OPTICAL PROPERTIES OF AN ELECTRODELESS-DISCHARGE PLASMA IN AN AIR FLOW

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We report here a spectroscopic study of the emission of an air plasma. The spectrum in the range 0.2–0.8 μ is described and identified, and the relative radiation intensity is reported for the characteristic lines at a plasma temperature of 9800° K and at a pressure of 1 kgf/cm^2.

Electrodeless discharge in a gas flow looks promising as a source of a stable cool plasma. In our apparatus, which was based on a high-frequency electrodeless discharge, the plasma temperature reaches 10 000° K, in order-of-magnitude agreement with the calculated value [1].

The primary advantage of this type of plasma source is that it can be used to produce a spectrally pure plasma, i. e., one in which there is no emission from electrode-destruction products, etc. In this respect, it is better than such familiar plasma sources as the shock tube, various arc devices, etc.

To the best of our knowledge, the plasma of an electrodeless discharge has been studied spectroscopically only in argon [2–4].

We photographed and identified the spectrum of the air plasma in the UV, visible, and near-IR regions; determined the absolute intensity of the radiation and the rotational, vibrational, and electron temperatures; determined the effective cross sections for collisions between molecules and atoms; and determined the concentrations of electrons in the plasma from the lines and from the continuous spectrum of oxygen and nitrogen atoms. We report here an identification of the spectrum of the air plasma and measurement of the relative intensity of the radiation in several characteristic lines.

The discharge source was the high-frequency electrodeless plasmatron described in [5]. The heart of the plasmatron was an LGD-32 vacuum-tube oscillator with a modified oscillator circuit. The discharge power was determined from the current and voltage measured in the plate power circuit of the oscillator tube. The losses in the various oscillator elements were taken into account by a balance method. The useful power in the discharge was therefore 27 kW at a pressure of 1 kgf/cm^2, a gas flow rate of 0.2 g/sec, and a frequency of 17.7 MHz. The discharger consisted of a quartz tube having an i. d. of 60 mm, around which a two-turn inductor 2 (Fig. 1) was wound; the inductor was fed from the oscillator 1. The antechamber of the discharge chamber had a device for hydrodynamic stabilization of the plasma stream and cooling of the inner walls of the discharge tube.

Figure 1 shows the optical setup. The radiation spectra were photographed in the wavelength range from 0.22 to 0.8 μ with an ISP-51 glass spectrograph (camera 8 in Fig. 1, having f = 1300 mm, and 9 having f = 270 mm) and an ISP-30 quartz spectrograph (7 in Fig. 1). For photography in the spectral range 0.22–0.65 μ, the entrance slits of the spectrographs were 0.145 mm wide; for the range above 0.65 μ, they were 0.05 mm wide. In addition to the spectrographs, the optical system contained condensers 6 and a Dove prism 4. The Dove prism was used to project an image of the source, rotated through 90°, along the spectrograph slits, so that the plasma regions transverse to the discharge axis and in a cross section about 30 mm from the upper turns of inductor 2, at a cut in the discharger tube 3 were projected on the slits. Preliminary studies showed that at distances of 30 mm and more from the cut, the intensity of the radiation from the plasma column has axial symmetry; therefore, calculations based on the integral relations of Abel [6] can be used to obtain the radial distribution of the radiation intensity. Figure 2 shows the axisymmetric radiation profile of the (1.3) band edge of the N_2^+ system (1–) and the oxygen line 0I 4368.3 Å.

The spectrum was photographed in various wavelength regions by specially selected photographic emulsions sensitized in these regions. In the range 0.22–0.38 μ, UFSh-4 plates were used; WU-1 plates in the range 0.38–0.42 μ; WP-1 plates in the range 0.42–0.65 μ; and J-750 plates in the range 0.65–0.8 μ.

The spectra of iron and a PRK-2 mercury lamp were also photographed for spectral identification. Blackening curves from standard SI-8-200 and LLS-7 tungsten lamps (with glass and quartz windows, respectively) were obtained for a determination of the absolute radiation intensity from the spectra. The radiation intensities were determined through treatment of the spectrograms by heterochromatic photometry; an MF-4 apparatus was used for the photometry of the spectrograms.

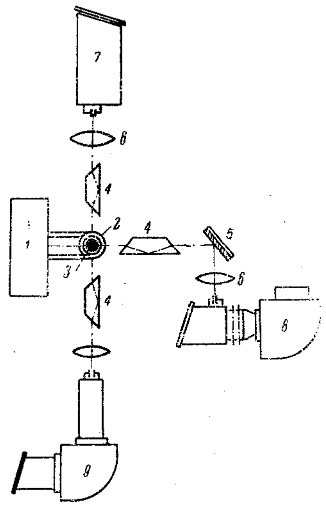

Fig. 1

Figure 3 shows the radiation spectra of the air plasma under the operating conditions described above. Spectra were photographed for the temperature measurements with an account of the radial distribution of the radiation intensity. A sample of these spectrograms is shown in the upper frame in Fig. 4. The results of the spectrum identification are shown in the accompanying table.

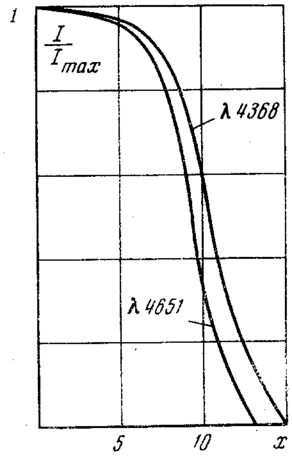

Fig. 2

As is evident from Figs. 3 and 4, the radiation spectra of the air plasma at the wavelengths tested contain many atomic lines (mainly oxygen) and the branch systems of the bands of diatomic molecules. In Figs. 3 and 4 and in the table: $N_2^+(1-)$ is the first negative system of the bands of the N_2^+ molecule, $N_2(1+)$ and $N_2(2+)$ are the first and second positive bands of the N_2 molecule, and NO(γ) is the γ-system of NO bands. The plasma spectrum contains the lines H_α, H_β, H_γ, and the lines CI 2478.6 Å of neutral carbon, indicating that the decomposition products of water vapor and carbon dioxide (present as impurities in the laboratory air) are present in the plasma. The spectrograms in Fig. 4 show that there are no C, CO_2, or H_2O near 5330 Å, where the temperature was evaluated. Moreover, there are no lines corresponding to the elements from which the discharge apparatus was made or the elements which usually come from plasmatron walls (K, Na, Ba, CaO, etc.).

The most intense system in the spectrum is the first negative system of the N_2^+ molecule, for which the band sequence +1, +2, 0, −1, −2, −3 was observed. The bands of the second positive system of the N_2 molecule are shown by the sequence +2, +1, 0, −1, −2. Also visible in the spectrum are the double edges of the band of the γ-system of

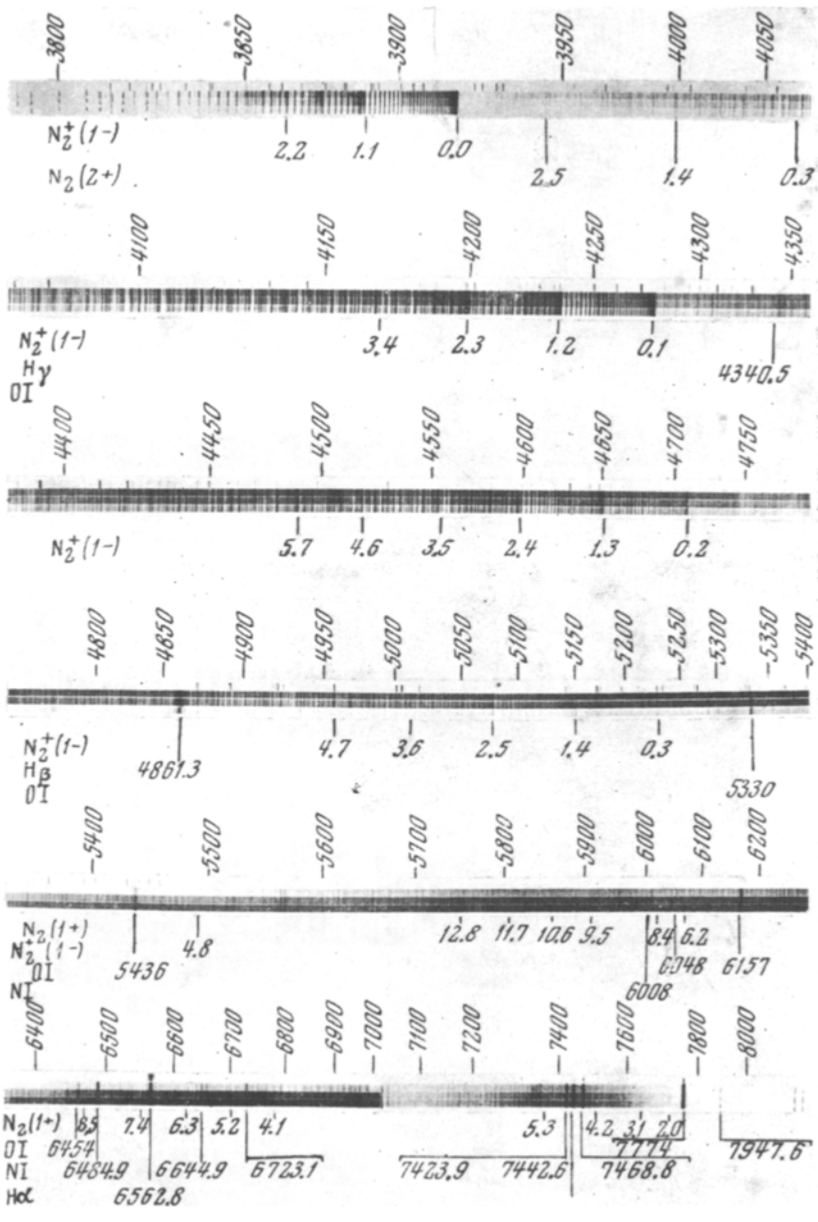
3800 3850 3900 3950 4000 4050
N₂⁺(1-) 2.2 1.1 0.0
N₂(2+) 2.5 1.4 0.3
4100 4150 4200 4250 4300 4350
N₂⁺(1-) 3.4 2.3 1.2 0.1
Hγ 4340.5
OI
4400 4450 4500 4550 4600 4650 4700 4750
N₂⁺(1-) 5.7 4.6 3.5 2.4 1.3 0.2
4800 4850 4900 4950 5000 5050 5100 5150 5200 5250 5300 5350 5400
N₂⁺(1-) 4.7 3.6 2.5 1.4 0.3
Hβ 4861.3
OI 5330
5400 5500 5600 5700 5800 5900 6000 6100 6200
N₂(1+) 12.8 11.7 10.6 9.5 8.4 6.2
N₂⁺(1-) 4.8
OI 5436 6048 6157
NI 6008
6400 6500 6600 6700 6800 6900 7000 7100 7200 7400 7600 7800 8000
N₂(1+) 8.5 7.4 6.3 5.2 4.1 5.3 4.2 3.1 2.0
OI 6454 7774
NI 6484.9 6644.9 6723.1 7423.9 7442.6 7468.8 7947.6
Hα 6562.8

Fig. 3

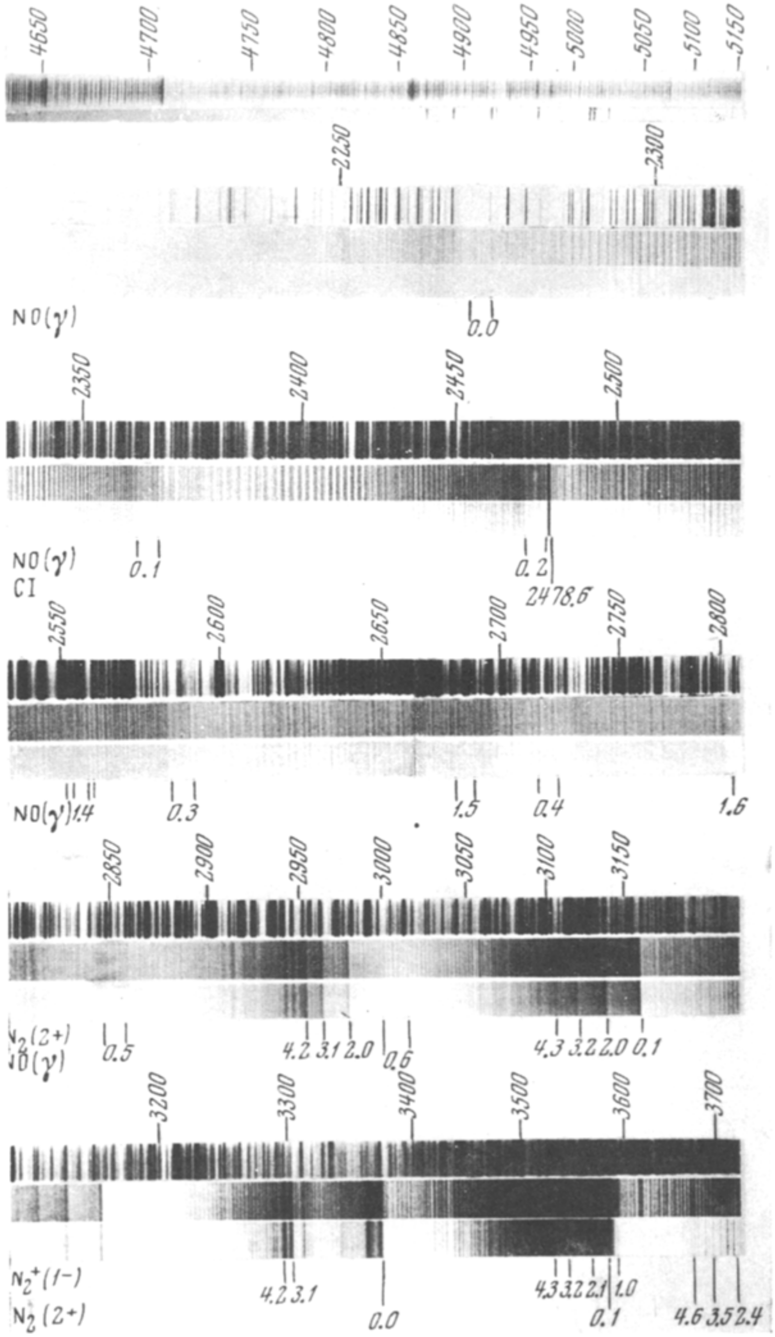
4650 4700 4750 4800 4850 4900 4950 5000 5050 5100 5150
2250 2300
NO(γ)
0.0
2350 2400 2450 2500
NO(γ)
CI
0.1
0.2
2478.6
2550 2600 2650 2700 2750 2800
NO(γ) 1.4
0.3
1.5
0.4
1.6
2850 2900 2950 3000 3050 3100 3150
N2(2+)
NO(γ)
0.5
4.2 3.1 2.0
0.6
4.3 3.2 2.0 0.1
3200 3300 3400 3500 3600 3700
N2+(1−)
N2(2+)
4.2 3.1
0.0
4.3 3.2 2.1 1.0
0.1
4.6 3.5 2.4

Fig. 4

Table

Characteristics of the Atomic and Molecular Spectra of the Air Plasma

1	2	3
$NO(\gamma)$	$^2\Sigma \rightarrow {}^2\Pi$	
2263.0	(0,0)	
2269.4	(0,0)	
2363.2	(0,1)	
2370.2	(0,1)	
2471.1	(0,2)	
2478.7	(0,2)	
CI	$2p^1S_0 \rightarrow 3s^1P_1^0$	
2478.6		
$NO(\gamma)$	$^2\Sigma \rightarrow {}^2\Pi$	
2551.0	(1,4)	
2558.6	(1,4)	
2587.5	(0,3)	
2595.7	(0,3)	
2671.0	(1,5)	
2680.0	(1,5)	
2713.2	(0,4)	
2722.2	(0,4)	
2810.4	(1,6)	
2849.8	(0,5)	
$N_2(2+)$	$C^3\Pi \rightarrow B^3\Pi$	
2953.2	(4,2)	
2962.0	(3,1)	
2976.8	(2,0)	
$NO(\gamma)$	$^2\Sigma \rightarrow {}^2\Pi$	
2997.6	(0,6)	
3008.8	(0,6)	
$N_2(2^+)$	$C^3\Pi \rightarrow B^3\Pi$	
3136.0	(2,1)	
3159.3	(1,0)	
$N_2^+(1^-)$	$^2\Sigma \rightarrow {}^2\Sigma$	
3293.4	(4,2)	
3298.7	(3,1)	
$N_2(2^+)$	$C^3\Pi \rightarrow B^3\Pi$	
3371.3	(0,0)	
$N_2^+(1^-)$	$^2\Sigma \rightarrow {}^2\Sigma$	
3538.3	(4,3)	
3548.9	(3,2)	
3563.9	(2,1)	
$N_2^+(1^-)$	$^2\Sigma \rightarrow {}^2\Sigma$	
4957.9	(4,7)	
5076.6	(2,5)	
5148.8	(1,4)	
5228.3	(0,3)	0.4
OI	$3p^5P_{1,2,3} - 5d^5D^0_{0,1,2,3,4}$	
5328.98		
5329.59		
5330.66		1.0
OI	$3p^5P_{1,2,3} - 6s^5S_2^0$	
5435.2		
5435.8		0.4
5436.8		
$N_2^+(1-)$	$^2\Sigma \rightarrow {}^2\Sigma$	
5485.5	(4,8)	
$N_2(1+)$	$B^3\Pi \rightarrow A^3\Sigma$	
5755.2	(12,8)	
5804.3	(11,7)	
5854.4	(10,6)	
5906.0	(9,5)	
5959.0	(8,4)	
NI		
6008		2.1
OI	$3p^3P_{0,1,2} - 6s^3S_1^0$	
6048		0.6
$N_2(1+)$	$B^3\Pi \rightarrow A^3\Sigma$	
6069.7	(6,2)	
OI	$3p^5P_{1,2,3} - 4d^5D^0_{0,1,2,3,4}$	
6156.0		2.6
6156.8		3.4
6158.2		6.6
$N_2(1+)$	$B^3\Pi - A^3\Sigma$	
6394.7	(9,6)	
OI	$3p^5P_{1,2,3} - 5s^5S_2^0$	

The symbol (m, n) denotes the corresponding change m → n in the vibrational quantum number. The asterisks indicate reabsorbed lines and edges. The line intensities are given with respect to the intensity of the 0I 5330 A line at 9800° K. Column 1) line identification and its wavelength (A); column 2) corresponding transition; column 3) relative intensity.

Table (cont'd)

1	2	3
N_2 (2+)	$C^3\Pi \to B^3\Pi$	
3576.9	(0,1)	
N_2^+ (1—)	$^2\Sigma \to {}^2\Sigma$	
3582.1	(1,0)	
N_2 (2+)	$C^3\Pi \to B^3\Pi$	
3641.7	(4,6)	
3671.9	(3,5)	
3710.5	(2,4)	
N_2^+ (1—)	$^2\Sigma \to {}^2\Sigma$	
3857.9	(2,2)	
3884.3	(1,1)	
3914.4 *	(0,0)	
N_2^+ (1—)	$^2\Sigma \to {}^2\Sigma$	
4166.8	(3,4)	
4199.1	(2,3)	
4236.7 *	(1,2)	
4278.1 *	(0,1)	
H_γ 4340.5	$2s - 5p$ $2p - 5s$ $2p - 5d$	0.7
OI	$3s^3S_1^0 - 4p^3P_{0,1,2}$	
4368.3		2.8
N_2^+ (1—)	$^2\Sigma \to {}^2\Sigma$	
4490.3	(5,7)	
4515.9	(4,6)	
4554.1	(3,5)	
4599.7	(2,4)	
4651.8	(1,3)	
4709.2	(0,2)	1.2
H_β 4861.3	$2s - 4p$ $2p - 4s$ $2p - 4d$	0.7

1	2	3
6453.7		
6454.6		
6456.0		1.7
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
6468.5	(8,5)	
NI		
6484.9		3.4
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
6544.8	(7,4)	
H_α 6562.8 *	$2s - 3p$ $2p - 3s$ $2p - 3d$	
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
6623.6	(6,3)	
NI 6644.9	$3p^4D^0_{1/2,3/2,5/2,7/2} - 5sP^4_{1/2,3/2,5/2}$	2.2
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
6704.8	(5,2)	
NI		
6723.1		9.3
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
6788.6	(4,1)	
7386.6	(5,3)	
NI	$3s^4P_{1/2,3/2,5/2} - 3p^4S^0_{3/2}$	
7423.9		
7442.6		
7468.8		
N_2 (1+)	$B^3\Pi \to A^3\Sigma$	
7503.9	(4,2)	
7626.2	(3,1)	
7753.2	(2,0)	
OI	$3s^5S_2^0 - 3p^5P_{1,2,3}$	
7771.9		
7774.1		
7775.4		
OI	$3^1s^3D^0_{3,2,1} - 3^1p^3F_{4,3,2}$	
7947.6		

NO, corresponding to the sequence +6, +5, +4, +3, +2, +1, 0. The spectrum of the first positive system of the N_2 molecule is shown by the complex set of rotational lines. There is a complete overlap of the rotational lines at the edges of the $N_2(2+)$, $N_2^+(1-)$, and NO(γ) bands. Between the lines there is an intense continuous radiation.

A preliminary estimate of the temperature on the basis of the absolute intensity of the oxygen line OI 5330 Å showed that the temperature along the axis of the stream was 9800° K.

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