Optics and Spectroscopy, 2024, Vol. 132, No. 7

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Radiation of the conductive lightning channel

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Received July 02, 2024
Revised July 02, 2024
Accepted July 29, 2024

We unify the classical theory of photo-recombination radiation in thermodynamically equilibrium plasma in which the contribution of each final state does not depend on the temperature, and measurements of plasma parameters for the conductive lightning channel. It was shown that this plasma is optically thin one. Maximum plasma temperature of lightning return stroke is nearly of 30 kK. It is restricted by the sharp increase of radiation power with temperature/ More that 90% of radiation is found in the vacuum ultraviolet spectral region. We suggest to include the classical radiation theory into the contemporary computer calculations of lightning models, since then the energy balance of plasma is fulfilled.

Keywords: lightning, radiation, plasma, photo-recombination.

DOI: 10.61011/EOS.2024.07.59650.6849-24

Introduction

Lightning is a complex physical phenomenon when an electric current pulse passes through the atmosphere via a previously provided conductive path [1–6]. This phenomenon is induced by charge separation in atmosphere [7], therefore, lightning carries the charge that partially eliminates this separation. By the electric current flow, lightning may be divided into several stages, including such important ones as the stepped leader that forms the conductive path, and the return stroke when a considerable portion of the lightning charge is transferred. For medium and high intensity lightning, current flow via the conductive path may be repeated. It is restored after the passage of a dart leader followed by the return stroke. At the return stroke stage, the lightning electromagnetic wave propagates in the conductive medium and its speed is of the order of the speed of light. Maximum lightning currents and maximum luminescence are implemented at this stage. Our study is focused on this lightning development stage.

Lightning studies show that electric current at the return stroke stage rises to its peak value within several microseconds and then drops by half during $30\,\mu$s [8,9]. Spectroscopic examination by comparing radiation intensities of various spectral lines of a particular multiplet restores the electronic temperature of lightning plasma that achieves 30 kK at its maximum. At this temperature in case of electron and gas equilibrium, this plasma becomes fully ionized. The specified spectroscopic method is applicable to different transition lines for singly and doubly charged nitrogen and oxygen ions.

As long as doubly charged ions exist at higher temperatures than singly charged ions, this method makes it possible to restore the lightning plasma temperature averaged with respect of different lightning parameters [10]. Additionally, broadening of spectral lines, in particular of hydrogen atom lines, may be used to determine the pressure of lightning plasma, where the corresponding spectral line is created. Hereinafter we will rely on measurements [11–13]. Though, modern instruments can provide a higher resolution than that required for the above-mentioned measurements, Orville et al [11–13] conducted simultaneous temperature and pressure measurement of plasma in the conductive path of lightning.

The objective of this study is to add conductive path plasma radiation power to these measurements to define an energy balance during conductive path plasma development. Analysis of radiation of the studied plasma is based on the idea that photorecombination and braking radiations of electrons on ions as a primary photon generation process in atomic particle collision processes are the main radiation mechanisms in plasma with a perceptible degree of ionization (more than 1% [14]) [15–17]. These mechanisms define the radiation power of krypton and xenon lamps as well as high-pressure mercury-vapor lamps because radiation, as a result of transition between discrete states of atomic particles, makes a minor contribution to the total radiation power due to the narrow width of spectral lines. With a limited radiation source size when radiation is not locked within plasma, the major contribution to the plasma radiation intensity is made by photorecombination radiation as in case of the return stroke plasma.

Photorecombination radiation of lightning plasma

Photorecombination process in plasma containing singly charged ions flows as follows

$$e + M^+ \to M^* + \hbar\omega, \quad (1)$$

where M is an atom. In case of formation of a highly excited atom when the initial and final states meet the classical electron motion pattern, electron and ion photorecombination cross-section can be calculated by the Kramers formulas [18] that uses a classical electron motion in the Coulomb center field in the studied process. Moreover, in case of a hydrogen atom for which quantum-mechanical photorecombination cross-sections of an electron and proton can be easily calculated, the difference of this cross-section from that calculated using the Kramers formulas is 25% [15–17]. This makes it possible to use the Kramers formulas for the photorecombination cross-sections involving nitrogen and oxygen ions for any states with the specified accuracy. Therefore the photorecombination process calculations in this study are based on the Kramers formulas.

In addition to the information mentioned above, we have found that the relative contribution to the radiation power for photorecombination transition into a particular electronic state of the formed atom does not depend on plasma temperature and pressure. This makes the calculation much easier and vivid. In particular, the specific radiation power derived from the Kramers formulas, i.e. the radiation intensity integrated by spectrum and averaged by the Maxwell electron energy distribution, is given by the following expression in atomic units

$$P(T) = \varphi(T)\sum_k g_k J_k^{5/2}; \quad \varphi(T) = \frac{8\sqrt{2\pi}}{3\sqrt{3}}\frac{N_e^2}{c^3\sqrt{T}}, \quad (2)$$

where T is the electron temperature, g_k, J_k is the static weight and ionization potential of the formed atom, N_e is the electron density in quasi-neutral lightning plasma, c is the speed of light. It follows from this equation that the temperature dependence of power and dependence on the parameters of the formed atom are separated.

Figure 1 shows a temperature dependence for the spectrum-integrated specific radiation power of the equilibrium plasma at atmospheric pressure that was obtained using the Kramers formulas and for the real spectrum of nitrogen and oxygen atoms and their concentration in air. More than 90% of the radiation power is produced in the VUV spectrum region. This radiation portion is absorbed near the conductive path boundary, and only visible and adjacent UV spectrum radiation is recorded and defines approx. 8% of the radiation power.

Measurements [11–13] provide the return stroke plasma temperature and pressure during plasma evolution that are shown in Figure 2. Assuming that the plasma is equilibrium,

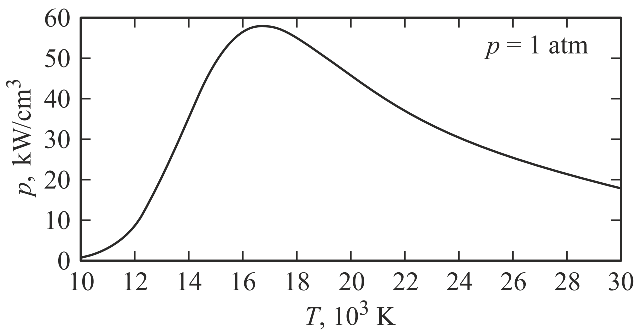

Figure 1. Temperature vs. radiation power of thermodynamically equilibrium air plasma at 1 atm.

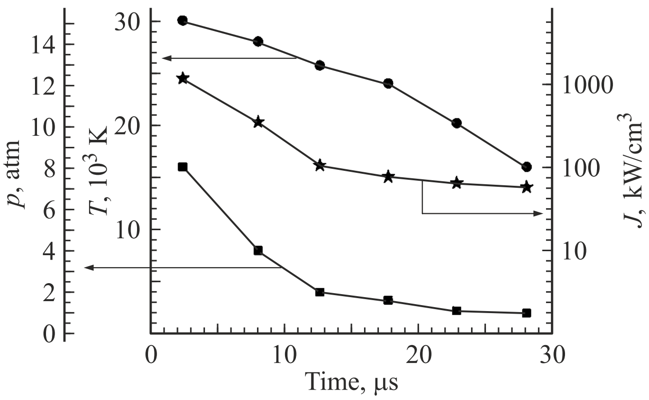

Figure 2. Evolution of the return stroke plasma temperature and pressure, and the specific radiation power calculated on the basis of these parameters. Temperature vs. radiation power of thermodynamically equilibrium air plasma at 1 atm.

i.e. the plasma temperature and pressure are determined at each of the plasma evolution stages, Figure 2 also shows evolution of the specific radiation power of plasma that is treated as optically thin. These dependences will be addressed below.

Equilibria in lightning plasma

The return stroke plasma is treated as equilibrium, while, according to Figure 2, typical plasma evolution times are equal to several microseconds and dozens of microseconds. Our objective is to estimate the equilibration time for different parameters of the return stroke plasma considering the undergoing processes in the same way as it was used at the stepped leader formation and propagation stage [19]. We use a standard method for this (for example, [20,21]) by comparing the equilibration time or this degree of freedom with typical plasma temperature and pressure variation time of the conductive path as shown in Figure 2.

The given plasma contains electrons, ions and atoms, and we'll first estimate the equilibration time in the electronic subsystem that is equal to $N_e v\sigma$, $N_e \sim 10^{17} - 10^{18}\,\text{cm}^{-3}$ — is the electron density, $v \sim 10^8$ cm/s — is the typical electron velocity, and the electron collision cross-section is defined by the Coulomb interactions between electrons. For $T = 20\,\text{kK}$ and the Coulomb logarithm equal to 3, we have scattering in collision of two electrons $\sigma^* \sim 10^{-14}\,\text{cm}^2$ for the diffusion cross-section. Hence, for the equilibration time, we have approx. $10^{-12} - 10^{11}\,\text{s}$ for the electronic subsystem.

In the same way, we get the typical gas temperature stabilization time $\tau \sim 10^{-8} - 10^{-7}\,\text{s}$ in the given conditions and cross-section of about $10^{-15}\,\text{cm}^2$. Thus, gas equilibrium is set faster than the typical equilibrium variation time. Assuming that equilibration between the electronic and gas subsystems is defined by elastic collisions between electrons and atoms, using the cross-section of collision between the electron and nitrogen atom in this energy region $\sigma = 10^{-16}\,\text{cm}^2$ [22] and considering minor energy exchange in elastic collision between the electron and atom, we have for the typical time of equilibration between the electronic and gas subsystems approx. $10^{-8} - 10^{-5}\,\text{s}$.

Thus, in typical conditions of lightning conductive path plasma evolution at the return stroke stage we have that equilibration takes place inside the electronic, atomic and ionic subsystems during plasma evolution. Whereby, the time of equilibration between the electronic and gas components is comparable with the system evolution time. In other words, the electronic and gas subsystem states are characterized by the corresponding temperatures, but they may differ.

Radiation in the conductive path plasma

Along with measurements, an important role in understanding the conductive path plasma evolution is played by computer models that describe plasma evolution in particular conditions considering the plasma behavior and electrodynamics. These models give electric field and current variations in space and time considering the particle and charge balance in plasma. We propose to include radiation in a common form in these models [1], which also makes it possible to use the plasma energy balance in these models.

The role of VUV radiation that makes the main contribution to the lightning hot plasma radiation may be roughly estimated. Inclusion of this radiation into the lightning plasma models can improve the evolution description at the stepped leader and dart leader stages and doesn't play any role at the low continuous current stage. However, the VUV radiation plays a fundamental role at the return stroke stage. Actually, during overcurrent passage, this is the radiation that limits the maximum plasma temperature equal to approx. 30 kK because the plasma radiation power increases dramatically with temperature.

Note that these conclusions are applicable to optically-thin plasma. Let's represent a relevant criterion. Let the homogeneous lightning plasma with the temperature T occupy a space in a cylinder with the radius R. At small sizes, the radiation power per unit column length is $\pi R^2 P$, and at larger sizes, when the radiation is locked within the cylindrical plasma column, is equal to $2\pi R \sigma T^4$, so the criterion of small optical thickness of the plasma layer is written as

$$R \ll R_0 = \frac{2\sigma T^4}{P(T)}. \qquad (3)$$

In particular, at $T = 20\,\text{kK}$, we have $R_0 = 40\,\text{cm}$, and at $T = 30\,\text{kK}$, equation (3) gives $R_0 = 5\,\text{m}$. However, the lateral dimension of the conductive path plasma at the return stroke stage is equal to several centimeters [10], so criterion (3) is met.

Note that one of the results of this study is Figure 2, where the specific lightning plasma radiation power is represented simultaneously with the plasma parameters obtained from measurement processing. According to this figure, the lightning return stroke stage after overcurrent passage may be divided into two pats such as at the first stage the air pressure drops to the atmospheric pressure as a result of plasma expansion, and at the second plasma relaxation stage, when the plasma pressure is close to the atmospheric pressure, the conductive path plasma parameters vary weaker with time.

Conclusion

Lightning is a complex physical phenomenon, so its evolution at different stages is defined by different processes. One of them is the plasma radiation that is particularly important at the return stroke stage, and the VUV absorbed at the plasma boundary constitutes the major portion of the radiation. Thus, radiation intensity measurement in the visible spectrum region (see, for example, [23–25]) makes it possible to restore the total radiation power on the basis of the classical photorecombination plasma radiation theory. Addition of the classical radiation theory to modern computational models of the lightning conductive path makes it possible to include the lightning plasma energy balance in them.

Funding

This study was supported by the Ministry of Science and Higher Education of the Russian Federation (№ FSMG-2023-0013).The paper is supported according to the state assignment of the Ministry of Science and Higher Education of the Russian Federation (No. 075-00270-24-00).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by E.Ilinskaya