

On the Efficiency of Radio Emissions at the Double Plasma Frequency in the Magnetosphere of Exoplanet HD189733b

V. V. Zaitsev^{a,*}, V. E. Shaposhnikov^{a,b,**}, M. L. Khodachenko^c, and M. S. Rumenskikh^{d,e}

^a *Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia*

^b *National Research University Higher School of Economics, Nizhny Novgorod Branch, Nizhny Novgorod, Russia*

^c *AAS Space Research Institute, Graz, Austria*

^d *Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia*

^e *Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Russia*

*e-mail: za130@ipfran.ru

**e-mail: sh130@ipfran.ru

Received February 14, 2023; revised February 14, 2023; accepted April 28, 2023

Abstract—On exoplanets with a weak magnetic field, the so-called plasma maser can be effectively implemented instead of an electron cyclotron maser. This maser involves the generation of plasma waves by energetic electrons and their conversion into radio emissions at the plasma frequency or at the double frequency. Under specific conditions, a maser effect occurs at the plasma frequency, which manifests itself in an exponential increase in radio emissions intensity with an increase in the energy of plasma waves. In this paper, we study the Raman scattering of excited plasma waves with the formation of an electromagnetic wave at the double plasma frequency in the plasmasphere of the exoplanet HD189733b, for which the three-dimensional structure of the plasma envelope has been studied. Although the maser effect is absent in the case of Raman scattering, the collisional absorption of radiation is significantly reduced at the second harmonic and the requirement for the brightness temperature in the source is reduced as well. It has been shown that the radio flux at the second harmonic increases sharply for this exoplanet from a few millijanskys at a frequency of 20 MHz to tens of janskys at a frequency of ≈ 4 MHz. This means that the decameter range near the cutoff frequency of the Earth's ionosphere is the most promising range for the detection of second harmonic radio emissions by modern radio telescopes. In this case, the radio emissions of the second harmonic can provide information about the properties of plasmaspheres around exoplanets at considerable distances that are inaccessible during observations at the main plasma frequencies.

Keywords: masers—plasmas—radiation mechanisms: non-thermal—methods: analytical—planets and satellites: individual: exoplanets

DOI: 10.1134/S0016793223070307

1. INTRODUCTION

Radio emissions from exoplanets, i.e., planets outside the Solar System, provide important information about the characteristics of their plasmaspheres, including details about plasma and energetic particle concentrations, magnetic fields, and the extent of the plasma envelopes surrounding exoplanets. The search for radio emissions from exoplanets has been ongoing even before their experimental discovery and continues to this day (e.g., de Gasperin et al., 2020; Narang et al., 2021; Turner et al., 2021, and references therein). However, no radio emissions that could be definitively associated with exoplanets have been observed thus far. The have been reported of the discovery of faint radio sources that coincided with or were in close proximity to exoplanetary systems. However, it was emphasized the need for further research to

establish the nature of these radio emissions conclusively.

One of the causes of this situation may be the lack of reliable information regarding the frequency ranges and possible intensities of radio emissions within which the search is feasible. Therefore, it is crucial to investigate the effectiveness of possible mechanisms for nonthermal radio emissions using exoplanets with well-modeled plasma envelope. Similarly to the radio emissions from certain planets in the Solar System, one commonly considered mechanism is the electron cyclotron maser (ECM). The ECM acts in plasmas with strong magnetic fields, when the gyrofrequency of electrons ω_B in the radio source significantly exceeds the Langmuir frequency ω_L , $\omega_B \gg \omega_L$. If this condition is not met, the ECM efficiency is significantly lower, and the instability increments at $\omega_B \leq \omega_L$

are approximately two orders of magnitude smaller. Therefore, it was concluded that exoplanets with a weak magnetic field, such as, HD 209458b and HD 189733b, possess no intrinsic intense radio emissions (Weber et al., 2017). Using HD 189733b as an example, Zaitsev and Shaposhnikov (2022) demonstrated that on exoplanets with a weak magnetic field, when the plasma frequency exceeds the electron gyrofrequency, an alternative to the electron cyclotron maser is the plasma mechanism of radio emission. This mechanism involves the generation of plasma waves by energetic electrons within the source, followed by their conversion into electromagnetic radiation either at the plasma frequency through scattering by plasma particles or at double the plasma frequency via Raman scattering (the merging of plasma waves). Under specific conditions, when the conversion occurs at the plasma frequency, a maser effect arises, resulting in an exponential increase in the intensity of electromagnetic radiation with increasing energy of plasma waves. The possible frequency range of radio emissions in this model is determined by the density and spatial distribution of plasma in the planet's plasmasphere, rather than the strength of the magnetic field in the source. The studies determined the plasma parameters for which the maser effect facilitates the detection of emerging radiation by modern radio telescopes. Furthermore, a significant dependence was revealed between the radio-emission efficiency and its absorption due to electron-ion collisions during propagation through the plasmasphere, as well as the energy and density of fast electrons that excite plasma waves.

In this paper, the Raman scattering (merging) of excited plasma waves with the formation of an electromagnetic wave at the double plasma frequency is studied for the same exoplanet. Although there is no maser effect in the case of Raman scattering due to the decay of an electromagnetic wave into two plasma waves at high radio emissions intensities, the required brightness temperature in the source necessary to achieve the observed radio emissions flux at a given frequency may be lower. This is because the collisional absorption of radiation is significantly reduced at the second harmonic. It is worth noting that the generation of radio emissions at the second harmonic of the plasma frequency in the context of the plasma mechanism has been studied in relation to active processes on the Sun, planets of the Solar System (e.g., Zheleznyakov, 1996), and stars (Stepanov et al., 1999). In this study, the problem is investigated as applied to the plasmasphere of the "hot" Jupiter, HD189733b.

2. GENERATION OF RADIO EMISSIONS AT THE DOUBLE PLASMA FREQUENCY IN THE PLASMASPHERE OF HD189733b

The exoplanet HD189733b, which is located in the Chanterelle constellation at a distance from the Earth $R_{SE} \approx 63$ light years, with a mass $M_p \approx 1.13M_J$ and

radius $R_p \approx 1.14R_J$ (M_J and R_J are the mass and radius of Jupiter, respectively) belongs to the class of hot Jupiters. The planet's orbit is located at a distance $R_{orb} \approx 0.03$ AU from the parent star, which is a yellow dwarf similar to the Sun in size and temperature. The estimates of the maximum magnetic field for HD189733b vary depending on the field formation model from ≈ 1.8 G (Greissmeier et al., 2007) to ≈ 14 G (Reiners and Christensen, 2010). Three-dimensional models of the atmosphere of HD189733b based on the analysis of the evolution of hydrogen and helium spectral lines during the transit of the exoplanet across the stellar disk, taking into account its interaction with the stellar wind of the parent star, were presented by Rumenskikh et al. (2022). Figure 1 shows the distributions of plasma density n and temperature T in the plasmasphere of the exoplanet HD189733b for one of the sets of possible model parameters considered by Rumenskikh et al. (2022). The increase in temperature in the plasmasphere starting from 8 radii is due to the interaction of the plasmasphere with the stellar wind flow. It follows from this figure that the condition of a weak magnetic field $\omega_B \ll \omega_L$, which is necessary for the effective action of the plasma mechanism, is satisfied across the entire plasmasphere for the values of the planetary magnetic field indicated above.

Let us now analyze the plasma mechanism, in which the electromagnetic radiation is generated at the second harmonic of the plasma frequency as a result of Raman scattering of plasma waves, to clarify the conditions under which the level of this radiation will be sufficient for observations on Earth.

According to the model, plasma (Langmuir) waves are excited due to a small admixture of energetic electrons with a concentration $n_1 \ll n$, which are nonequilibrium in velocities transverse to the magnetic field. Here, n , and n_1 are the density of the main (equilibrium) and nonequilibrium plasma components. Taking the aim of our study into account, we will not discuss the cause of the appearance of the nonequilibrium component in the plasmasphere of exoplanets. Under the condition of a weak magnetic field $\omega_B \ll \omega_L$, the plasma permittivity coincides with the corresponding expression for an isotropic plasma (see, for example, Rosenbluth and Post, 1965), and the dispersion expression for excited Langmuir waves has the form $\omega_p^2 = \omega_L^2 + 3k_p^2 v_T^2$, where k_p is the wave vector of plasma waves, $v_T = \sqrt{k_B T / m_e}$ is the thermal velocity of electrons in the equilibrium plasma component with temperature T , m_e is the electron mass, and k_B is the Boltzmann constant.

As a result of Raman scattering of plasma waves, electromagnetic radiation is generated at a double plasma frequency $\omega_t(\mathbf{k}_t) = \omega_p^{(1)}(\mathbf{k}_p^{(1)}) + \omega_p^{(2)}(\mathbf{k}_p^{(2)}) \approx 2\omega_p$ with a wave vector $\mathbf{k}_t = \mathbf{k}_p^{(1)} + \mathbf{k}_p^{(2)}$. The frequency ω_t

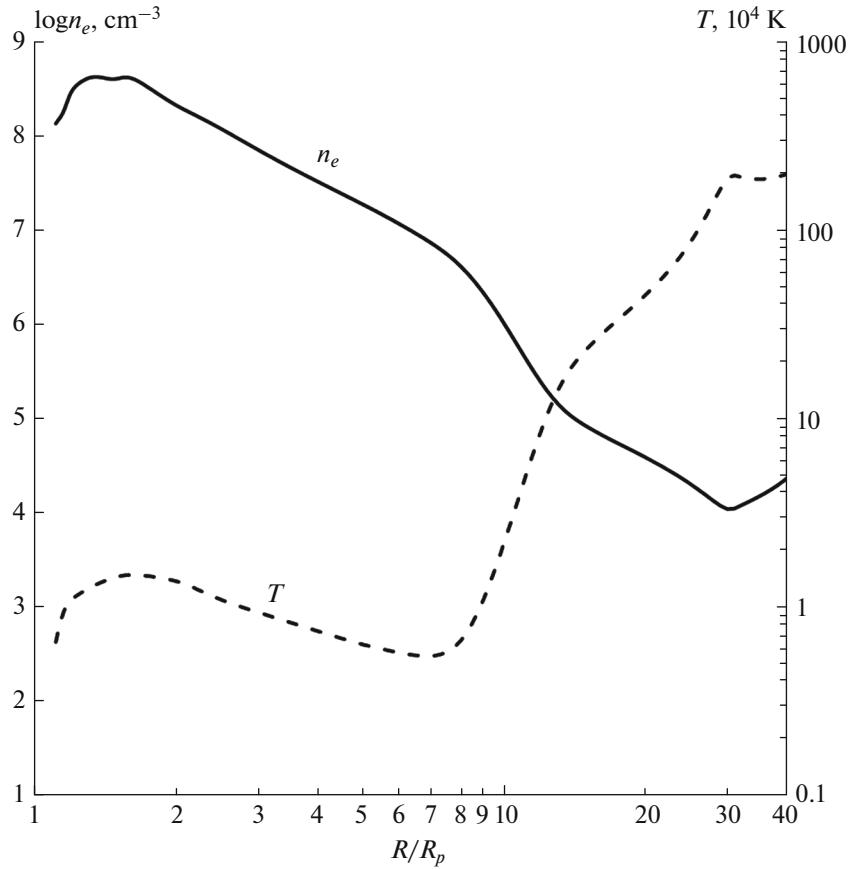


Fig. 1. The distributions of plasma density n and temperature T for a three-dimensional model of the exoplanet HD189733b interaction with the parent star's stellar wind, obtained from the analysis of the evolution of hydrogen and helium spectral lines during the exoplanet's transit across the star's disk (Rumenskikh et al., 2022).

and wave number k_t of an electromagnetic wave are related as $\omega_t^2 = \omega_L^2 + k_t^2 c^2$, where c is the speed of light.

In radio astronomy, the efficiency of a radiation source is usually characterized by the brightness temperature T_B , which is related to the radio flux F detected at a distance R_{SE} from the radiation source via the expression

$$F = \frac{k_t^2 k_B T_B R_s^2}{(2\pi)^2 R_{SE}^2}, \quad (1)$$

where R_s is the characteristic size of the source across the line of sight. The transfer equation for the brightness temperature has the form

$$\frac{dT_B}{dl} = a - (\mu_c + \mu_N) T_B, \quad (2)$$

where a is the emissivity and μ_c and μ_N are the absorption coefficients. The coefficients μ_c and μ_N characterize the radiation absorption at the second harmonic due to electron–ion collisions with a frequency ν_{ei} and due to the reverse process of decay of the second-harmonic electromagnetic wave into two plasma waves,

respectively. In the case of an isotropic spectrum of plasma waves, these coefficients have the following form (Zheleznyakov, 1996):

$$a \approx \frac{(2\pi)^5}{15\sqrt{3}} \frac{c^3}{\omega_L^2 \langle v_{ph} \rangle \xi^2} w^2 n T, \quad (3)$$

$$\mu_N \approx \frac{(2\pi)^2}{5\sqrt{3}} \frac{\omega_L}{\langle v_{ph} \rangle \xi} w, \quad \mu_c = \frac{\nu_{ei}}{2c\sqrt{3}}.$$

Here, $\langle v_{ph} \rangle = \omega_p / \langle k \rangle$ is the average phase velocity of plasma waves; $w = W_p / nk_B T$ is the ratio of the plasma wave energy density W_p to the plasma thermal energy density; the parameter ξ characterizes the spectral volume of plasma waves, $(\Delta \mathbf{k})^3 = \xi \omega_L^3 / c^3$. The parameter ξ in formulas (3) for coefficients a and μ_N can be estimated as follows. The presence of even a relatively weak magnetic field in the planet's plasmasphere leads to a natural anisotropy of the energetic electron distribution function due to the existence of a “loss cone” and the corresponding deficit of particles with relatively low velocities transverse to the magnetic field. In

the case of cone instability, the spectrum of plasma waves is axially symmetric with respect to the magnetic field; therefore, the following formula is valid for the spectral volume:

$$(\Delta\mathbf{k})^3 = 2\pi \iint k^2 \sin \alpha dk d\alpha, \quad (4)$$

where integration is performed over the interval of wave vectors and the interval of angles between \mathbf{k} and magnetic field \mathbf{B} of interacting plasma waves. To determine the limits of integration over the angle and wave vector, we study the increment of plasma waves in the case of cone instability.

We will assume that the distribution function of the main plasma in the exoplanet's ionosphere is a Maxwellian function with the electron density n and temperature T , while the velocity distribution of energetic electrons with the density $n_s \ll n$ and temperature $T_s \gg T$ will be described for definiteness by the function

$$f_s(v_{\parallel}, v_{\perp}) = \frac{n_s}{4\sqrt{(2\pi)^3}} \left(\frac{m_e}{k_B T_s} \right)^{\frac{5}{2}} v_{\perp}^2 \exp \left[-\frac{m_e(v_{\perp}^2 + v_{\parallel}^2)}{2k_B T_s} \right]. \quad (5)$$

This function models the velocity distribution of fast electrons in the presence of a loss cone in the exoplanet's magnetic field, providing the necessary anisotropy associated with a deficit of electrons with low transverse velocities. In (5), v_{\parallel}, v_{\perp} are the longitudinal and transverse components of the velocity vector of energetic electrons with respect to the direction of the magnetic field in the region of plasma wave generation.

The increment of the loss cone instability in this case has the following form (Zaitsev and Stepanov, 1975)

$$\gamma(\omega, k) = \frac{1}{4} \sqrt{\frac{\pi}{2}} \frac{\omega_p^4}{k^3 v_{Ts}^3} \frac{n_s}{n} \frac{\omega^2 k^{-2} v_{Ts}^{-2} + 2 \cot^2 \alpha - 1}{1 + \cot^2 \alpha} \times \exp \left(-\frac{\omega^2}{2k^2 v_{Ts}^2} \right), \quad (6)$$

where $v_{Ts} = \sqrt{k_B T_s / m_e}$ is the characteristic velocity of fast electrons. According to (6), the increment is negative ($\gamma < 0$), i.e., the system is unstable with respect to perturbations for plasma waves with phase velocities v_{ph}

$$v_{ph}^2 < v_{Ts}^2 (1 - 2 \cot^2 \alpha), \quad (7)$$

which propagate at angles $\alpha > \alpha_{cr} = \tan^{-1} \sqrt{2}$ to the magnetic field (α is the angle between vectors \vec{k} and \vec{B}). The instability increment reaches its maximum value

$$|\gamma_{max}| \approx 4 \times 10^{-2} \frac{n_s}{n} \omega_L \quad (8)$$

for waves propagating orthogonally to the magnetic field, $\alpha \approx \pi/2$, with phase velocities $v_{ph} \approx 0.74 v_{Ts}$ and wave

numbers $k_{opt} \approx 1.35 \omega_L / v_{Ts}$. The increment decreases by a factor of 3 when deviating from the optimal value up to $k_{min} \approx 1.04 \omega_L / v_{Ts}$ and $k_{max} \approx 2.5 \omega_L / v_{Ts}$, as well as when deviating by an angle $\pm 30^\circ$ from $\alpha \approx \pi/2$. As a result, we obtain the following estimate for the spectral volume (4):

$$(\Delta\mathbf{k})^3 \approx 2\pi k_{opt}^2 (k_{max} - k_{min}) \times \int_{\alpha_{min}}^{\alpha_{max}} \sin \alpha d\alpha \approx 11.5 \frac{c^3}{v_{Ts}^3} \frac{\omega_L^3}{c^3}. \quad (9)$$

Hence, it follows that

$$\xi \approx 11.5 \frac{c^3}{v_{Ts}^3} \quad (10)$$

and it depends on the characteristic velocity of energetic electrons generating plasma waves. For example, for $v_{Ts} = c/3, c/2$ and c we obtain $\xi \approx 3 \times 10^2, \xi \approx 0.9 \times 10^2$, and $\xi \approx 11.5$, respectively.

3. THE BRIGHTNESS TEMPERATURE AND RADIO FLUX AT THE DOUBLE PLASMA FREQUENCY

The solution of the transfer equation (2) has the form

$$T_B = \frac{a}{\mu_c + \mu_N} [1 - \exp(-\tau_c - \tau_N)] \exp(-\tau_{ext}). \quad (11)$$

Here, τ_c and τ_N refer to the absorption of an electromagnetic wave in the conversion region on the scale of the amplification length L of a plasma wave with a fixed frequency ω_p during the cone instability in the inhomogeneous plasmasphere of an exoplanet, and τ_{ext} characterizes the absorption during propagation from the conversion region to the observer.

In an inhomogeneous plasma and with a limited interval $\Delta\mathbf{k} = \mathbf{k}_{max} - \mathbf{k}_{min}$ of wave vectors of excited plasma waves, the amplification length L of a plasma wave at a fixed frequency ω_p is limited:

$$L \approx 3L_n \frac{v_T^2}{\omega_L^2} (k_{max}^2 - k_{min}^2) \approx 15.5L_n \frac{v_T^2}{v_{Ts}^2}, \quad (12)$$

where $L_n = n |dn/dR|^{-1}$ is the characteristic scale of the regular inhomogeneity of the planet's plasmasphere.

For the plasma density distribution in the exoplanet's plasmasphere (Fig. 1), the amplification length of a fixed-frequency plasma wave at a distance R from the surface can be approximately represented as $L \approx 2.3 R v_T^2 / v_{Ts}^2$. The estimates show that the collisional absorption of second-harmonic radiation on the amplification scale L can be neglected if the energy density of plasma waves $w > 10^{-3}$. In this case, the optical thickness of the second-harmonic absorption due to

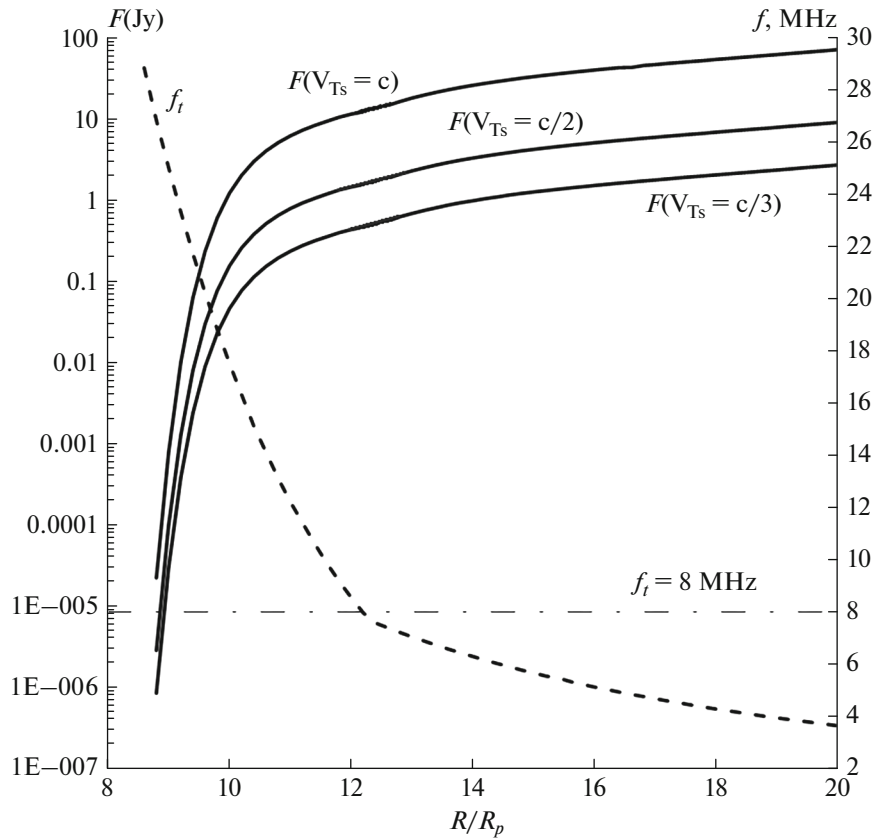


Fig. 2. The radio flux at the second harmonic of the plasma frequency for various velocities of energetic electrons, $f_i = \omega_i/2\pi$.

the decay process reaches $\tau_N = \mu_N L \approx 10^3 w$ at distances $R > (6-20)R_p$ from the surface of the planet. At this distance, for $w > 10^{-3}$, the optical thickness becomes greater than unity, which corresponds to the case of an optically thick source. Further, we restrict ourselves to the case of an optically thick source ($w > 10^{-3}$), which corresponds to the maximum radio flux.

For an optically thick source, the brightness temperature of radiation is determined by the equation

$$T_b(2\omega_L) \approx \left(\frac{a}{\mu_N}\right) \exp(-\tau_{\text{ext}}). \quad (13)$$

Figure 2 shows the radio emissions fluxes at the Earth level for the energy density of plasma waves $W_p = 10^{-3} nk_B T$. When constructing graphs in Fig. 2, the distance from the exoplanet HD189733b to the Earth in Eq. (1) was taken as $R_{SE} = 6 \times 10^{19}$ cm, and the area of the radio source in the plasmasphere at a distance R corresponding to the plasma frequency $\omega_L \approx \omega_i/2$ is equal to the maximum $R_S = 2\pi R^2$. It can be seen from this figure that the radio flux increases sharply, by approximately four orders of magnitude, from a few millijanskys at a frequency of 20 MHz to tens of janskys at a frequency ≈ 4 MHz.

Figure 3 shows the plasma wave energy densities necessary to obtain a radio flux of 1 Jy at the second harmonic of the plasma frequency at the Earth level, depending on the received radio frequency f_i . It follows from the figure that the lowest plasma wave energy densities required to achieve radio fluxes accessible for observation by modern radio astronomy instruments correspond to the frequency range $f_i \leq 10$ MHz.

4. CONCLUSIONS

— We studied Raman scattering (“merging”) of excited plasma waves with the formation of an electromagnetic wave at the double plasma frequency in the plasmasphere of the exoplanet HD189733b, for which three-dimensional models of the plasma envelope are developed, taking into account its interaction with the stellar wind of the parent star.

— It has been shown that the most promising range for detecting second harmonic radio emissions from the exoplanet HD189772b is the decameter range near the cutoff frequency of the Earth’s ionosphere.

— The radio fluxes observed by modern means can be achieved at sufficiently high energy densities of plasma waves $W_p \geq 10^{-3} nk_B T$ and source sizes on the

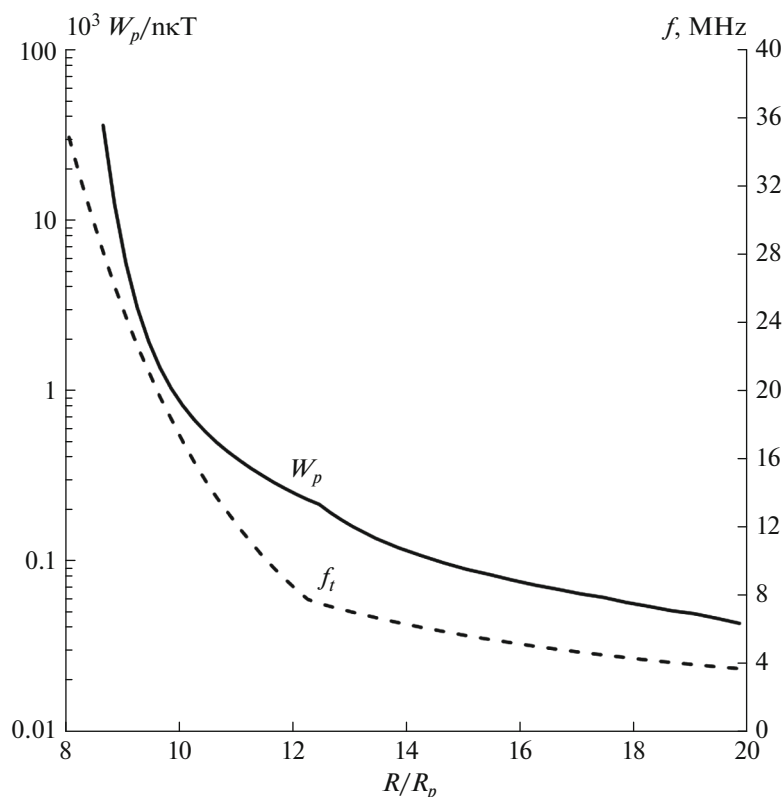


Fig. 3. The necessary energy densities of plasma waves in the source, at which at a frequency $f_t = \omega_t/2\pi$, a radio flux of 1 Jy is created at the Earth level.

order of the scale of the planet's plasmasphere. At the same time, the question of the mechanisms and efficiency of acceleration of energetic particles in the plasmasphere of exoplanets remains important.

— The radio emissions of the second harmonic can provide information about the properties of an exoplanet's plasmasphere at significant distances that are inaccessible during observations at the frequencies of the primary tone of the plasma frequency.

FUNDING

The study was supported by the Russian Science Foundation under grant no. 23-22-00014 (Sections 1, 3, 4) and the State Assignment FFUF-2023-0002 (Section 2).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

de Gasperin, F., Lazio, T.J., and Knapp, M., Radio observations of HD 80606 near planetary periastron. II. LOFAR low band antenna observations at 30–78 MHz, *Astron. Astrophys.*, 2020, vol. 644, p. A157. <https://doi.org/10.1051/0004-6361/202038746>

Grießmeier, J.-M., Zarka, P., and Spreuw, H., Predicting low-frequency radio fluxes of known extrasolar planets, *Astron. Astrophys.*, 2007, vol. 475, pp. 359–368. <https://doi.org/10.1051/0004-6361:20077397>

Narang, M., Manoj, P., Ishwara Chandra, C. H., et al., In search of radio emission from exoplanets: GMRT observations of the binary system HD 41004, *Mon. Not. R. Astron. Soc.*, 2021, vol. 500, pp. 4818–4826. <https://doi.org/10.1093/mnras/staa3565>

Reiners, A. and Christensen, U.R., A magnetic field evolution scenario for brown dwarfs and giant planets, *Astron. Astrophys.*, 2010, vol. 522, p. A13. <https://doi.org/10.1051/0004-6361/201014251>

Rosenbluth, M.N. and Post, R.F., High-frequency electrostatic plasma instability inherent to “loss-cone” particle distributions, *Phys. Fluids*, 1965, vol. 8, no. 3, pp. 547–550. <https://doi.org/10.1063/1.1761261>

Rumenskikh, M.S., Shaikhislamov, I.F., Khidachenko, M.L., et al., Global 3D simulation of the upper atmosphere of HD189733b and absorption in metastable HeI and Ly α lines, *Astrophys. J.*, 2022, vol. 927, no. 2, p. 238. <https://doi.org/10.3847/1538-4357/ac441d>

Stepanov, A.V., Kliem, B., Kruger, A., et al., Second-harmonic plasma radiation of magnetically trapped electrons in stellar coronae, *Astrophys. J.*, 1999, vol. 524, pp. 961–973.

- Turner, J., Zarka, P., Grießmeier, J.-M., et al., The search for radio emission from the exoplanetary systems 55 Cancri, υ Andromedae, and τ Boötis using LOFAR beam-formed observations, *Astron. Astrophys.*, 2021, vol. 645, p. A59. <https://doi.org/10.1051/0004-6361/201937201>.
- Weber, C., Lammer, H., Sheikhislamov, I.F., et al., How expanded ionospheres of radio emission generated by the cyclotron maser instability, *Mon. Not. R. Astron. Soc.*, 2017, vol. 469, pp. 3505–3517. <https://doi.org/10.1093/mnras/stx1099>
- Zaitsev, V.V. and Stepanov, A.V., On the origin of fast drift absorption bursts, *Astron. Astrophys.*, 1975, vol. 45, pp. 135–140.
- Zaitsev, V.V. and Shaposhnikov, V.E., Plasma maser in the plasmasphere of HD 189733b, *Mon. Not. R. Astron. Soc.*, 2022, vol. 513, pp. 4082–4089. <https://doi.org/10.1093/mnras/stac1140>
- Zheleznyakov, V.V., *Radiation in Astrophysical Plasmas*, Dordrecht: Kluwer Academic, 1996.

Translated by M. Chubarova

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.