Influence of dust particles on the neon spectral line intensities at the uniform positive column of dc discharge at the space apparatus “Plasma Kristall-4”

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Abstract. Influence of the elongated dust cloud on the intensities of different neon spectral lines in visible and near-infrared spectral ranges in the uniform positive column has been experimentally investigated using the Russian-European space apparatus “Plasma Kristall-4” (SA PK-4) on board of the International Space Station (ISS). The investigation was performed in the low pressure (0.5 mbar) direct current (dc, 1 mA) gas discharge in neon. Microgravity allowed us to perform experiments with a large dust cloud in the steady-state regime. To avoid the dust cloud drift in the dc electric field a switching dc polarity discharge mode has been applied. During the experiment a dust cloud of 9 mm in diameter in the discharge tube of 30 mm in diameter with the length of about 100 mm has been observed in the steady-state regime. In this regard, the intensities of neon spectral lines corresponding to $3p \rightarrow 3s$ electronic transitions have increased by a factor of 1.4 times, while the intensities of neon spectral lines corresponding to $3d \rightarrow 3p$ electronic transitions have increased by a factor of 1.6 times. The observed phenomenon is explained on the basis of the Schottky approach by a self-consistent rising dc electric field in the dusty plasma cloud resulting in an increase of the electron temperature.

1. Introduction

The new space apparatus “Plasma Kristall-4” (SA PK-4) has been commissioned on board of the International Space Station (ISS) in June, 2015. The setup is intended for experimental investigation of dusty plasma under microgravity conditions [1]. Unlike the previous space apparatus PK-3 [2] and PK-3 Plus [3], where dusty plasma was created in a capacitive radio frequency (rf) gas discharge, the SA PK-4 creates dusty plasma in a uniform positive column of the low pressure direct current (dc) gas discharge or in a combined dc and inductive rf discharge as well. Due to microgravity conditions promoting the creation of elongated huge dust clouds in the uniform positive column [4], it becomes possible to create a small dust cloud typically of 1 cm in size under laboratory conditions [5]. Dust particles essentially change the ionization equilibrium in the gas discharge owing to the intense recombination of ions and electrons on the...
Figure 1. Scheme of setup and experiment: CCD1 and CCD2—high resolution cameras; CCD3—low resolution overview plasma glow observation (PGO) video camera; M1, M2, and M3—flat mirrors; SP—OceanOptics USB2000+ minispectrometer; OF—optical fiber; FL—fiber head with a lens.

dust particle surfaces that leads to modification of plasma parameters—electron number density \( n_e \) and temperature \( T_e \), space potential distribution \( \phi_s \), electric fields \( E_{r,z} \) and populations of atomic excited levels. All these processes are of fundamental scientific interest.

The most useful plasma diagnostic method is a Langmuir probe, but it dramatically disturbs the dust component of the diagnosed dusty plasma. In addition, an application of Langmuir probes in a compact space apparatus is quite complicated. Optical noninvasive spectroscopic diagnostic methods are more suitable in this case. Nevertheless, interpretation of spectral information is rather difficult due to hundreds of kinetic processes with appropriate rates resulting in observable spectral line intensities \( I \). In general, the determination of plasma parameters on the basis of measured spectra is a reversal task, which doesn’t have a general solution \[6\]. In practice, the researchers always take a set of simplifying assumptions to obtain a solution of the diagnostic task. We have found only a few works regarding emission spectral diagnostics of dusty plasmas. Samsonov and Goree \[7\] applied the line ratio method for quantitative imaging electron temperature distribution in a capacitive rf discharge with dust particles and found an enhanced \( T_e \) in the plasma region occupied by dust particles. Mitic et al. \[8\] have proposed a method of electron temperature determination in a capacitive rf discharge by means of optical emission spectroscopy based on a comparison of spectral lines intensities recorded from two volumes of the steady-state plasma with different electron temperatures, \( T_{e,1} \) and \( T_{e,2} \) with the Maxwellian electron energy distribution functions (EEDF) and a simplified collision-radiative model. The method suffers from large uncertainties. Quite recently, Kostenko et al. \[9\] have investigated an influence of dust particles (polydispers sapphire \( \text{Al}_2\text{O}_3 \) with transverse dimensions \( a = 6 \pm 4 \mu m \) on the relative intensities of Ar (518.7 nm) and He (587.6 nm) spectral lines emitted from a stratum of the dc discharge (\( I_{dc} = 2 \text{ mA} \)) in the mixture–50% of Ar and 50% of He at the pressure of 0.5 mbar. The authors have detected an enlargement of the \( I_{\text{He}}/I_{\text{Ar}} \) ratio by 1.26 ± 0.1 times due to the presence of dust particles, that indicates rising the electron temperature \( T_e \).

In fact, the stratum of the dc discharge is not a convenient medium for experiments due to its inhomogeneity. The uniform positive column with calibrated dust particles is more suitable for a physical interpretation of the obtained experimental results. In this work, we present the results of experimental investigation of an influence of the elongated dust cloud on emission spectra of the uniform positive column under microgravity conditions at the ISS.

2. Setup and experiment
The present experiment has been performed using the SA PK-4 \[1\] during the commissioning tests on board of the ISS in June, 2015. The scheme of the setup and experiment is presented in figure 1. The experimental arrangement consists of a II-shape glass discharge tube of 30 mm
in inner diameter with a total length of 85 cm filled by neon at the pressure of 40 Pa. The tube was equipped by two dc cylindrical stainless steel electrodes installed at the ends of the tube. The vacuum pumping and gas filling systems were connected to the ends of the tube via the electrodes. The tube was pumped down to the base pressure $< 2 \times 10^{-5} \text{ mbar}$ during 2 days and then filled by neon up to the discharge operating pressure of 0.5 mbar. The discharge current was $I_{\text{dc}} = 1 \text{ mA}$. Under the given conditions, the dust free dc glow was a uniform positive column filling the whole visible tube discharge volume (figure 2(a)). Monodisperse plastic (melamine formaldehyde) microspheres (dust particles) with a diameter of $d = 3.38 \pm 0.07 \mu \text{m}$ were injected into the discharge plasma in the vicinity of the right cathode side of the discharge tube using a shake dust injector and were transported to the experimental area in the tube center by the dc electric field. The dust particles were illuminated by the green (532 nm) laser “sheet” and recorded by two high resolution particle observation (PO) video cameras. The field of view (FoV) of each PO camera was of $22 \times 17 \text{ mm}^2$ with a spatial resolution of $1600 \times 1200$ pixels and the frame rate of 35 fps. Two PO FoVs were jointed by their small sides into the single FoV with an overall dimension of $44 \times 17 \text{ mm}^2$. The effective full width at half the maximum (FWHM) of the laser “sheet” was measured to be equal to 50 $\mu \text{m}$ in the center of the total field of view, and 180 $\mu \text{m}$ near the edges. In addition to the PO video cameras the SA PK-4 was equipped by the third plasma glow observation (PGO) camera with a resolution of $640 \times 480$ pixels and the frame rate of $f_{\text{PGO}} = 15$ fps.

Using a kaleidoscopic system [1], the PGO camera observes the plasma glow from the whole central part of the discharge tube through 3 spectral filters—a gray filter with a transmittance of 12% and 2 narrowband interference filters tuned on 705 and 587 nm. To perform spectral diagnostics, the SA PK-4 is equipped by a minispectrometer OceanOptics USB2000+. The 2048-pixel CCD sensor of the spectrometer with a linear output allows to obtain simultaneous acquisition of the spectrum in the wavelength range of 350–1100 nm with a spectral resolution of 1.5 nm. The receiving optics of the spectrometer is installed together with the PO cameras and connected to the spectrometer via an optical fiber (figure 1). Plasma emission is collected
Figure 3. Dust cloud in uniform positive column recorded by two HR cameras. Each frame is 22.1 mm × 16.6 mm in size. Laser knife width varies from 50 µm in the center to 150 µm at half the maximum of the double frame. Dust number density concentration is $1.5 \times 10^5$ cm$^{-3}$. Plasma emission was collected from white point in FoV center.

from the center of the PO FoV. The readout time of the full spectrum is 4 s. The spectrometer permits to effectively control plasma purity during the experiments.

Being injected into plasma near the cathode, the dust particle cloud drifts to the anode side of the tube with the velocity of about 3 cm/s (figure 2(b)). To prevent the dust cloud drift in the axial dc discharge electric field $E_z$ and to observe the steady state dusty plasma, the polarity switching (PS) dc discharge (dc/PS-mode) was used. In this respect, the absolute value of the direct current was equal to $I_{dc} = 1$ mA and the polarity was switched at the frequency of $f_{dc} = 500$ Hz. Such a frequency is bigger than the dust plasma frequency, hence the axial field $E_z$ does not affect the dust dynamics. As the injected dust cloud filled the whole PO cameras FoV (figure 3), the dc mode was switched into the dc/PS mode. In this case, the cloud drift was stopped, and 5 emission spectra were recorded and averaged. The dust cloud diameter and dust number density in the cloud were calculated as $r_c = 0.45$ cm and $N_d = 1.5 \times 10^5$ cm$^{-3}$, correspondingly. Two emission spectra of the positive column without and with the dust cloud are presented in figure 4. Each spectrum was obtained by averaging 5 spectrum samples and subsequent subtraction of dark spectra measured just before the experiment. CCD exposure time was equal to 0.5 s. The line of 585.25 nm was registered with saturation, and it was not used in our analysis. The super intense wide spectral line at 532 nm is the scattered light from the dust particle illuminating laser.

3. Gas discharge plasma emission
Due to electron impact ionization, gas discharge plasma always contains excited atoms or molecules that are accompanied by their irradiation. Intensities of spectral lines emitting by plasma are proportional to the populations of upper atomic levels. The excited atom number densities are determined by a balance of population and depopulation processes. As a rule, they are very diverse and strongly depend on particular discharge conditions, namely, gas pressure and discharge current. The main aim of plasma spectral diagnostics is to determine plasma parameters using spectral data. Some plasma parameters such as populations of excited atomic and molecular levels or concentration of different species can be determined quite easily. Other plasma parameters, such as electron number density $n_e$ and temperature $T_e$ are difficult enough to be extracted from emission spectra. Different plasma models are used to relate the observable
spectra with these plasma parameters. There are two limiting theoretical approaches having an analytical solution, namely, the coronal model for very low density plasmas and the local equilibrium model for high pressure plasmas. Most practical cases (including PK-4 plasma) strongly represent non-equilibrium plasmas, which can be modeled using collisional radiative models [10]. We note here, that there is no universal collisional-radiative model: it depends on the particular experimental conditions. In this work we estimate a variation of the electron temperature $T_e$ of the uniform positive column in the large dust cloud using the Schottky approach presented in [4].

The simplified scheme of the considered Ne energy levels and kinetic processes are presented in figure 5. Plasma in the PK-4 positive column is characterized by low electron density with $n_e = 3 \times 10^8$ cm$^{-3}$ [1] and a very low degree of ionization. Under these conditions the stepwise excitation of 3$p$ and 3$d$ levels from the metastable 3$s$ levels is mini [11], and excitation of the 3$s$, 3$p$ and 3$d$ levels are mostly performed by the direct excitation from the ground state $^{1}S_0$ of neon atom. The ratio $X_{0i}$ for electron impact excitation from the ground level $E_0$ to the excited level $E_i$ can be written in a standard form

$$X_{0i} = \sqrt{2/m_e} \int_{E_i}^{+\infty} \sigma_{0i}(E) E f(E, T_e) dE,$$

(1)

where $E$ and $m_e$ are the electron energy and mass, respectively, $f(E, T_e)$ is the electron energy
distribution function (EEDF) normalized as $\int_0^\infty f(E)\,dE = 1$, $\sigma_0(E)$ is the cross section of excitation of the level $i$ by an electron with energy $E$ from the ground level $E_0$, index $i$ indicates one of the excited energy levels from 3s, 3p, or 3d, groups of levels presented in figure 5. To calculate the ratio $X_{0i}$, one has to know the EEDF for the particular discharge plasma conditions and the cross section $\sigma_0(E)$ for the used interval of electron energies. As a rule, both values are known with a large uncertainty and have to be substantiated for each particular case. The convolution $\sigma(E)f(E)$ can be expressed graphically as it is shown in figure 6. Two plotted EEDFs $f_1$ and $f_2$ are the Maxwellian ones and correspond to $T_{e1} = 7$ eV and $T_{e2} = 9$ eV, respectively. In the low pressure gas discharge, the EEDFs differ from the Maxwellian ones. As a rule they have depleted tails as it is shown in figure 6 by the dotted line. In this case we can characterize the tail by an “effective” or “excited” electron temperatures $T^*_{e}$. The $\sigma_{3p}(E)$ profile in relative units indicates a cross-section of the excitation of one of the levels from the 3p-group from the ground state [12]. One can see that the rate $X_{3p}$ is formed only by the EEDF tail. The excitation of the 3d levels is performed even by more energetic electrons comparing with those populating the 3p levels. The growth of $T^*_{e}$ leads to growing the $X_{3p}$ and $X_{3d}$ rates, and the rate $X_{3d}$ grows faster with $T^*_{e}$ than $X_{3p}$. This feature can be useful for the analysis of $T^*_{e}$.

4. Results and discussions
We have compared the neon spectral line intensities $I_0$ emitted by the uniform positive column with those filled by the elongated dust particle cloud $I_{cl}$. The ratios $I_{cl}/I_0$ vs the energy $E_u$ of the excited upper levels are presented in figure 7. According to the investigations [11], under the present experimental conditions, self-absorption of all spectral lines corresponding to $3p \rightarrow 3s$ transitions is less than 1% except the strongest 585 nm line, which will not be taken into account. One can see that in the presence of the dust particles the intensities $I_{cl}$ are sufficiently growing by 1.4 times for those having 3p upper levels and by 1.6 times for those having 3d upper levels with respect to the initial spectral lines intensities $I_0$. In this regard, all ratios $I_{cl}/I_0$ for the $3p \rightarrow 3s$ spectral lines are equal within experimental errors. The ratios $I_{cl}/I_0$
Figure 6. Convolution $f(E)g(E)$ resulting in the excitation of the ratio $X_{3p}$: $f_1(E)$ and $f_2(E)$ are Maxwellian EEDF for $T_{e,1} = 7$ eV and $T_{e,2} = 5$ eV; respectively, dotted line is a depleted EEDF tail; dashed line is a typical view of excitation cross-section of $3p$-levels from the ground level.

Figure 7. Ratios of neon spectral lines intensities recorded with $I_{cl}$ and without $I_0$ the dust particle cloud in the positive column vs energy $E_u$ of the upper levels in the corresponding electronic transitions.

for the $3d \rightarrow 3p$ spectral lines do not have a sufficient statistics for the similar conclusion due to their relative low intensities and corresponding low signal-to-noise ratios. The intensities $I_{cl}$ can rise with respect to the intensities $I_0$ due to two reasons, namely, due to growing $n_e$ or $T_e$ (or both). There has been shown [4] that under the steady state conditions the electron number density inside the dust cloud $n_{e,cl}$ is constant and equal to the ambient electron number density $n_e$. Otherwise the cloud will be destroyed by plasma fluxes. Hence, in our steady state conditions the plasma glow enhancement is caused only by rising the excitation of the electron temperature $T_{e}^*$ in the presence of the dust cloud. The electron temperature is rising due to a self-consistent enlargement of the axial electric field strength $E_z$. It was shown in the Schottky (diffuse) approximation at the discharge current stabilization mode $E_z \sim I_0$ [4]. The electron temperature also grows as $T_e \sim E_z \sim I_0$. Thus, we can conclude that the axial electric field
strength achieves the value of $E_z \sim 3$ V/cm inside the dust cloud instead of $E_z \sim 2.1$ V/cm in the pure positive column [1] and the mean electron temperature $T_e$ rises up to about 10 eV from initial 7 eV in the pure positive column.

5. Conclusion
In this work, the influence of the elongated dust cloud on the neon spectral lines intensities of the uniform positive column of the low pressure low current dc gas discharge plasma has been experimentally investigated under microgravity conditions. It has been revealed that the presence of the elongated dust cloud leads to the increase of neon spectral lines intensities having upper 3p-levels by a factor of 1.4 times and having upper 3d-levels by a factor of 1.6 times. In this respect, all spectral lines having 3p-levels have increased their intensity by the same times. The observed phenomenon is explained on the basis of the Schottky approach by rising the dc electric field in the dusty plasma cloud and subsequent additional heating up plasma electrons.

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