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Letter to the Editor

UHF electromagnetic emission stimulated by HF pumping of the ionosphere

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Abstract. UHF electromagnetic emission (with a frequency near 600 MHz) from the F-region of the ionosphere pumped by an HF powerful radio wave is revealed. Possible mechanisms of the emission excitation, such as plasma mode conversion, scattering or Earth thermal noise emission off the plasma density irregularities, bremsstrahlung and excitation of high Rydberg states of the neutral particles by the accelerated electrons are discussed.

Key words. Ionosphere (active experiments; wave-particle interactions) – Solar physics, astrophysics, and astronomy (radio emissions)

1 Introduction

A powerful O-polarized HF pump radio wave transmitted vertically into the ionospheric F-region from the ground excites a wide range of plasma processes, particularly the pondermotive (Perkins et al., 1974; Al'ber et al., 1974; DuBois et al., 1990) and thermal (Grach et al., 1977; Vas'kov and Gurevich, 1977) parametric instabilities in the region occupying 2–5 km below its reflection point z_R ∼200–300 km. The instabilities lead to the development of different HF electrostatic plasma waves and LF disturbances (Hagfors et al., 1983; Showen et al., 1987; Minkoff et al., 1974). In their turn, the HF plasma waves generate the HF stimulated electromagnetic emissions (HF SEE) (Thide et al., 1982; Leyser et al., 1992, 1993; Karashtin et al., 1986), occurring as a result of conversion of the plasma modes into electromagnetic waves (Grach, 1985; Mjolhus, 1998; Grach et al., 1998), and accelerate electrons until energies 5–30 eV (Carlson et al., 1982). The electron acceleration causes an airglow enhancement (Sipler et al., 1974; Haslett and Megill, 1974; Bernhardt et al., 1991) and additional ionization (Vas'kov et al., 1981; Grach et al., 1997) of the ionospheric plasma due to excitation of neutral particles by an electron impact; the LF disturbances cause scattering (Fialer, 1974) and anomalous absorption of radio waves (Kopka et al., 1982).

In this Letter we report a newly found phenomenon occurring in the pumped volume of the ionosphere, namely a generation of stimulated electromagnetic emission in the UHF range (UHF SEE), with a frequency $f \sim 600$ MHz, which exceeds the pump wave frequency f_0 by approximately two orders. The emission is conditioned, most likely, by the excitation of high Rydberg states of the neutral particles by the accelerated electrons. The radiation of the high Rydberg states is known in astrophysics as radio recombination lines (Dalgarno, 1983).

2 Experimental results

Our experiments were performed in 1997–2000. For the pumping of the ionosphere, we used the "Sura" radio facility situated near Nizhny Novgorod, Russia (geographic coordinates 56.13°N, 46.10°E). In the experiments, the pump wave frequency f_0 was chosen to be below the ionospheric F-region critical frequency; practically, the frequencies $4.7 < f_0 < 6.8$ MHz were applied. The equivalent radiated power used was about 80 MW or 180 MW, which corresponds to the pump wave EM power flux of 0.18 mW/m^2 and 0.40 mW/m^2, respectively, at the altitude 200 km. A typical schedule of the "Sura" radiation was an alternation of "on" and "off" time periods of several minutes; after 30 min, as a rule, the pump frequency was changed. For the diagnostics of ionospheric conditions, the ionograms and spectra of the HF SEE were registered at the "Sura" facility. The HF SEE spectra were used for the estimation of the altitude of interaction between the pump wave and ionospheric plasma (for details, see Leyser et al., 1992, 1993; Grach et al., 1997).

In 1998–2000 a reception of the UHF SEE with a frequency $f \approx 600$ MHz was handled by a two-channel receiver connected with a radio telescope RT-15 antenna (2.3° pattern width). Central frequencies of the receiver channels were separated by 8 MHz. A bandwidth and time constant

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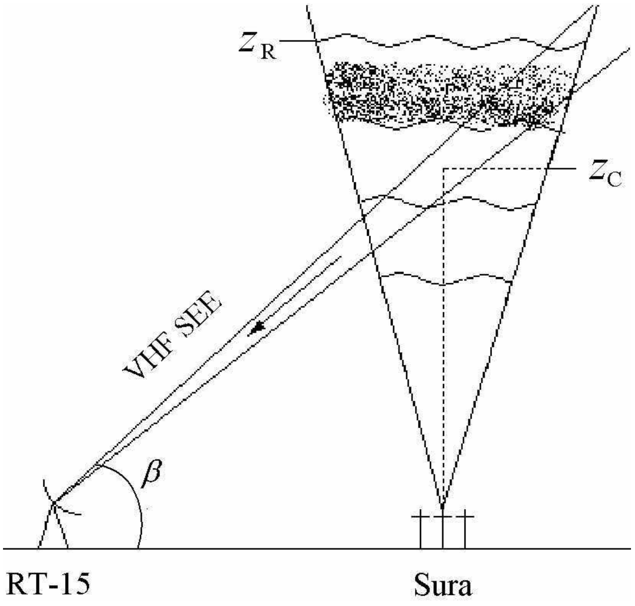

Fig. 1. Schematic plot of the experiment.

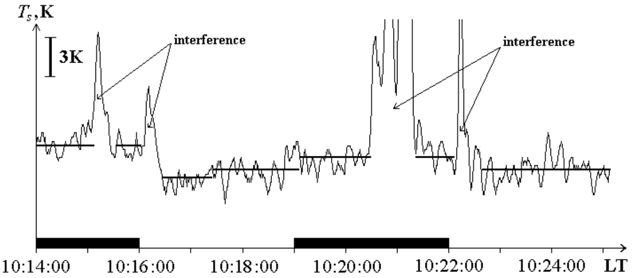

Fig. 2. Temporal evolution of the signal temperature T_S obtained on 20 September 1998 at $f = 598$ MHz. The pump wave frequency is $f_0 = 5.455$ MHz. The "Sura" "on" periods are shown by black bars; radio interference is shown by arrows. Horizontal solid lines correspond to average values of T_S over "on" and "off" periods. The jump of T_S by 0.5 K at 10:17:10 LT corresponds to the change in the elevation angle β from 64° to 59°.

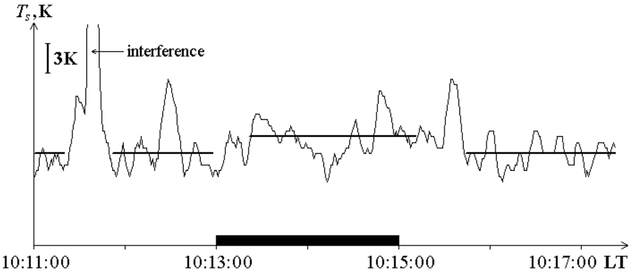

Fig. 3. The same as in Fig. 2, but for 27 September 1998. $f = 598$ MHz, $f_0 = 5.455$ MHz, $\beta = 60°$.

of each channel were ≈ 6 MHz and ≈ 1 s, respectively. The RT-15 radio telescope is situated 114 km to the west from the "Sura" facility at the Radio Astronomical Station (RAS) "Zimenki" (56.17° N, 44.28° E). A schematic plot of the experiment is shown in Fig. 1. The receiving equipment was calibrated with the use of the Cassiopeia, the standard source of the space radio emission, and had a sensitivity threshold 0.15 K. For the identification of radio interference, an additional receiver with a dipole antenna was used. During the experiments, we scanned the RT-15 antenna elevation angle β (see Fig. 1) in the limits from 58° untill 64°, to obtain an altitude profile of the UHF SEE generation efficiency. The specific values of β shown correspond to the cross of the central rays of RT-15 and "Sura" antenna patterns at the altitudes $z_\mathrm{C} \approx 185$ km and $z_\mathrm{C} \approx 240$ km above the "Sura" facility, respectively. In the experiments of 1997, the reception of the UHF SEE was handled at the RAS "Zimenki" at the frequencies 9144, 2950, 930 and 600 MHz by a set of smaller radio telescopes RT-1, RT-2 and RT-4 with the sensitivity threshold of 0.5 K; the digits in the nomenclature of radio telescopes mean the antenna diameter in meters.

Samples of data obtained for the input signal temperature T_S at the frequency $f = 598$ MHz for the pump frequency $f_0 = 5.455$ MHz are presented in Fig. 2 and Fig. 3. The average values of T_S over pump "on" and "off" periods are shown in the figure by solid horizontal lines (the radio interference shown in the figures by arrows is excluded from averaging), with the "on" periods also shown by black bars. A jump of T_S by 0.5 K at 10:17:10 LT in Fig. 2 corresponds to the change in the elevation angle β from 64° to 59°. It is seen that an enhancement of the T_S by 0.9–2.5 K occurs during pump wave "on" periods. Figure 4 displays a sample of temporal behaviour of the signal temperature T_S at $f = 606$ MHz. To reduce noises, we used here current averaging of the received signal over 15 s and averaging over two successive pumping sessions with 3 min "on" and 7 min "off" periods at $f_0 = 6.6$ MHz and 6.56 MHz. The T_S enhancement by ~ 0.7 K during the "on" periods is seen well in the figure.

Our results obtained in 1998–2000 at $f = 598$ MHz are summarized in Table 1, which includes the date and time of the experiment, pumping schedule, pump wave frequency f_0, RT-15 elevation angle β, reflection altitude of the pump wave z_R (when available), and the signal temperature enhancement $\Delta T_\mathrm{S} = T_{\text{“on”}} - T_{\text{“off”}}$. Here $T_{\text{“on”}}$ and $T_{\text{“off”}}$ are the signal temperature during pump wave "on" and "off" periods, respectively. As it is seen from the table, the signal temperature enhancement was observed for the elevation angles $59° \lesssim \beta \lesssim 62°$, which correspond to the altitude range $195 \lesssim z_\mathrm{C} \lesssim 220$ km above the "Sura" facility, and for the pump wave reflection altitudes z_R ~190–220 km during the daytime measurements and for z_R ~260–270 km during the nighttime. A magnitude of the enhancement was ΔT_S ~0.3–1.3 K, which corresponds to the additional energy flux $\sim (2\text{–}8) \cdot 10^{-25}\,\mathrm{mW/m^2 \cdot Hz}$. One exception occurred on 20 September 1998 (see Fig. 2, 10:14 LT), when the $\Delta T_\mathrm{S} \sim 2.5$ K was registered for $\beta = 64°$. In addition, during the experiments of 20 September 1998 and 24 August 2000, in parallel with emission at $f = 598$ MHz, the T_S enhancement by 0.5–0.7 K was registered during pump "on"

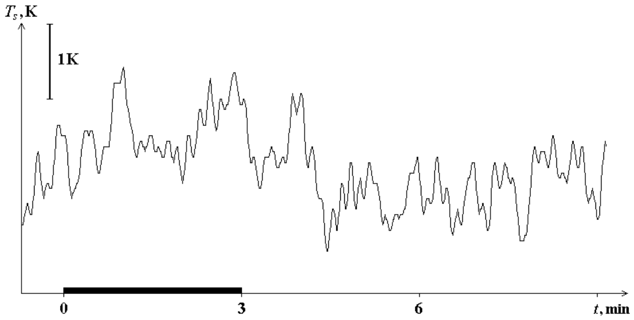

Fig. 4. The signal temperature T_S at $f = 606$ MHz versus time after the pump wave turn on, obtained on 24 August 2000 at 22:30–22:50 LT. The data are averaged over two successive pumping sessions with 3 min "on" and 7 min "off" periods at $f_0 = 6.6$ MHz and 6.56 MHz, $\beta = 61°$.

periods at the frequency $f = 606$ MHz (see Fig. 4). During the daytime measurements of 18 May 1999, with a pumping schedule 1 min "on", 1 min "off" and during the nighttime measurements of 26 and 27 August 2000, with the schedule 30 s "on", 4 min 30 s. "off", no T_S enhancement was obtained.

According to the data presented in Figs. 2–4, the characteristic times of the UHF SEE development and decay are of the order of 20–40 s and 30–60 s, respectively. The quite small signal-to-noise ratio did not allow one to determine the characteristic times in the other measurements, but larger values ΔT_S were obtained for longer pumping durations.

In the earlier experiments of 1997, a small increase in the received signal was suspected to appear at $f = 600$ MHz and $f = 930$ MHz during several "Sura" runs. However, we can not assert for certain due to a sensitivity threshold of the receiving equipment that is worse than in the later experiments. Any noticeable decrease in T_S during the HF pumping was never observed in our experiments. Also, no similar signal variations were obtained during testing experiments, when the UHF signal reception was handled without HF pumping of the ionosphere.

3 Discussion

Based on the data we obtained, we can state that the HF pumping of the ionospheric F-region at the frequencies 4.5–7 MHz causes the enhancement of the electromagnetic emission from the pumped volume of the ionosphere at the frequencies $f \sim 600$ MHz by $\Delta T_\mathrm{S} \sim 0.3$–1.3 K. The emission is excited at the altitudes 195–220 km above the "Sura" facility. The characteristic times of the UHF SEE development and decay were found to be of the order of a few tens of seconds, but this requires additional confirmation.

What is the reason for the emission observed? Certainly, the conversion of the plasma modes, which is responsible for the HF SEE generation (Grach, 1985; Karashtin et al., 1986; Mjolhus, 1998; Grach et al., 1998), cannot provide the radiation at the frequencies exceeding the Langmuir frequency $f_{Pe} \sim f_0$ by two orders. Then, in order to attribute the signal observed to scattering of the Earth's black-body radiation, with the temperature ~ 300 K off the pump-made plasma density irregularities, with the scales $\sim c/f \sim 0.5$ m (here, c is the speed of light), a relative irregularity intensity $dN^2 \sim 3 \cdot 10^{-5}$ is necessary. This value exceeds the experimentally observed one (Minkoff et al., 1974; Fialer, 1974) by 3–4 orders. So, such a possibility has also to be rejected.

The observed effect is most likely conditioned by the electron acceleration by the pump-driven HF plasma turbulence and the following generation of the UHF emission under the collisions between suprathermal electrons and neutral particles of the ionospheric plasma. We consider two possibilities of such a generation. The first one is the bremsstrahlung. To estimate an energy flux of UHF SEE due to the bremsstrahlung, we used an expression of Erukhimova et al. (1990) obtained for the emission intensity from the horizontal layer of suprathermal maxwellian electrons with the temperature T_a and density N_a situated in the ionosphere. For the estimations, we used the layer width 10 km, the layer altitude 220 km, $T_\mathrm{a} \sim 15$ eV, and $N_\mathrm{a} \sim 10^{-4} \cdot N_e \sim 30$ cm^{-3}, where N_e is the background electron density. The values of N_a and T_a were taken from estimations of Grach et al. (1997), which were made on the basis of additional ionization data obtained by multi-frequency Doppler radar observations of the HF pumped ionosphere. The results for the UHF SEE flux gave the values of 4–5 orders less than the obtained ones experimentally.

A more credible mechanism of the emission generation conditioned by the electron acceleration is related to the excitation of the high Rydberg states of the neutrals (atomic oxygen O and molecular nitrogen N_2) by the electron impact, and the transition of electrons between high Rydberg levels. The frequency of such a transition is given by an expression (Dalgarno, 1983)

$$f = \frac{R_M c}{1 + m/M} \cdot \left(\frac{1}{n^2} - \frac{1}{(n + \Delta n)^2} \right), \tag{1}$$

where $R_M = 109737.31$cm^{-1} is the Rydberg constant, n is the principal quantum number, m is the electron mass, and M is the nuclear mass of the neutral particle. At the electron transition between neighbour levels ($\Delta n = 1$), with $n = 190$–250, the emission with $f = 400 - 1000$ MHz is generated. Particularly, for the transition between 222^d and 221^d levels ($n = 221$) of the atomic oxygen $f_{\mathrm{O},\ 221\alpha} = 605.4444$ MHz, and for the molecular nitrogen $f_{\mathrm{N}_2,\ 221\alpha} = 605.4532$ MHz. At $n = 222$, $f_{\mathrm{O},\ 222\alpha} = 597.3177$ MHz and $f_{\mathrm{N}_2,\ 222\alpha} = 597.3264$ MHz; here, α in the subscripts mean that $\Delta n = 1$. A width Δf of the emission line must be defined by Doppler widening due to thermal motion of the neutrals in the ionosphere. For the neutral temperature of 300 K, it is easy to obtain $\Delta f_{\mathrm{O}\ n\alpha} \sim 700$ Hz and $\Delta f_{\mathrm{N}_2\ n\alpha} \sim 400$ Hz, and $\Delta f_{\mathrm{O}\ n\alpha}, \Delta f_{\mathrm{N}_2\ n\alpha} < f_{\mathrm{N}_2,\ n\alpha} - f_{\mathrm{O},\ 222\alpha}$. However, the emission lines of different gases could not be resolved in our measurements because the difference between $f_{\mathrm{O}\ n\alpha}$ and $f_{\mathrm{N}_2\ n\alpha}$ was much less than the bandwidth of the receiver used (6 MHz).

Table 1. Results of UHF SEE observation at $f = 598$ MHz. f_0 is the pump frequency, β is the elevation angle of RT-15 antenna; z_R is the reflection altitude of the pump wave, "?" means that z_R was not obtained in this particular measurements, ΔT_s is the signal temperature enhancement during pump wave "on" periods

Date	Pumping schedule	f_0, kHz	LT=UT+4 h	β	z_R, km	ΔT_s, K
98/09/05	±3 min.	5300	09:34–09:40	62°	?	0.3 K
			09:40–09:55	60.5°		0.45–0.6 K
		5455	10:07–10:22	62.5°	$\lesssim 160$	–
		5828	10:31–10:51	60–62°	$\lesssim 180$	–
98/09/20	±3 min.	5455	10:01–10:07	60°	190–200	1.3 K
			10:17–10:25	59°		0.9–1 K
		5828	10:33–10:52	62–64°		–
98/09/27	±2 min.	5300	09:30–09.56	60–64°	?	–
		5455	10:01–10:12	62–64°	~ 180	–
			10:12–10:17	60°		1 K
			10:20–10:25	58°		–
		5828	10:42–10:50	62°	~ 200	0.4–1 K
99/22/05	±1 min.	5752	15:10–15:20	61°	200	–
			15:21–15:30	62°	200	0.23 K
			15:30–15:50	63–64°	205	–
			15:50–15:55	62°	210	0.4 K
00/08/24	$+3-7$ min.	6500	22:01–22:30	62.5°	?	–
		6600	22:31–22:41	61°	260–270	0.4 K
		6560	22:41–22:51			0.8 K
		6540	22:51–23:00		~ 280	–

A similar mechanism of UHF/VHF emission generation, namely the excitation of the high Rydberg states of atmospheric gases by photoelectrons, is attracted by Avakian et al. (1997) for an interpretation of sporadic UHF/VHF radio emission of the ionosphere with the energy flux of $1-40\cdot 10^{-22}$ mW/m$^2\cdot$Hz, which is registered during geoeffective solar events (Troitskii et al., 1973; Nesmyanovich et al., 1976; Musatenko et al., 1999). No calculations have been done yet for the energy flux of the UHF emission generated under such a process neither for the sporadic emission, nor for one stimulated by the HF pumping. However, rough estimates for our experiments show that the energy deposited to the high Rydberg states by accelerated electrons, with the density N_a and the temperature T_a, is quite enough to provide the emission obtained. Moreover, the altitude profile of Rydberg state excitation rates for O and N_2, calculated by Avakian et al. (1997), exhibits a maximum at ~ 200 km, which coincides roughly with the region of the UHF SEE generation in our experiments.

Notice finally, that the radiation of Rydberg atoms (radio recombination lines) is well known in the observation of HII galactic regions, interstellar gases, planetary nebulas, etc., and the radiation is observed for principal quantum numbers n until 390 (Dalgarno, 1983).

4 Conclusions

Our results indicate that during HF pumping of the ionosphere the noticeable enhancement of the UHF electromagnetic emission flux from the ionospheric modified volume is registered by a radio telescope placed more than 100 km away from the pumping facility.

Such an emission cannot be related to the conversion of pump-driven plasma modes, as well as to the bremsstrahlung of suprathermal electrons and scattering, or Earth thermal noise emission off the plasma density irregularities. The most plausible mechanism for the UHF SEE generation is the excitation of high Rydberg states of the ionospheric neutral particles by accelerated electrons and a further transition of electrons between such states. If further investigations of UHF SEE properties (such as a spectrum, line widths, temporal characteristics) confirm such a model, the effect revealed can be utilized for the study of atmospheric gaze Rydberg states, as well as, together with the airglow and additional ionization, for diagnostics of the electrons accelerated by HF plasma turbulence.

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