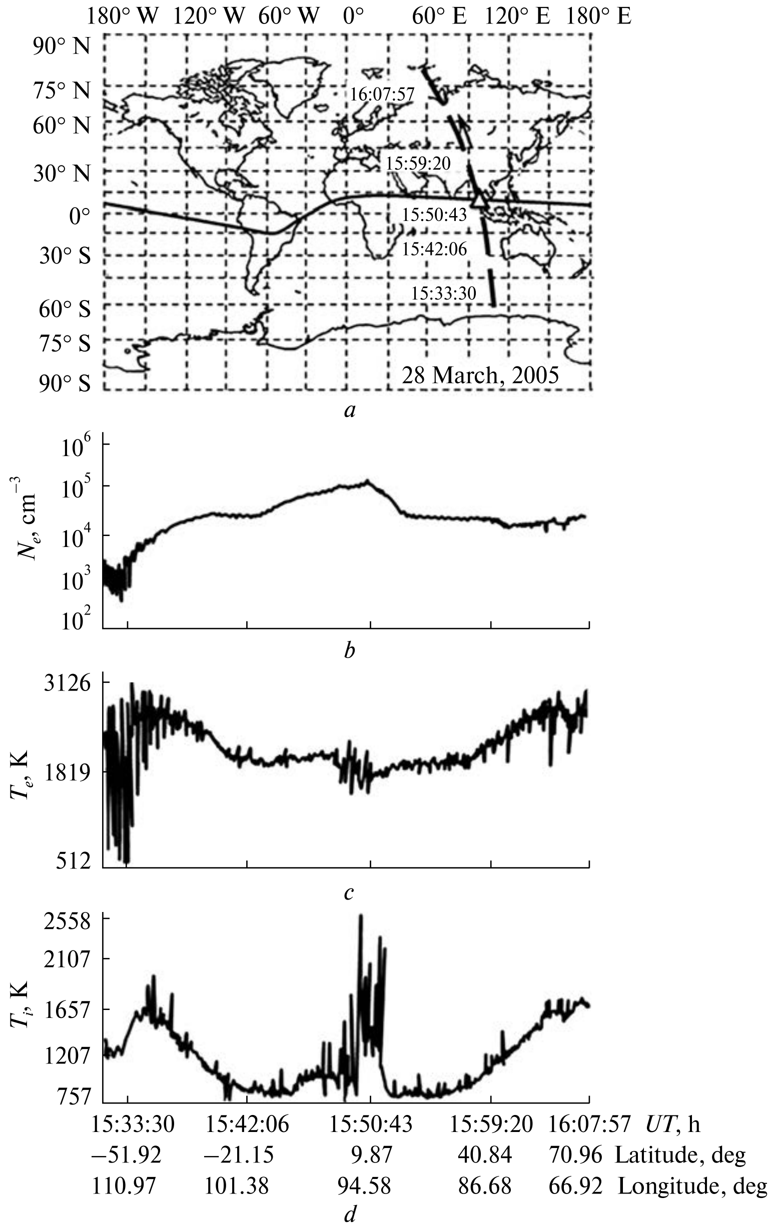

Figure 1. Space-time localization of the Sumatra earthquake (DEMETER, March 28, 2005): *a* — earthquake localization (dashed curve — ground track, solid curve — magnetic equator, triangle — epicenter), *b—d* — distribution of the electron density N_e, electron temperature, T_e and ion temperature T_i along the orbit

shock. The disturbed parameter values $N_e^{\max}/N_{0e}$, $T_e^{\max}/T_{0e}$, and $Q_e^{\max}/Q_{0e}$ are shown in Table 1: $T_e^{\max} =$ = 4,400 K (day), and T_{0e} is the electron temperature averaged over ±40 days before and after the first shock: $T_{0e} = T_e^{mid}$ = 2,300 K. The electron density is adopted as $N_e^{\max}$ = 1.6×10^4 cm^{-3} and $N_{0e} = N_e^{mid}$ = 10^4 cm^{-3}.

January 2010 was the beginning of a new solar activity cycle, a minimum-to-mid activity transition. For "transitional" solar activity (between min and mid), the AO temperature and density at the DEMETER orbit altitude ~660 km [18] are adopted as $T_{0n} \approx$ 1,000 K, $T_n^{\max}$ = 1,300 K, and N_O =

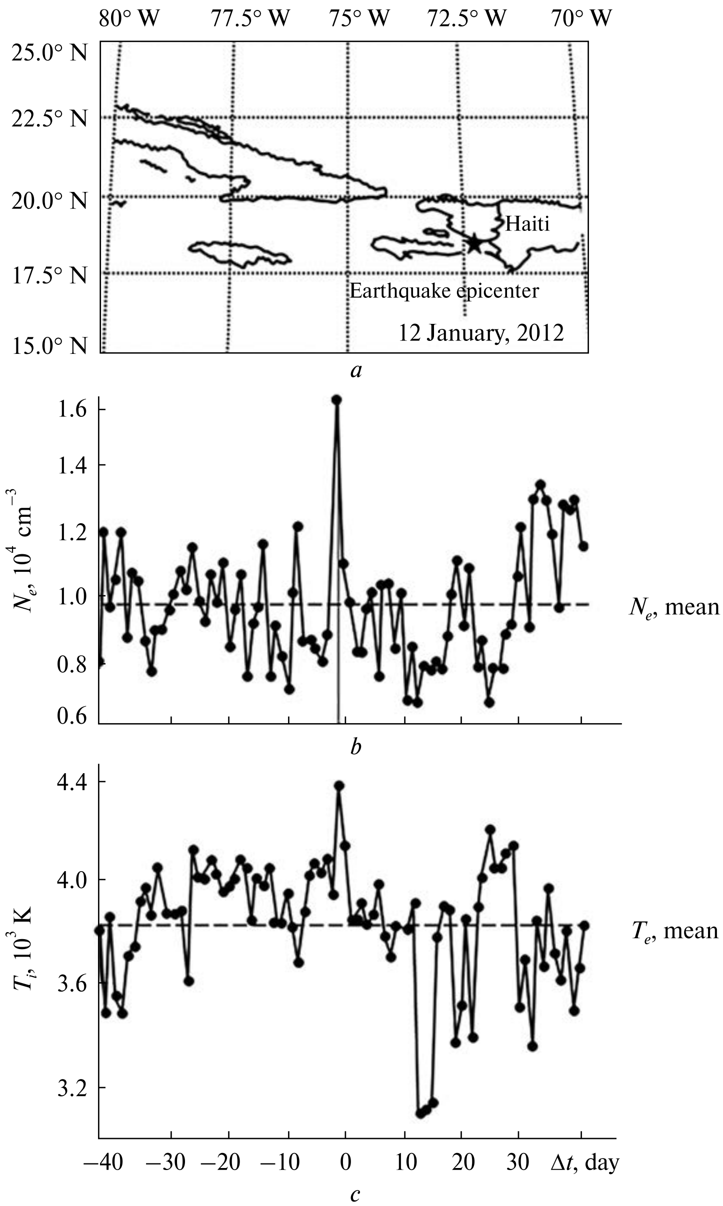

Figure 2. Electron parameter disturbance, induced by the Haiti earthquake (DEMETER, January 1, 2010): *a* — spatial localization of the earthquake epicenter, *b* — disturbance in the electron density N_e before and after the earthquake, *c* — time history of the electron temperature T_e before and after the earthquake (Δt — time reckoned from the first shock January 12, 2010)

$= 4 \times 10^5$ cm^{-3} according to [6, 12]. For these parameter values and the DEMETER flyover time $\mathrm{LT}_1 = 10{:}00$ h, the following particle temperature relaxation time is obtained using Eq. (7): $t_{r_2} \approx 18{:}36$. As a result, for t_{r_2} and the January 12, 2010 first shock time $\mathrm{LT}_2 =$ 16:53 h the time advance is $\Delta \tilde{\mathrm{LT}}_2 = \mathrm{LT}_2 - \left(\mathrm{LT}_1 + t_{r_2}\right) \approx$ +11:17. The relaxation time was estimated using the neutral particle parameters by the International Reference Ionosphere — 2012 (IRI-2012) and the NRLMSIS-00 model [6, 12].

On August 21, 2018, the Langmuir probe (LAP) and the retarding potential analyzer (RPA) onboard the CSES (China) detected peaks in the AO ion density N_{O^+} and the electron density N_e over the epicenter of an M 7.3 earthquake, which was incipient at the CSES flyover time and struck in the coastal waters Carúpano, Venezuela, at Lat = 10.74°N, Long = 62.98°W at UT_2 = 21:31. The sharp peaks in N_{O^+} and N_e are shown in Fig. 5 of [9]. The CSES was launched on February 2, 2018 into an orbit with an altitude of ~507 km and an inclination of ~97.4°.

Table 1 shows the relative values $\delta F_\alpha = F_\alpha^{\max} / F_{0\alpha}$, $F_\alpha^{\max} = T_\alpha^{\max}$, $N_\alpha^{\max}$, $Q_\alpha^{\max}$, and $E_{\alpha p}^{\max}$ ($\alpha = e, i, n$ for T, and $\alpha = e$ for N and Q) measured with the probes onboard the DEMETER and the Sich-2 and calculated in geomagnetically quiet conditions (the $F_{0\alpha}$'s are the undisturbed plasma parameters). Values greater than one ($\delta F_\alpha > 1$) are characteristic not only of δN_e, δT_e, and δT_i, but of δQ_e and $E_{\alpha p}^{\max}$ as well.

5.2. Sich-2. Figure 3 shows the earthquake epicenters localized by the output signals of the electric probes onboard the DEMETER (1 and 2) and the Sich-2 (3—6). The Sich-2 ground track and the magnetic equator are shown as a dashed and a solid curve, respectively.

In the Northern Hemisphere on May 24, 2012, when the Sich-2 flew over the area with the coordinates Lat = 73.0°N, Long = 5.7°E at $UT_1 \approx 19.8$ h, its probes detected local disturbances in the neutral and charged components of the ionospheric plasma: $T_e^{\max} \sim 3{,}100$ K and $T_n^{\max} \sim 1{,}300$ K. The space-time distributions of N_e, T_e, T_n, and N_n calculated from the output signals of the Sich-2 probes are shown in Figure 4.

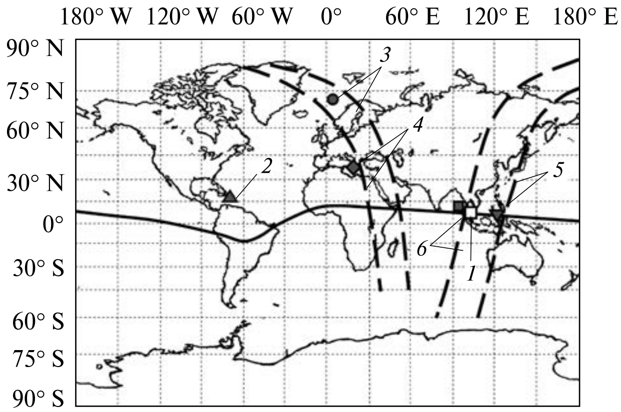

Figure 3. Earthquake epicenter localization by the output signals of the electric probes onboard the DEMETER (*1*— March 28, 2005, Sumatra, *2* — January 12, 2012, Haiti) and the Sich-2 (*3* — May 24, 2012, *4* — November 11, 2011, *5* — September 14, 2011, *6* — October 2, 2011). Dashed curves — ground track, solid curve — magnetic equator

The earthquakes on the ground track:

- May 24, 2012:
  $UT_{21} \approx 22.05$ h, Lat = 72.96°N,
  Long = 5.68°E, $h_d \approx 10$ km; and M 6.1;
- May 25, 2012:
  $UT_{22} \approx 0.05$ h, Lat = 72.94°N,
  Long = 5.52°E, $h_d \approx 10$ km; and M 5.0;
- May 25, 2012:
  $UT_{23} = 4.05$ h, Lat = 72.90°N,
  Long = 5.54°E, $h_d \approx 10$ km; and M 4.9.

Table 1. **Relative values of the ionospheric plasma parameters**

Relative plasma parameter values $\delta F_\alpha = F_\alpha^{\max} / F_{0\alpha}$	Spacecraft flight over the epicenter			
	DEMETER March 28, 2005 Sumatra	DEMETER January 12, 2010 Haiti	Sich-2 May 24, 2012 Norwegian Sea	Sich-2 November 23, 2011 Mediterranean Sea
$N_e^{\max} / N_{0e}$	1.25	1.60	1.54	2.67
$T_e^{\max} / T_{0e}$	1.12	1.91	1.11	1.73
$T_i^{\max} / T_{0i}$	1.38	—	—	—
$T_n^{\max} / T_{0n}$	—	—	1.23	1.42
$Q_e^{\max} / Q_{0e}$	1.74	8.68	3.21	4.62
$E_{\alpha p}^{\max} / E_{0\alpha p}$	—	—	1.44	1.68

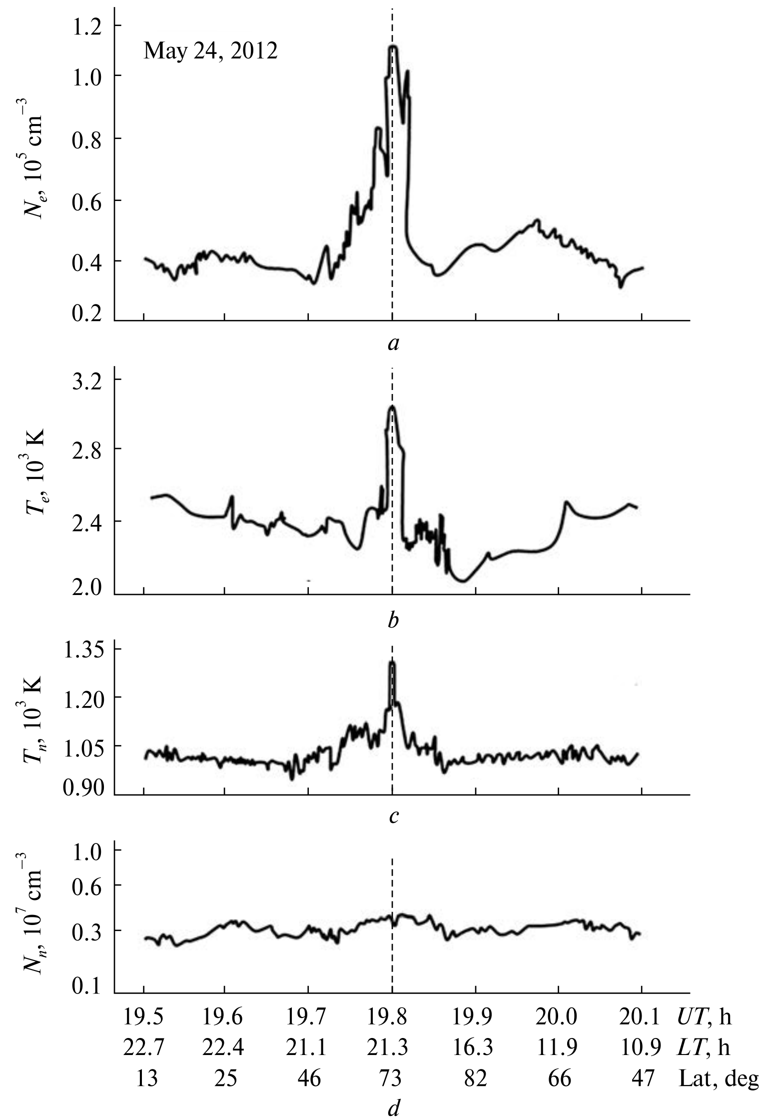

Figure 4. Space-time distributions of the ionospheric plasma parameters, measured by the Sich-2 probes on May 24, 2012: *a* — electron density N_e, *b* — electron temperature T_e, c — neutral particle temperature T_n, *d* — neutral particle density N_n

The shock nearest to the Sich-2 flying over the May 24, 2012 earthquake epicenter ($\mathrm{UT}_1 \approx 19.8$ h) struck at $\mathrm{UT}_{21} \approx 22.05$ h: the local parameter disturbances were detected $\Delta\mathrm{UT} \approx \mathrm{UT}_{21} - \mathrm{UT}_1 \approx +2.25$ h in advance of the first shock. The disturbances were detected at night in geomagnetically quiet conditions: from May 22 to May 26, 2012, the geomagnetic activity indices *Kp* and *Ap* varied from 3 to 0 and from 15 to 12, respectively, at sunspot number $R_s \approx 69$. The May 24, 2012 values of $\delta F_\alpha = F_\alpha^{\max} / F_{0\alpha}$ are shown in Table 1 ($Q_e^{\max} = 1.06\times10^{-11}$ W/m^3 and $E_{\|p}^{\max} = 2.91\times10^{-7}$ V/m). The relaxation times $t_{r_{1,2}}$ of the temperatures $T_e^{\max}$ and $T_n^{\max}$ by Eqs. (6) and (7) are $t_{r_1} \approx 1.8$ h and $t_{r_2} \approx 3.1$ h. Therefore, the estimated time of the first shock after the Sich-2 flyover is $\mathrm{UT}_{21}^{*} = \mathrm{UT}_1 + t_{r_1} \approx 21.64$ h and $\widetilde{\mathrm{UT}}_{21} = \mathrm{UT}_1 + t_{r_2} \approx 22.50$ h. The variation of the actual first shock time UT_{21} from its estimated value is $\Delta\mathrm{UT}_{21}^{*} = \mathrm{UT}_{21} - \mathrm{UT}_{21}^{*} \approx +0.41$ h and $\Delta\widetilde{\mathrm{UT}}_{21} = \mathrm{UT}_{21} - \widetilde{\mathrm{UT}}_{21} \approx -0.45$ h for $t_{r_1} \approx 1.8$ h and for $t_{r_2} \approx 3.1$ h, respectively.

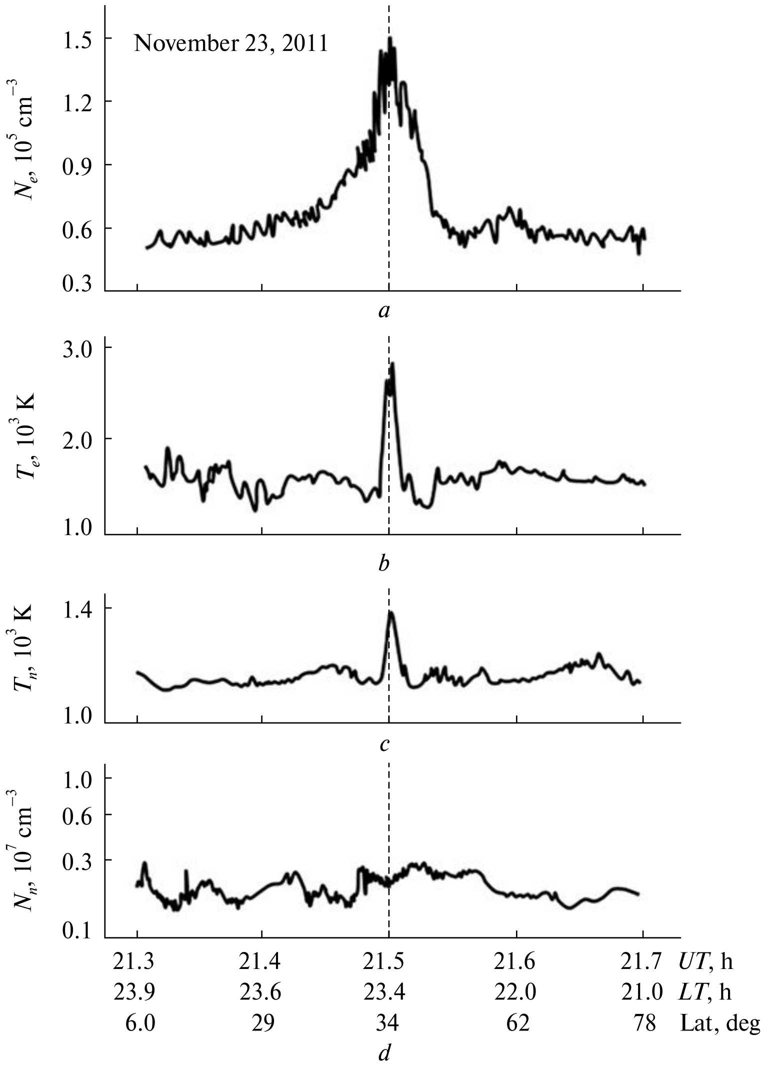

Figure 5. Ionospheric plasma parameter distribution along the Sich-2 orbit, measured by the onboard electric probes on November 23, 2011: *a* — electron density N_e, *b* — electron temperature T_e, *c* — neutral particle temperature T_n, *d* — neutral particle density N_n

When on the night of November 23, 2011 at $UT_1 =$ $= 21.5$ h the Sich-2 flew over the point Lat = 34.3°N, Long = 25.1°E, its probes detected the following maxima: $N_e^{max} = 1.6\times10^5$ cm^{-3}, $T_e^{max} = 2{,}900$ K; $T_n^{max} = 1{,}350$ K; $Q_e^{max} = 1.45\times10^{-11}$ W/m^3; and $E_{\|p}^{max} = 3.83\times10^{-7}$ V/m. The November 23, 2011 space-time distributions of the ionospheric plasma parameters along the Sich-2 orbit are shown in Figure 5 ($UT_1 \approx 21.5$ h). The measurements were made at night in geomagnetically quiet conditions at $Kp = 1_+ - 2$, $Ap = 6$-7, and $R_s = 81$.

According to the USGS (United States Geological Survey; https://earthquake.usgs.gov) data, two shocks were detected at the point Lat = 34.3°N, Long = 25.1°E on the ground track on November 23, 2011 before the Sich-2 flyover: $UT_{21} = 12.53$ h, $h_d = 10$ km, and M 5.5; $UT_{22} = 13.53$ h, $h_d =$ $= 10$ km, and M 4.8, and an earthquake was detected on November 24, 2011 after the Sich-2 flyover: $UT_{23} = 17.53$ h, $h_d = 5$ km, and M 4.0.

From November 19 to November 26, 2011, the geomagnetic activity indices Kp and Ap varied from 1 to 2 and from 3 to 7, respectively. Thus, the most probable sources of the local disturbances in the ionospheric plasma parameters were the shocks that struck on the ground track at $\Delta UT_{21} = UT_{21} - UT_1 \approx \approx -9.0$ h and $\Delta UT_{22} = UT_{22} - UT_1 \approx -8.0$ h before or $\Delta UT_{23} = UT_{23} - UT_1 \approx +20.0$ h after the Sich-2 flyover.

The relaxation time of the electron temperature $T_e^{\max}$ and the neutral particle temperature $T_n^{\max}$ to their unperturbed values in the ionospheric plasma is estimated by Eqs. (6) and (7) as $t_{r_1} \approx 19.3$ h and $t_{r_2} \approx \approx 20.9$ h. For these values of $t_{r_{1,2}}$, the estimated time $UT_{23}^* = UT_1 + t_{r_1}$ of the first shock after the Sich-2 flyover is about $UT_{23}^* \approx 16.8$ h for $t_{r_1} \approx 19.3$ h and about $U\tilde{T}_{23} = UT_1 + t_{r_2} \approx 18.4$ h for $t_{r_2} \approx 20.9$ h. The variation of the actual first shock time from estimated values is $\Delta UT_{23}^* = UT_{23} - UT_{23}^* \approx +0.73$ h and $U\tilde{T}_{23} \approx -0.87$ h for $t_{r_1} \approx 19.3$ h and $t_{r_2} \approx 20.9$ h, respectively.

5.3. Equatorial ionization anomaly. The identification of sources of local disturbances in the ionospheric plasma parameters is complicated in the case of the combined effect of several sources, for example, an earthquake in the zone of the magnetic equator and the equatorial ionization anomaly (EIA) in the daytime. The EIA effect manifests itself in the daytime as maxima in the space-time distributions of the electron and ion density N_e and N_i and minima in the distributions of the electron and ion temperature T_e and T_i over the intersection of the magnetic equator and the ground track.

On September 1, 2011 at UT = 01.1 h (LT = = 10.7 h) over the point Lat ≈ 6.9°N, Long ≈ 141°E at the intersection of the ground track and the magnetic equator, the Sich-2 electric probes detected a maximum in the distribution of N_e and a minimum in the distribution of T_e (Figure 6). The measurements were made in geomagnetically quiet conditions at $Kp = 1_+$, $Ap = 5$, and $R_s = 78$ (British Geological Survey https://geomag.dgs.ac.uk/data service/data/magnetic indices/apindex.html).

Figure 6 shows the space-time distributions of the ionospheric plasma parameters measured by the Sich-2 probes on September 1, 2011: Fig. 6, *a* shows the ground track and the magnetic equator as a dashed and a solid curve, respectively; Figs. 6, *b* and *c* show the measured values of the plasma parameters N_e, T_e, and T_n (curves *1*) and the values of the electron density N_e, the electron temperature T_e, the ion temperature T_i, and the neutral particle temperature T_n calculated according to the IRI-2012 and the NRLMSIS-00 model [6, 12].

5.4. Earthquakes + EIA. Figure 7 shows the values of N_e, T_e, and T_n measured onboard the Sich-2 on September 14, 2011. The measurements were made in geomagnetically quiet conditions at medium solar activity: $Kp = 1_+ ... 1$, $Ap = 5...4$, and $R_s = 78$. The maxima in the distributions of N_e, T_e, and T_n at the intersection of the ground track and the magnetic equator ($UT_1 \approx 1.7$ h) may be indicative of ionospheric plasma disturbances caused by seismic activity. According to the USGS data, no earthquakes of magnitude M ≥ 5 and depth $h_d \le 50$ km were detected on the Sich-2 ground track on September 14, 2011, but the following events occurred there on September 13 and 15, 2011:

September 13, 2011: $UT_{21} \approx$ 09:10:21; Lat = 35°N, Long = 141°E, $h_d \approx 35$ km; and M 4.8;

September 15, 2011: $UT_{22} \approx$ 08:00:09; Lat = 36°N, Long = 141°E; $h_d \approx 28$ km; and M 6.1;

September 15, 2011: UT_{23} = 10:46:31, Lat = 3.3°N, Long = 126.7°E; $h_d \approx 44$ km; and M 4.9.

It is seismic activity on the ground track that is responsible for the maxima $N_e^{\max}$, $T_e^{\max}$, and $T_n^{\max}$ in the distributions of ionospheric plasma parameters found from the probe output signals measured on September 14, 2011. The disturbances $N_e^{\max}$, $T_e^{\max}$, and $T_n^{\max}$ caused by seismic activity occurred against the background of the EIA effect at $UT_1 \approx 1.7$ h ($LT_1 \approx 10.5$ h).

The most probable source of the ionospheric disturbances detected by the Sich-2 as $N_e^{\max}$, $T_e^{\max}$, and $T_n^{\max}$ at $UT_1 = 1.7$ h (Figure 7) was the M 4.9 and $h_d = 44$ km earthquake detected by the USGS on September 15, 2011 at UT_{23} = 10:46:31, which was incipient at the Sich-2 flyover time. The difference in time between the ionospheric plasma disturbance detection by the Sich-2 at $UT_1 = 1.7$ h and the shock time UT_{23} is $\Delta UT = UT_{23} - UT_1 \approx +33$ h. The plasma electron energy gain rate due to the earthquake is $Q_e^{\Sigma} = 5.4 \times 10^{-11}$ W/m^3, and that one due to the EIA effect is $Q_e^{EIA} = 9.1 \times 10^{-12}$ W/m^3.

The ratios of the plasma parameters disturbed by the earthquake to those disturbed by EIA are shown in Table 2. The relaxation time values of $T_e^{\max}$ and $T_n^{\max}$ to the values T_{0e}^{EIA} and T_{0n}^{EIA} (Table 2) by Eqs.

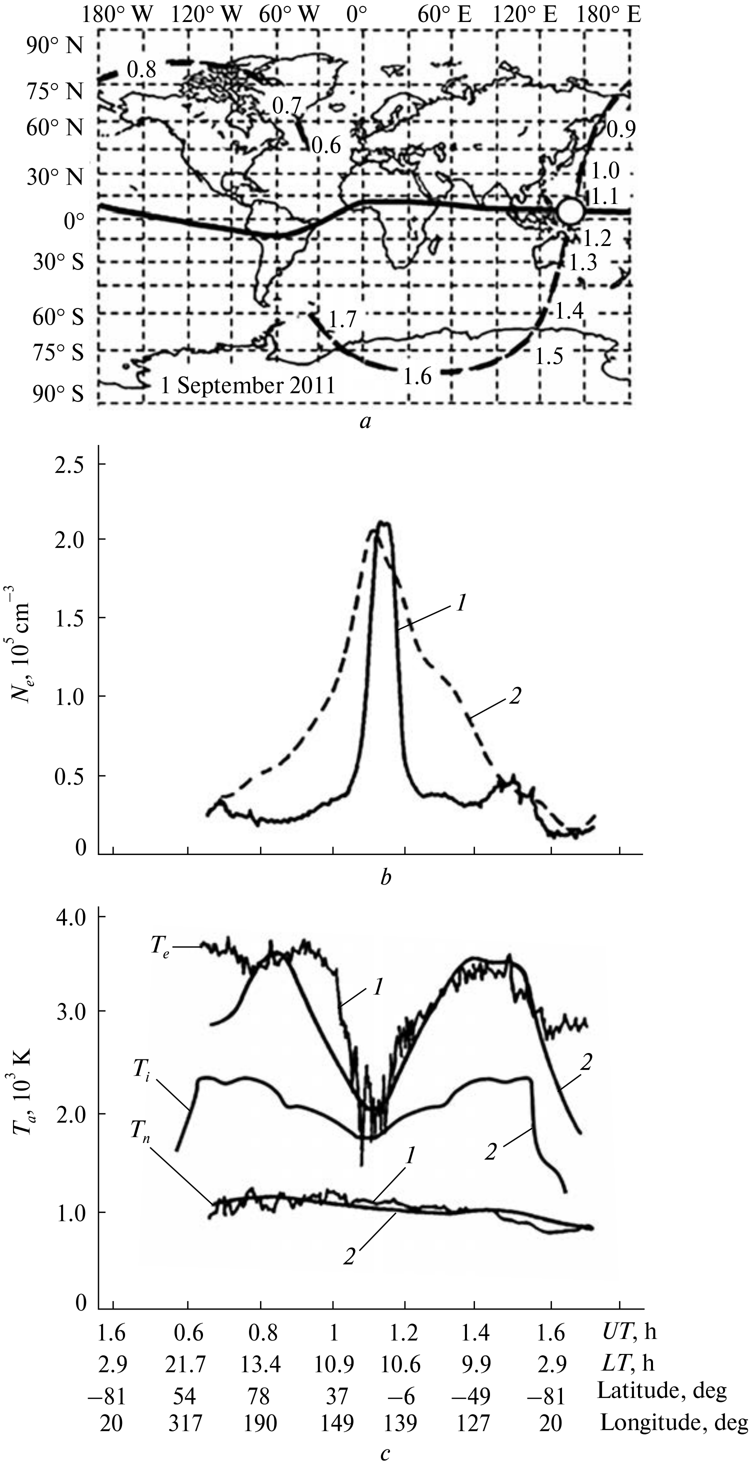

Figure 6. EIA-induced disturbances in the ionospheric plasma parameters, detected by the Sich-2 probes on September 1, 2011: *a* — localization (dashed curve — ground track, solid curve — magnetic equator), *b* — distribution of the electron density N_e (*1* — measurements, *2* — calculations), *c* — distribution of the electron, ion, and the neutral particle temperature T_e, T_i and T_n (*1* — measurements, *2* — calculations)

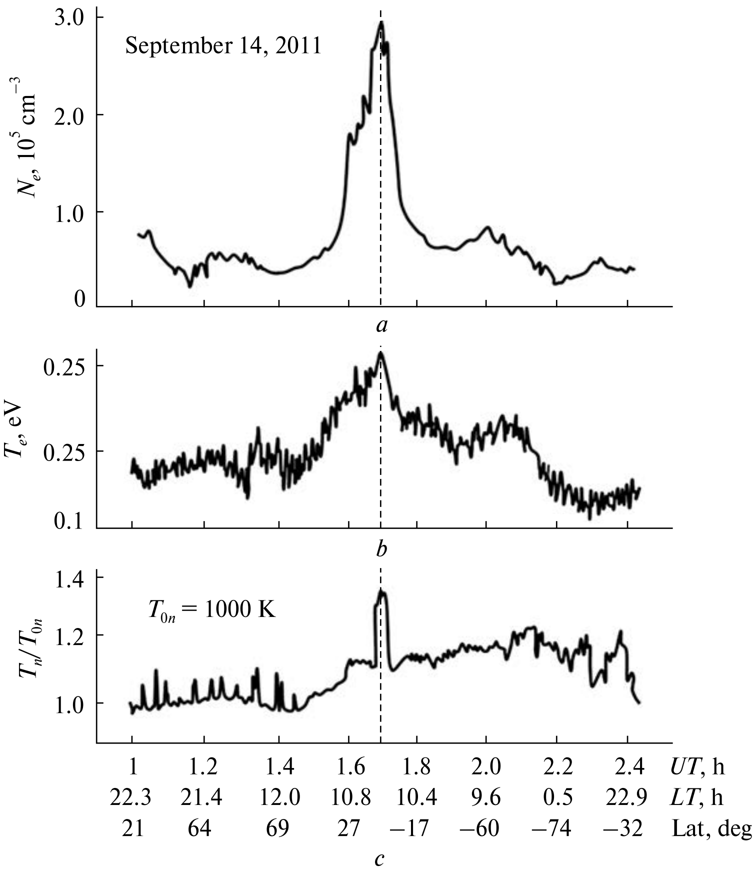

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Figure 7. Ionospheric plasma parameter disturbances along the Sich-2 orbit, detected on September 14, 2011 (probe measurements): *a* — electron density N_e, *b* — electron temperature T_e, *c* — neutral particle temperature T_n (T_{0n} — undisturbed values)

Table 2. **Relative values of the disturbed parameters of the ionospheric plasma**

Ionospheric plasma parameters (Sich-2 measurements)	Measurement date	
	September 14, 2011	October 2, 2011
$Q_e^{\Sigma}/Q_{0e}^{EIA}$	5.93	6.05
$N_e^{\max}/N_{0e}^{EIA}$	1.38	1.12
$T_e^{\max}/T_{0e}^{EIA}$	2.12	2.06
	1.31	1.39

(6) and (7) are $t_{r_1} \approx 25.38$ h and $t_{r_2} \approx 27.81$ h, respectively. According to the USGS data, in the vicinity of the intersection of the magnetic equator and the Sich-2 ground track, the first shock after the Sich-2 flyover struck on September 15, 2011 at UT_{23} = 10:46:31. The estimated first shock time $\mathrm{UT}_{23}^{*}=\mathrm{UT}_1+t_{r_1}$ is about 03.08 h and about $\tilde{\mathrm{UT}}_{23} \approx$ $\approx$ 05.51 h for $t_{r_1} \approx 25.38$ h and $t_{r_2} \approx 27.81$ h, respectively. The variation of the actual shock time UT_{23} = = 10:46:31 from the estimated time is $\Delta\mathrm{UT}_{23}^{*} \approx$ $\approx$ +07.69 h and $\Delta\tilde{\mathrm{UT}}_{23} \approx$ +05.26 h for t_{r_1} and t_{r_2}, respectively.

The effect of an earthquake in the presence of EIA was detected by the Sich-2 electric probes on October 2, 2011. The space-time distributions of N_e, T_e, and T_n are shown in Figure 8. The measurements were made in geomagnetically quiet conditions near the magnetic equator (shown in Figure 3 as a solid curve; the ground track is shown as a dashed curve) at $Kp = 2_+ - 3_-$, Ap = 5...12, and R_s = 81.

The location of $N_e^{\max}$, $T_e^{\max}$, and $T_n^{\max}$ (earthquake plus EIA) corresponds to the intersection of the ground track and the magnetic equator (Lat = = 12.9°N, Long = 95.85°E, and UT_1 = 04.0 h). Before the Sich-2 flew over that point, on October 1, 2011, the USGS detected seven shocks of magnitude M 4.1...5.2 at depth h_d = 14...46 km from UT_{21} = = 01.47 h to UT_{27} = 17.47 h. On October 3, 2001, a shock was detected at the point with the coordinates Lat = 13.1°N, Long = 95.8°E after the Sich-2 flyover (UT_2 = 04.53 h, h_d = 42 km, and M 4.8). From October 1 to October 4, 2011, the geomagnetic activity indices Kp and Ap varied from 2_+...3 to 1_+ and from 9...12 to 5, respectively. According to the plasma parameter values measured onboard the Sich-2, the electron energy gain rate was $Q_e^{\mathrm{EIA}} = 8.1\times10^{-12}$ W/m^3 for the EIA effect alone and $Q_e^{\Sigma} = 4.9\times10^{-11}$ W/m^3 for the combined effect of seismic activity and EIA.

The maximum relative values of the disturbed ionospheric plasma parameters calculated from

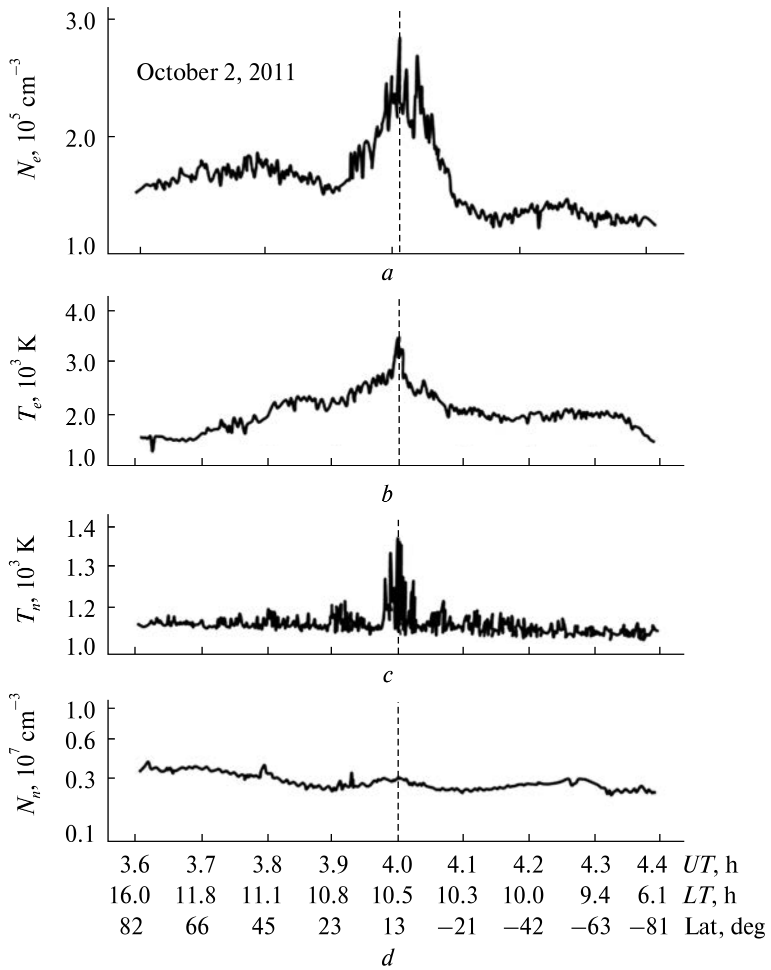

Figure 8. Ionospheric plasma parameter distributions along the Sich-2 orbit, measured on October 2, 2011 (ground track portion *6* in Fig. 3): *a* — electron density N_e, *b* — electron temperature T_e, *c* — neutral particle temperature T_n, *d* — neutral particle density N_n

the probe signals measured on October 2, 2011 are shown in Table 2. If the October 2, 2011 undisturbed values of the ionospheric plasma parameters are taken to be equal to those calculated by the IRI-2012 model at the point Lat = 12.9°N, Long = 95.85°E at $\mathrm{UT}_1 \approx 04.0$ h for EIA, then it can be assumed that the local disturbances in the ionospheric plasma parameters were caused by the October 3, 2011 earthquake, which was incipient on the ground track at the Sich-2 flyover time $\mathrm{UT}_1 = 04.0$ h. The impact of the earthquake on ionospheric plasma was detected by the Sich-2 probes $\Delta\mathrm{UT}_2 \approx +24.53$ h before the shock.

The relaxation time of $T_e^{\max}$ and $T_n^{\max}$ for the earthquake incipient at the Sich-2 flyover time is $t_{r_1} = 24.1$ h and $t_{r_2} = 23.63$ h; correspondingly, $\mathrm{UT}_2^* = 04.10$ h and $\tilde{\mathrm{UT}}_2 = 03.63$ h. The variation of the actual shock time from estimated values is $\Delta\mathrm{UT}_2^* = +0.43$ h and $\Delta\tilde{\mathrm{UT}}_2 = +0.90$ h.

The vertical dashed lines in Figures 3, 4, 7, and 8 connect $N_e^{\max}$, $T_e^{\max}$, and $T_n^{\max}$ to the location of the earthquake epicenters on the abscissa axis.

The data presented in this section demonstrate that the set of the charged and neutral particle parameters determined from the output signals of a spacecraft's electric probes, namely, δT_e, δT_n, δN_e, and δQ_e, and the relaxation time of the temperatures $T_e^{\max}$ and $T_n^{\max}$ to their unperturbed values T_{0e} and T_{0n} allow one to identify ionospheric plasma disturbance sources, in particular, to localize in space and time the epicenter and the first shock of an earthquake incipient on the ground track.

6. CONCLUSIONS

It is shown that the output signals of the electric probes onboard the Sich-2 (a cylindrical Langmuir probe and a two-channel pressure probe) allow one to determine local values of the electron and neutral particle temperatures and densities in the nonequilibrium rarefied ionospheric plasma.

It is found that local disturbances in the charged and neutral particle temperatures and densities along the spacecraft orbit may serve as earthquake precursors. Maxima in the space-time distributions of the charged and neutral particle temperatures and densities along the spacecraft orbit make it possible to localize the epicenter of an incipient earthquake.

The relaxation times of maxima in the electron and neutral particle temperatures to their undisturbed values give an estimate of the time to the first shock of an incipient earthquake.

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ПРО ІДЕНТИФІКАЦІЮ ПРОСТОРОВО-ЧАСОВОЇ ЛОКАЛІЗАЦІЇ ЗАРОДЖУВАНИХ ЗЕМЛЕТРУСІВ ЗА ЗОНДОВИМИ ВИМІРЮВАННЯМИ ПАРАМЕТРІВ ЗБУРЕНОЇ ІОНОСФЕРНОЇ ПЛАЗМИ НА КОСМІЧНИХ АПАРАТАХ

Наведено результати зондової діагностики локальних збурень в іоносферній плазмі *in-situ*. Результати представлено у вигляді просторово-часових розподілів температури і щільності заряджених частинок, виміряних електричними зондами на борту DEMETER (Франція), а також розподілів температури і щільності електронів і нейтральних частинок, виміряних зондом Ленгмюра і двоканальним зондом тиску на борту «Січ-2» (Україна). На прикладі інтерпретації вихідних сигналів електричних зондів на борту DEMETER (Франція), «Січ-2» (Україна) і CSES (Китай) встановлено, що максимуми в розподілах температури і щільності електронів і нейтральних частинок вздовж орбіти КА в іоносферній плазмі відповідають розташуванню епіцентрів землетрусів, що зароджуються на підсупутниковій трасі. Додатковим параметром, який підвищує точність локалізації епіцентрів, є швидкість зростання енергії електронів у іоносферній плазмі. Показано, що час релаксації максимумів температури електронів і нейтральних частинок в іоносферній плазмі визначає час до першого поштовху землетрусу, що зароджується на підсупутниковій трасі.

Ключові слова: землетрус, іоносферна плазма, наземний трек, електричний зонд, час температурної релаксації.