ON THE POSSIBILITY OF OBSERVING THE LASER EFFECT IN THE EARTH ATMOSPHERE

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The method for analysis of the processes in the upper atmosphere associated with a possibility of obtaining laser effects in it is proposed in the paper. It is found, that in despite of the presence of inverse population of the levels for some transitions in atmospheric gases, the radiation amplification fails to reach the threshold because of the diffraction losses, in none of them under natural conditions. Other prospects of obtaining the laser effect in the upper atmosphere are discussed. It is proposed to pay attention to the low atmosphere (up to 15–20 km*), where the laser effect may be feasible under certain conditions.*

Natural active media (lasers) are known to scientists rather for a long time. There are bodies of comets and atmosphere of Venus and Mars (see Refs. 1 and 2) basically consisting of carbon dioxide. In contrast, the Earth's atmosphere has completely different composition where CO_2 is only a minor gas. Attempts have been made to identify atmospheric active component which could provide laser effect. It is assumed that the upper atmosphere with powerful natural pumping sources is most suitable for this purpose. The results of calculations of the inverse population of vibrational-rotational levels of OH radicals in the Earth's atmosphere are presented in Ref. 2. The inversion arises in the following chemical reaction:

$$H + O_3 \rightarrow OH\ (v \leq 9) + O_2.$$

Due to a slow collisional relaxation of the OH vibrational levels and while fast for rotational ones the inversion is achieved only for the transitions $v, j \rightarrow v - 1; j + 1$ (P-branch). It is so called partial inversion. This inversion was really found to exist at heights of 85–90 km. Nevertheless, the inverse population is so low that overall gain in a single pass through the Earth's limb does not exceed $5\cdot10^{-5}$, i.e., the gain coefficient $\alpha \leq 10^{-12}$ cm^{-1}. The mechanism of the inversion formation for vibrational-rotational levels of NO molecules is similar:

$$N(^2D) + O_2 \rightarrow NO(v) + O, \quad (\lambda \approx 5.3\ \mu m).$$

This reaction is most efficient in the aurora at heights 105–120 km, but in this case the gain still remains insufficient for the laser effect to occur. Inverse population on ^2D–^4S nitrogen and ^1D–^3P oxygen atomic transitions in the aurora zone under pumping by scattered electrons were calculated in Refs. 3 and 4. The inversion was found to exist, but due to extremely low concentration of the active particles at heights about 200 km being optimal for this excitation the gain coefficient was estimated to be no higher than 10^{-22} cm^{-1}.

The review presented shows that the inversion population in the Earth atmosphere is quite possible and is not extremely unusual phenomenon. However in all cases considered it is insufficient for laser effects to be obtained. The search for appropriate transitions and conditions suitable for the realization of inverse population for these transitions is very laborious and requires knowledge of a great body of detailed information. As a rule, this information is not available and therefore further investigations are necessary for obtaining such information. In our opinion, for solving the problem, one has to concentrate the search by eliminating from the consideration the cases unable to provide the expected positive results. For this purpose reasonably general and simple threshold relationships should be formulated and then applied to particular transitions and pumping mechanisms in real atmospheric conditions. The present paper is devoted to this problem.

THRESHOLD CONDITIONS FOR LASING IN THE UPPER ATMOSPHERE.

From the above reasoning, the first and principle condition should be related to the threshold radiation gain coefficient on an optical transition of active particles (see Ref. 5):

$$\alpha = \sigma\, \Delta N = \frac{\lambda^3}{8\pi\, c}\left(\frac{\lambda}{\Delta\lambda}\right) A\, \Delta N \geq \alpha_{\min}, \qquad (1)$$

here α is the gain coefficient, σ is the cross-section of the stimulated emission at the wavelength λ; ΔN is the

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inverse population between the optical transition levels, c is the speed of light; A is the probability of spontaneous transition; α_{min} is the threshold gain coefficient.

Then, from the equations on the population balance of working transition levels (see Refs. 5 and 6), the following condition for pumping rate q^* can be obtained:

$$q^* = [A\ \Delta N/(1 - A\ \tau_l)] > A\ \Delta N, \quad (2)$$

here τ_l is the lifetime of the lower lasing level. From this follow the equations for a stationary lasing:

$$q^* > A\ \Delta N \geq \frac{8\pi\ c}{\lambda^3} \left(\frac{\Delta\lambda}{\lambda}\right) \alpha_{min} \quad (3)$$

and

$$A^{-1} < \tau_l. \quad (4)$$

The equations show, that the threshold conditions are easy to satisfy as the wavelength of optical transition is increased while the radiation bandwidth narrowed. Therefore $\Delta\lambda$ is the bandwidth of a single radiation line. There is also a limitation on λ associated with the mechanism of the upper lasing level excitation and the lower level depopulation. The fact is that for the majority of active media this mechanism is collisional (see Ref. 6) most efficient for transfer of energy on the order of or lower than thermal (see Ref. 7). Hence, for laser transition with the quantum energy of $\sim kT_g$ collisional processes are quenching that prevent creation of the inverse population. From this follows a restriction on the maximum wavelength of laser radiation:

$$\lambda_{max} = hc/(3\ kT_g) = 1.6 \cdot 10^{-11} \cdot c/T_g, \quad (5)$$

where h is the Planck constant. It should be emphasized that this restriction does not work when collisional processes are random as compared to the radiative ones. That is why generation of IR and microwave radiation is possible in the interstellar medium (see Ref. 1) whereas it is impossible in the atmosphere.

In the upper atmosphere (at heights over 50 km) lineshape broadening is determined by the Doppler mechanism (see Refs. 5 and 8):

$$\left(\frac{\Delta\lambda}{\lambda}\right)_D = \left(\frac{2}{c}\right) \sqrt{\frac{2\ \ln\ RT_g}{\mu}} \approx 7.16 \cdot 10^{-7} \sqrt{\frac{T_g}{\mu}}, \quad (6)$$

where R is the universal gas constant; $\mu = 29$ is the molecular weight of air. Let us now determine the threshold coefficient α_{min} in Eq. (3) such that the gain effect could be recorded in principle. It is obvious that this α_{min} is equal to the minimal intracavity radiation losses which can not be eliminated. These are the diffraction losses (see Refs. 5 and 6) and

$$\alpha_{min} = \lambda/r^2, \quad (7)$$

where r is the laser cavity mirror radius. From this relationship it follows in particular that at $r = 0.5$ m and $\lambda \sim 1$ μm $\alpha_{min} = 10^{-7}$ cm^{-1}. Therefore, in the examples considered in the Introduction the gain cannot be recorded in practice. In view of Eqs. (6) and (7), Eq. (3) takes the following form:

$$q^* > 10^{-5}\ (c\sqrt{T_g})/(3r^2\ \lambda^2), \quad (8)$$

while taking into account Eq. (5) we can write

$$q^*_{min} \geq 1.3 \cdot 10^{16}\ T^{5/2}/(c\ r^2), \quad (9)$$

or in practical units (q^* and λ are expressed in cm^{-3}·s^{-1} and μm, respectively) taking for certain $r = 0.5$ m and $T_g = 225$ K one can obtain

$$q^* > 6 \cdot 10^{10}/\lambda^2 \quad (8a)$$

and

$$q^*_{min} \geq 1.3 \cdot 10^8,\ (\text{cm}^3\cdot\text{s})^{-1}. \quad (9a)$$

By substituting this q^* into Eqs. (8) and (9) one obtains the threshold relationships for concentration of active particles for a particular pumping mechanism. Height distribution of the main components in the upper atmosphere is shown in Fig. 1 (see Refs. 9 and 10).

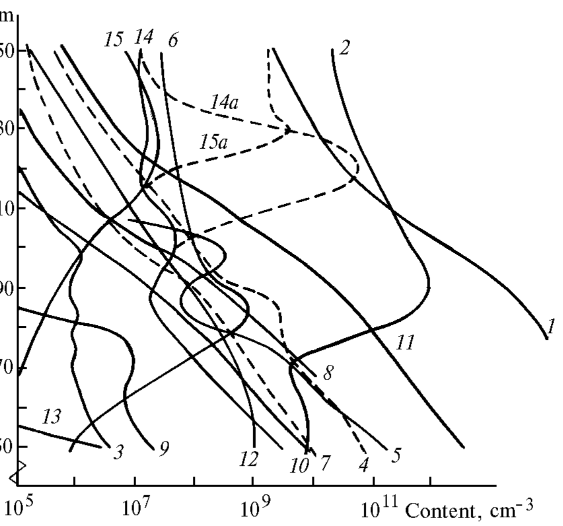

FIG. 1. Contents of the main gas components in the upper atmosphere of the Earth and their height distributions (see Ref. 9): O_2 *(1);* $O(^3P)$ *(2);* $O_2(^1\Sigma^+_g)$ *(3);* $O_2(^1\Delta_g)$ *(4);* O_3 *(5);* H *(6);* H_2 *(7);* H_2O *(8);* OH *(9);* CH_4 *(10);* CO_2 *(11);* CO *(12);* N_2O *(13);* NO *(14);* $N(^4S)$ *(15).* NO *and* $N(^4S)$ *in the aurora zone of 11 class in electric field* $E_{\parallel}$ a $3\cdot10^{-3}$ V/m *(14a and 15a, respectively, see Ref. 10).*

Given the composition of the atmosphere, one can estimate whether one the other mechanism or pumping channel is essential for obtaining the laser effect. Now let us come to a detailed consideration of this question.

ANALYSIS OF THE EXCITATION CHANNELS IN THE UPPER ATMOSPHERE

There are three powerful pumping sources in the upper atmosphere, namely, solar radiation, influxes of scattered particles and infrared radiation of the atmosphere. In general, the latter source being controlled by other two sources is not independent. It is identified for convenience of further consideration because there is information available on this source.

First we estimate the action of solar radiation. Spectral distribution of the flux density of solar radiation out of the atmosphere is presented in Fig. 2 (see Ref. 11).

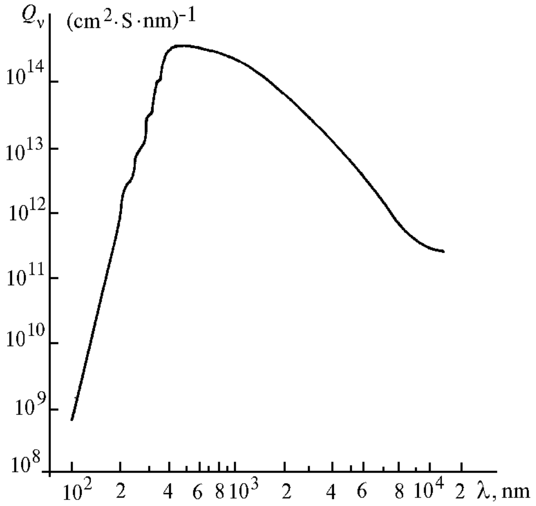

FIG. 2. Spectral distribution of the flux density of solar radiation photons out of the Earth atmosphere.

As the Sun activity changes, the intensity of its radiation varies only in far UV spectral region ($\lambda < 0.1$ μm), while the part of the spectrum presented in Fig. 2 remains unchanged. In the IR-range radiation of the atmosphere which strongly depends on solar activity and geomagnetic perturbations (see Refs. 9 and 10) superimposes on the solar one. Main atmospheric components (N_2 and O_2) substantially absorb radiation at $\lambda < 200$ nm while their absorption is extremely low in the visible and IR spectral regions. Solar radiation at the wavelengths from near UV to near IR (up to $\lambda \le 1.18$ μm) is absorbed by the ozone. Bands of H_2O molecules fall in that spectral region and far extend into the IR interval (the most intense band is centered at 6.25 μm, next one is centered at 2.66 μm). All the minor molecular components of the atmosphere have strong absorption bands in the near IR. The main result of the absorption of UV and visible solar radiation is the dissociation of atmospheric gases (detailed consideration of that process will be presented below), and only absorption in the IR region results in excitation of their vibrational-rotational levels (see Refs. 8, 9, 12, and 13).

The rate of optical pumping within a band $\Delta\lambda_0$ centered at λ_0 is

$$q_v^* \text{ a } \sigma_0 N_0 Q_v \Delta\lambda_0, \qquad (10)$$

where Q_v, σ_0, A_0 are the spectral density of the photon flux, the cross-section and probability of absorption of a photon at the wavelength λ_0 , respectively.

The distributions of Q_v are different at different heights. However, only knowledge of the distribution Q_v outside the atmosphere is sufficient for our consideration (see Fig. 2). The minimal absorption coefficient of the atmospheric active components at the pumping wavelength required for lasing may be derived from Eqs. (10) and (3)

$$\chi_{thr} \text{ a } \sigma_0 N_0 \ge \frac{8\pi c}{r^2 \lambda^2 Q_v \Delta\lambda_0} \left(\frac{\Delta\lambda}{\lambda}\right)_D . \qquad (11)$$

From the distribution Q_v and known character of solar radiation absorption by atmospheric components in different spectral ranges (see Refs. 8, 9, and 12) it follows, that χ_{thr} is minimum in the near IR range (~ 2–6 μm). Estimates made using Eqs. (6), (9), (11) and Fig. 2 give $\chi_{thr} \sim 5\cdot10^{-3}$ cm^{-1} (it is a very high value). Clearly, solar radiation propagating into the atmosphere with a monotonically increased χ_0 merely can not come to the height with χ_{thr} and hence can not provide the necessary pumping power.

Let us now consider the IR radiation of the atmosphere. Intense bands of NO (5.3 μm), CO_2 (15 and 4.3 μm), CO (4.7 μm), O (63 μm), OH (2.8 μm), and O_3 (9.6 and 14.8 μm) (see Refs. 10 and 12) are observed in that spectral range. Radiation of the band of NO molecules at λ a 5.3 μm generated in the aurora zone at heights ~ 120–140 km is most intense. Radiation fluxes at that wavelength with power up to ~ 100 erg/(cm^2·s) were recorded during strong geomagnetic storms (see Ref. 10). If we assume, that this flux is concentrated only within 10 Doppler broadened lines, χ_{thr} can be estimated to be ~ $5\cdot10^{-5}$ cm^{-1}. Hence, the threshold pumping density can take place only inside the radiating zone. NO molecule itself (vibrational transition $0 \to 1$ with A_0 a 12 s^{-1}, see Ref. 10) is the only atmospheric component strongly absorbing this radiation. Then from Eq. (11) we can obtain $N_{min} \ge 8\cdot10^{10}$ cm^{-3}, which is close to the extreme possible estimations obtained in Ref. 10 for the case of strong electrical fields in the electron scattering zone ($2\cdot10^{10}$ cm^{-3}). Considering that estimations made in the present work are obviously soft and the situation for other atmospheric components is similar to that for NO one may conclude that pumping by IR radiation from the atmosphere is far below the threshold power, as well.

In addition to the direct optical excitation solar radiation absorption in the UV and visible regions produces free radicals in the ground state and the following excited particles:

– molecular oxygen in $B^3\Sigma_u$, $A^3\Sigma_u^+$, $a^1\Delta_g$, and $B^1\Sigma_g^+$ states

– atomic oxygen in ^1D and ^1S states. However, $O(^1D)$ state is quenched practically in every collision with N_2 and O_2, while $B^1\Sigma_g^+$ state is populated in the quenching reaction of $O(^1D)$ by oxygen

$$O(^1D) + O_2 \rightarrow O_2(B^1\Sigma^+) + O(^3P) \quad (k \sim 6{\cdot}10^{-11}\ \text{cm}^3/\text{s})$$

and by O_3:

$$O_2(B^1\Sigma^+) + O_3 \rightarrow 2O_2 + O(^3P) \qquad (k \sim 2.5{\cdot}10^{-11}\ \text{cm}^3/\text{s})$$

(see Ref. 6).

Hence, the energy of excitation of $O(^1D)$ is spent mainly on the ozone dissociation. The excitation of $A^3\Sigma_u^+$ states has extremely low rate due to small cross-section of radiation absorption within the Hertzberg band ($\sigma_0 \le 10^{-23}$ cm^2, see Ref. 12). Relatively high concentration of $O_2(a^1\Delta_g,)$ (see Fig. 1) and its weak quenching by main components of the atmospheric gases (see Ref. 8) suggest that these molecules can be an appropriate energy source for pumping active particles. But for this to happen, the rate of $O_2(a^1\Delta_g)$ formation should satisfy the condition expressed by Eqs. (3) and (8). These molecules are mainly formed in the process of ozone dissociation when absorbing solar radiation within the Hartly band (200 – 320 nm) (see Ref. 8). The intensity of solar radiation within this band is as high as $\sim 6{\cdot}10^{15}$ photons/cm$^2{\cdot}$s while the corresponding radiation absorption cross-section is found to be $\sim 2{\cdot}10^{-18}$ cm^2 (see Refs. 8 and 12). Assuming ozone concentration to take its maximum value according to Fig. 1, one can obtain $q_v^* \sim 1{\cdot}10^8$ cm^{-3}/s. According to Eq. (8) that pumping rate is insufficient for lasing. Similar procedure with the same result is valid for $O_2(B^3\Sigma_u)$ state which is formed when absorbing solar radiation within the Shuman-Runge band. Thus, from the above estimates it follows that neither solar radiation nor IR radiation of the atmosphere can provide lasing under ambient conditions.

Now let us consider the action of scattered electrons on the atmosphere. In this case the following three channels are possible: a) excitation and ionization directly by the flux of scattered electrons; b) recombination excitation, c) excitation by electron impact in strong electric fields in the aurora zone.

The excitation by the electron flux can be estimated using the ionization rate which is determined by experiments and presented in literature. So, the rate in the aurora is as high as $\sim 2{\cdot}10^5$ cm^{-3}/s (see Refs. 9 and 10). The average kinetic energy of the electrons appearing in the act of ionization of 14 eV (see Ref. 10) is quite enough for excitation of the upper electron states of the atmospheric gas molecules. Assuming the excitation rate by such electrons to be one order of magnitude higher than that of the ionization and substituting obtained value of q_e^* into Eqs. (3) and (10) we can find in view of Eq. (5) that the flux of scattered electrons can not provide required pumping power.

The recombination flux reaches its peak at the restoring phase of substorm at heights ~120 km, where $q_{rec} \sim (2–3){\cdot}10^7$ cm^{-3}/s. By substituting q_{rec} into Eqs. (11) and (3) we obtain that $\lambda^2 \ge (3–2){\cdot}10^3$ μm or $\lambda \ge 45$ μm. Therewith the energy gap between the upper and lower laser levels is $\Delta E \le 320$ K. However, at heights over 120 km the gas temperature exceeds 400–500 K (see Refs. 9 and 12). Therefore according to Eq. (5) the inversion is impossible. Hence, the recombination mechanism should also be eliminated from the further consideration.

The density of pumping flux from heated electrons is described by the following expression

$$q_e^* \approx \langle\sigma_e v_e\rangle\, n\, N_0 \equiv k_e^*\, N_0, \qquad (12)$$

where σ_e is the particle excitation cross-section from its ground state by the electron impact, v_e is the electron velocity, n and N_0 are the electron number densities and that of gas particles, respectively. The averaging is made over the electron velocity distribution. Since $\langle\sigma_e v_e\rangle \le (10^{-7} - 10^{-9}) \exp(-\Delta E/kT_e)$, cm^3/s (here ΔE is the upper level excitation energy, T_e is the electron temperature), $n \le 10^5$ cm^{-3} (at heights ~ 100 km) and 10^6 cm^{-3} (at heights ~ 150 km) (see Refs. 9 and 10). Hence, $k_e^* \sim (10^{-3}–10^{-2}) \times \exp(-\Delta E/kT_e),{\cdot}$cm^3/s. By substituting this value k_e^* into Eqs. (12) and (8) we obtain (at $r \approx 0.5$ m and $T_g \sim 500$ K):

$$N_0 > 9 \cdot 10^{12}\ (1 - 10)\ \exp(\Delta E/kT_e)/\lambda^2. \qquad (13)$$

Since the electron number density at heights below 90 km rapidly falls to ~ 10^3 cm^{-3}, Eq. (13) means, that at heights from 100 to 150 km only main atmospheric components (N_2, O and O_2, NO, CO_2) of which only last two are promising for obtaining the laser effect under ambient conditions. It is evident that the conditions in the areas with the presence of electric fields, namely, in auroral zone, are most favorable for lasing. Electric field in this zone provides electron temperature up to 4000 K (see Ref. 10). Nevertheless, comparison of Eq. (13) with the maximum possible concentration of CO_2 and NO shows that the latter are small to satisfy this inequality.

Vibrationally excited nitrogen $N_2(v)$, whose concentration in the aurora is as high as ~ 10^{10} cm^{-3} (see Refs. 9, 10, and 12) and can serve as an energy reservoir from which the excitation energy may be transferred to active particles (CO_2 or NO). As applied to CO_2, there are known transitions $00^01 \rightarrow 10^00$ at $\lambda \approx 10.6$ μm and $00^01 \rightarrow 02^00$ at $\lambda \approx 9.6$ μm (see Ref. 6). The rate constant of the excitation energy transfer from $N_2(v)$ to CO_2 $k_k^* \sim 10^{-12}$ cm^3/s (see Refs. 7 and 10). Hence, the pumping rate $q_k^* \approx k_k^* [N_2(v)]\cdot[CO_2] \sim 10^7$ cm^3/s is far below that required for the lasing effect (see Eq. (8)). As for NO, due to high difference of its vibrational quanta and those of N_2, $k_k^* \sim 10^{-13}$–10^{-14} cm^3/s (see Refs. 7 and 10) the inequality (8) cannot be satisfied, as well.

Thus, the estimates done have shown that the fluxes of scattered electrons can not provide for the lasing effect in the atmosphere either.

Finally, let us consider the question on the possibility arising from the formation of a great number of free radicals in the atmosphere. It is well known that chemical reactions among radicals usually proceed without the activation energy and their rates can be comparable with the gas kinetic ones (see Ref. 7). They can serve as a pumping source:

$$A + C \to B^* + D; \quad q_{ch}^* \approx k_{ch}^* [A] [C],$$

where $k_{ch} \sim 10^{-10}$–10^{-12} cm^3/s. Note that both B and C can not be free atoms since chemical reaction between atoms is possible only in the presence of a third particle. Nevertheless, three-body collisions in the rarefied upper atmosphere rarely occur ($k_{ch} \sim 10^{-31}$–10^{-33} cm^6/s). That means that the presence of a component D is essential. Thus, only replacement reaction is suitable for pumping. Then, the condition expressed by Eq. (8) at maximum rate constant of the chemical reaction $\sim 10^{10}$ cm^3/s and $r \approx 0.5$ m, $T_n \approx 225$ K takes the following form:

$$[B]\ [C] \ge 6 \cdot 10^{20}/\lambda^2. \qquad (14)$$

It is seen that the requirements for chemical pumping are extremely tough and can not be satisfied in the upper atmosphere under ambient conditions.

So, the analysis done has shown, that in spite of the availability of powerful pumping sources in the upper atmosphere, no lasing should be expected here. This conclusion is valid in the middle atmosphere (heights 20–60 km).

PROSPECTS OF OBTAINING THE LASER EFFECT IN THE ATMOSPHERE

This purpose can be achieved using injection of foreign gases pollution products of combustion of rocket fuel or some gases from a special container into the upper and middle atmosphere or nuclear explosions in the atmosphere. Natural pumping can be complemented by direct energy transfer from the Earth or space stations along with scattered electron fluxes from the radiative belts.

In our opinion, further investigation should concentrate on the low atmosphere (heights up to 15–20 km). Its potentialities result from the presence of two groups of strongly essential factors: a) the variety and abundance of its composition, b) new potential pumping sources. Both these factors have natural and technogenic origin. Global processes such as evaporation from surfaces of ocean and rivers, soil, erosion, volcanic emissions and outflow of gases from underground and underwater sources enrich the low atmosphere in halogen-, sulfur- and metal-containing compounds, while solar radiation and atmospheric electricity excite and decompose them and their components.

Human activity strongly contribute to enriching the atmosphere in different compounds. Such accidents as large-scale forest fires, failures on chemical production and nuclear objects, transportation and pipelines are of special importance. Analysis of these phenomena is out of the framework of the present paper. Here we present only very brief discussion of such interesting subjects as atmospheric electricity and its effect on the atmospheric gases.

Thunderstorm discharge (lightning) is typical manifestation of the atmospheric electricity. At the pre-discharge stage atmospheric aerosol in the electric field creates big areas of uniform volume corona discharge. This discharge in the form of a column 1–5 m in diameter is accompanied by propagation of a step leader. The return impact following the leader runs a current of 10–100 kA through a channel with the diameter of ~ 5 cm during several microseconds and heats the discharge plasma ($n \sim 10^{17}$ cm^3) to temperatures up to ~ (24–30)$\cdot 10^3$ K. The radiation energy from the plasma channel at the wavelengths 400–1100 nm is over ~ 870 J/m at peak power of ~ $6\cdot 10^6$ W/m (see Ref. 14). Thus, thunderstorm discharge is a powerful source of electron, optical, recombination, and plasma-chemical pumping.

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