The Emission Coefficient of the Continuum in an Argon and Nitrogen Plasma at High Temperatures

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The continuum emission of an argon- and nitrogen plasma developed in an electrical discharge has been investigated in the wavelength range from 3000 Å to 6700 Å. To this purpose the time- and radial dependent plasma parameters such as temperature and the total pressure have been determined in the high conducting stage of the spark by measuring several line intensities. The continuum coefficient was calculated from these data according to the Kramers-Unsöld theory. The comparison of the theoretical and the measured values shows deviations which are discussed. In the case of the argon continuum the ξ-factors for $T = 14\,000$ K agree with the calculated values of Schlüter and the experimental ones of Schulz-Gulde. In the case of the nitrogen plasma the ξ-factors have been determined in the temperature interval from 18 000 K to 45 000 K. Since at these temperatures the particles N_{II}-N_{IV} contribute to the total continuum coefficient, the measured ξ-factors can only be correlated to ξ_{II}, ξ_{III}, ... in a narrow temperature range. The measured correction factor ξ for $\lambda = 5050$ Å has been applied to determine the temperatures and the pressure of a laser produced spark. The plasma parameters agree with those determined by measuring the line-intensity of the N_{II}-line at 5000 Å.

Introduction

The emission coefficient for continuum radiation of a thermal plasma has been calculated by Kramers [1], Unsöld [2], Maecker and Peters [3]. The Maecker-Peters formula requires that the emission coefficient is independent of the frequency in a certain spectral range and does not describe the observed frequency dependent edge structure of the coefficient. Therefore Bieberman, Norman and Ulyanov [4] have calculated the continuum coefficient for the rare gases introducing the correction factor ξ. In addition Schlüter [5] has calculated the ξ-factor for the neutral rare gases in a refined manner. While the continuum emission coefficient, especially for argon, is frequently investigated experimentally by Wende [6], Schulz-Gulde [7], Schnappauf [8], Richter [9], as well as theoretically, only a few experimental and theoretical investigations of the nitrogen continuum are known except that of Bold [10] who has investigated the recombination and minus continuum of nitrogen atoms for $T = 10\,500 - 13\,000$ K.

In the present study the continuum emission of a hot plasma produced in an electrical discharge in argon and nitrogen in the temperature range from 18 000 to 45 000 K is investigated. Our measurements show that also at these temperatures the deviation from the Kramers-Unsöld theorie (KU) as function of the wavelengths and the temperature is considerably. The influence of the Ar_{III} and the $N_{II, III, IV}$-ions on the continuum radiation must be taken into account. The experimental set up to produce the hot plasma and the procedure to get the plasma parameters are described in detail in [11, 12] by Tholl and coworkers.

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Method

In an electrical discharge which has been developed in argon and nitrogen, the emission of the hot plasma consists of lines of atoms, ions and continuum radiation due to free-free and free-bound transitions. The temperatures have been calculated from the measured line emission coefficient of the wavelength λ using equation [18]

$$\varepsilon_{\rm L}{}^i = \frac{h\,c}{4\,\pi}\,A_{nm}\,n_i\,\frac{g_m}{z_i(T)}\,\exp\{-E_m/k\,T\}\,. \qquad (1)$$

$\varepsilon_{\rm L}{}^i$ is the emission coefficient of an atom or an ion with the charge i. g_m and E_m are the statistical weights and the energy of the upper level of the line obtained by Striganov and Sventitskii [13]. The transition probabilities A_{nm} are given by Griem [14]. $z_i(T)$ is the partition function of the particle i. n_i can be calculated as function of the temperature and the total pressure p as parameter taking into account the lowering energy ΔE which was calculated using the formula given by Drawin and Felenbok [15]. The formula (1) is only valid in the case of local thermal equilibrium (LTE) and an optically thin plasma. Both conditions are verified experimentally for the given experimental conditions (see [16]). Therefore an uniform temperature can be defined, and we can calculate the electron densities from the Eggert-Saha equation. The total pressure is given by

$$p = (\sum_i n_i + n_e)\, k\, T$$

and has been determined with an accuracy of the measurements to $\Delta p/p \approx 20\%$. Since the Normtemperature (see [16]) depends only weakly on the pressure, the temperature T can be determined with an accuracy of $\Delta T/T \approx 13\%$. At temperatures above 13 000 K (as in our experiment) the plasma contains neither molecules nor negative ions.

The total emission coefficient of the continuum radiation in the wavelength range $\lambda > 3000$ Å is given by Maecker, Peters [3]

$$\varepsilon_{\mathrm{ff}} + \varepsilon_{\mathrm{fb}} = \varepsilon_k = 5.443 \cdot 10^{-39} \frac{c}{\lambda^2} \frac{n_e}{(k\,T)^{1/2}} \sum_i Z_i^2\, n_i \quad (2)$$

$$(\mathrm{erg\ sec^{-1}\ cm^{-3}\ Å^{-1}\ ster^{-1}})\,.$$

$\varepsilon_{\mathrm{ff}}$, $\varepsilon_{\mathrm{fb}}$ is the emission coefficient due to free-free and free-bound transitions. The temperatures T and the densities n_e, n_i can be determined from the measured line intensities, so that these parameters can be introduced into Equation (2).

As usual we define the deviation from the Kramers-Unsöld theory to

$$\xi = \varepsilon^k_{\mathrm{measured}} / \varepsilon_k\,. \quad (3)$$

$\varepsilon^k_{\mathrm{measured}}$ is the real coefficient measured by the emitted continuum radiation, ε_k is given by Equation (2).

Results and Discussion

A) Investigation of the Argon Continuum

In the following we discuss at first the measured dependence of the emission coefficient from the temperature and we compare the experimental values with the theory (i). Further we determine the ξ-factor depending on the wavelength for one temperature and compare it with measurements and calculations from other authors (ii).

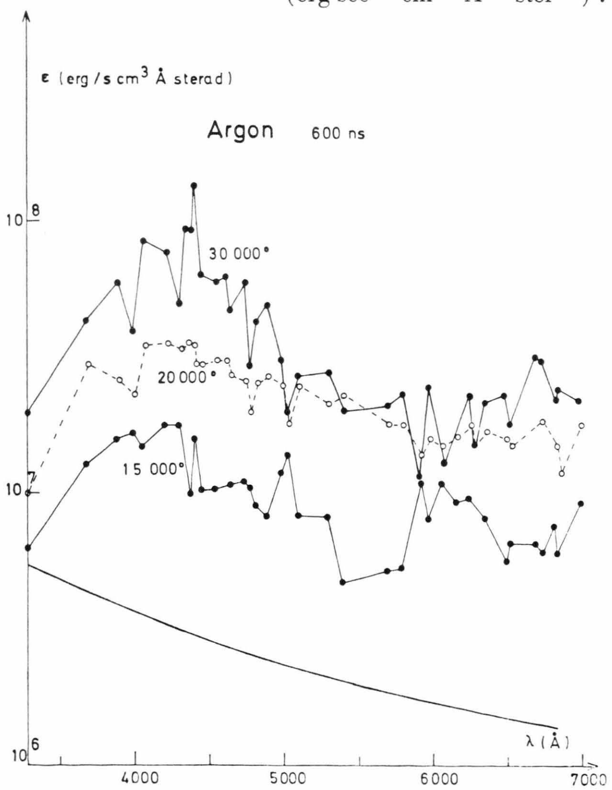

Fig. 1 a. The measured argon continuum at 600 nsec for different temperatures. The solid line shows the dependence of the emission coefficient calculated according to the Kramers-Unsöld theory. The pressure p is 3600 Torr.

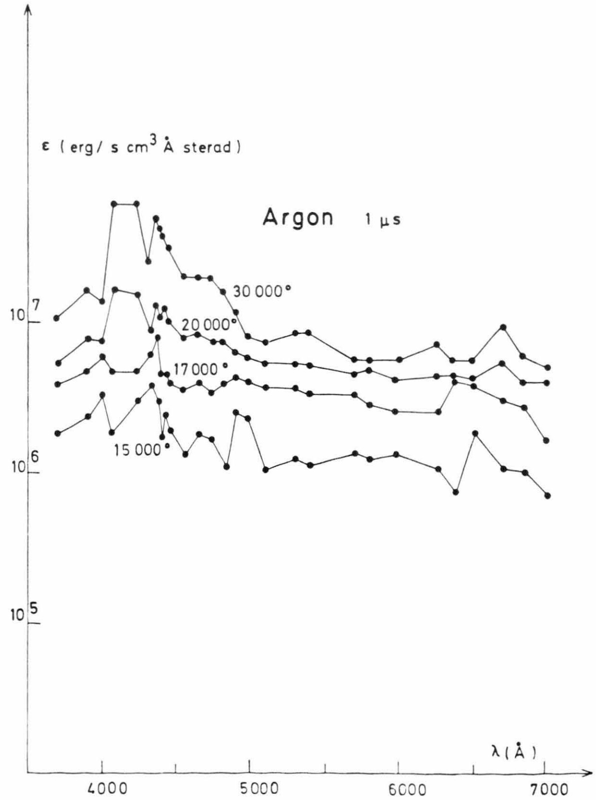

Fig. 1 b. The measured argon continuum at 1 μsec. The pressure p is 1200 Torr.

(i) The Argon continuum was investigated in the wavelength range of 3500 – 7000 Å at $t = 600$ nsec, 1 μsec and 3 μsec after releasing the first electrons from the cathode.

In Fig. 1 a – c the measured continuum intensities are outlined as function of the wavelength with p and T as parameter. These quantities have been determined by measuring the intensities of the Ar II lines at 4806 Å and 4348 Å at these times [see formula (1)]. The accuracy of the determination of the temperature is firstly at 600 nsec better than 10% and only up from this time a quantitative analysis of the real continuum coefficient can be considered, since at earlier times the spatial resolution is not sufficient.

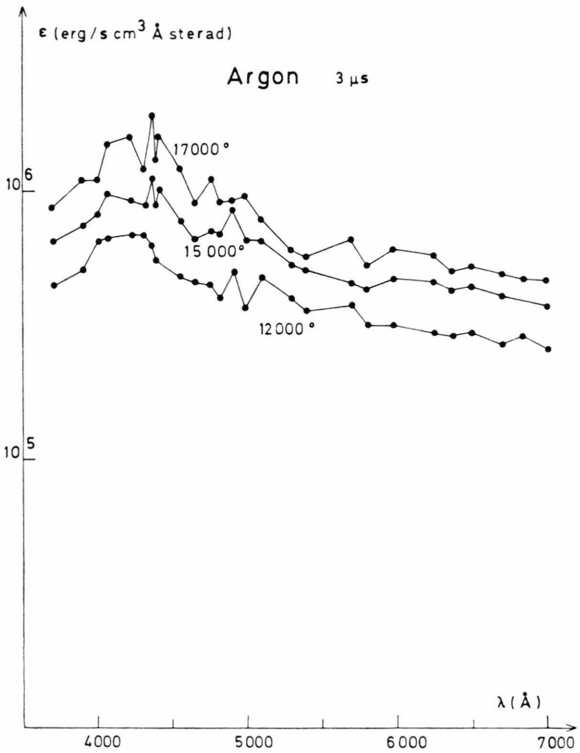

Fig. 1 c. The measured argon continuum at 3 μsec. The pressure p is 400 Torr.

Further one can see in Fig. 1 a – c that for t greater than 600 nsec and for a constant wavelength, the measured continuum intensity grows with increasing temperature.

In Fig. 2, 3 the measured continuum intensity $\varepsilon_{\text{measured}}$ as function of the temperature is shown for the range 3700 – 5980 Å corresponding to 600 nsec,

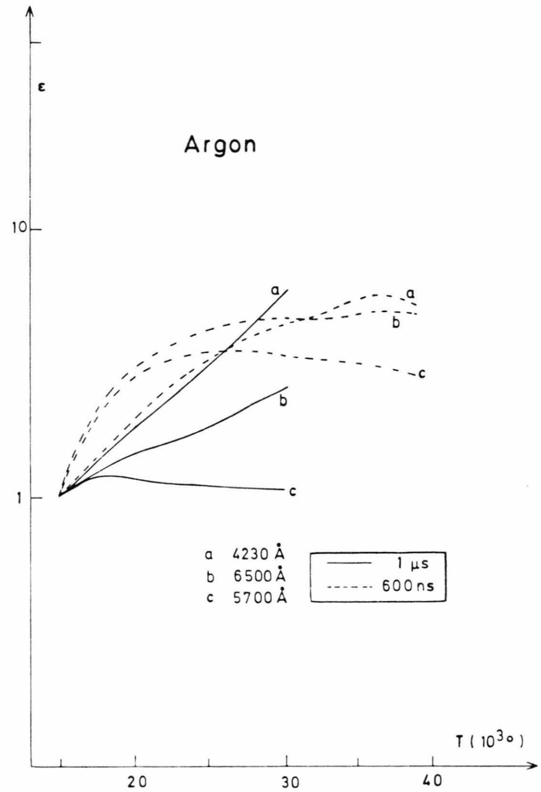

Fig. 2. Measured dependence of the continuum emission coefficient from the temperature at 600 nsec and 1 μsec at three wavelengths.

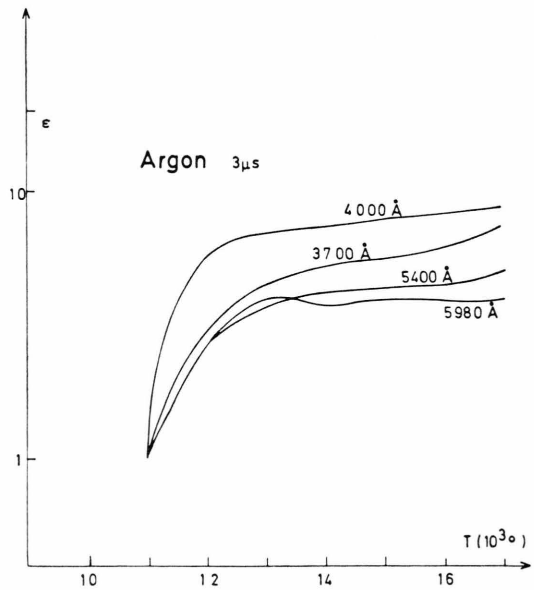

Fig. 3. Measured dependence of the continuum emission coefficient from the temperature at 3 μsec.

1 μsec, 3 μsec. A comparison of the experimental and the theoretical dependence according to the KU theory reveals essential differences:

For the KU continuum a definition of a Normtemperature between 16 000 and 19 000 K, depending on the pressure and the wavelength, is possible. This fact can be clearly seen in Fig. 4 for $p = 2800$ Torr and $\lambda = 3000$ Å. The calculated continuum intensity grows strongly for T less than 18 000 K and reaches a maximum at $T = 18\,000$ K (Normtemperature). For T greater than 18 000 K, the continuum radiation decreases slowly. In contrast to the KU theory, represented by the curves in Fig. 4, a Normtemperature as a maximum amount of the radiation cannot be found in the measured continuum of the Argon plasma in Figures 2, 3.

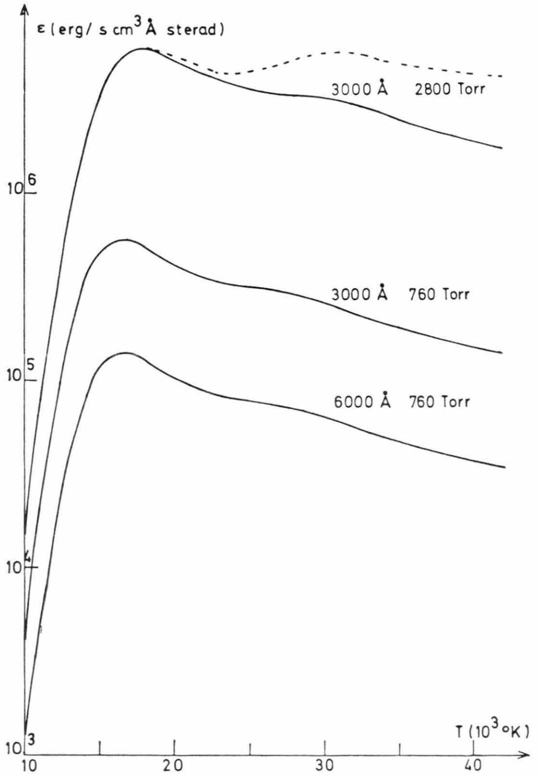

Fig. 4. The calculated emission coefficient of the Kramers-Unsöld continuum as function of the temperature. The dashed line means that multiple ionized atoms have been taken into account.

Nevertheless, the temperature behaviour at $\lambda = 5700$ Å, for $t = 600$ nsec (dashed curve c in Fig. 2) can be described by the calculated KU continuum, if one takes into account the higher ionized particles (see dashed line in Figure 4). No comparison between measurements and theory in this way can be made for other wavelength ranges (as for example curve a and c in Figure 2).

(ii) According to the theory of KU, in Argon and in the range of 3500 – 7000 Å, a dependence of $\varepsilon_K \propto 1/\lambda^2$ is expected [see formula (2)], as shown by the solid line in Figure 1 a. As one can see in Fig. 1, an averaging of the measured values would give the expected dependence only in a rough approximation. The ξ-factor resulting from our own measurements for $T = 14\,000$ K is shown in Fig. 5 together with the ξ of other authors taken from Schulz-Gulde [7]. In the range 3500 – 4400 Å our ξ-factor agrees with the calculated ones from Biberman [17] and above 4400 Å with the calculated values from Schlüter [5]. Further the values agree with the experimental values from Schulz-Gulde.

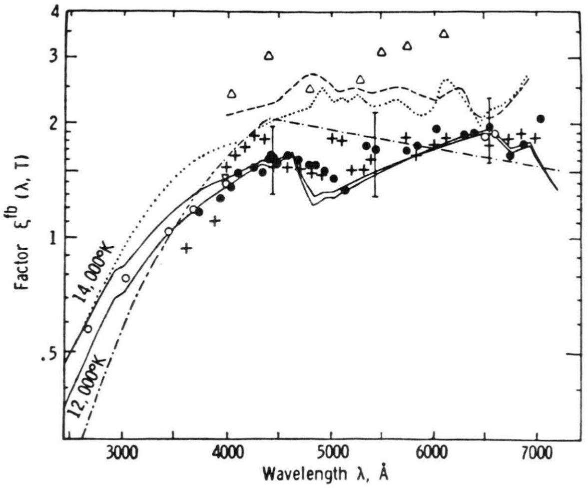

Fig. 5. The ξ-factor for argon: experimental values ●●● Schulz-Gulde, ○○○ Schnappauf, ······ Wende, ▽▽▽ Richter, — — — Schlüter, △△△ Berge [20], theoretical values: ——— Schlüter, — · — · — Biberman et al., taken from reference [7]. + + + present investigation.

The measured ξ-factors of the other authors diverge considerably in the absolute measurements, as in the relative spectral dependence. The quantum mechanical calculations of the ξ-factor [5, 17] show great divergences, too.

For T greater than 14 000 K, neither measurements nor theoretical calculations of the factor are known. The deviations of the observed radiation from the KU theory become greater with increasing temperature. The reason for this is that the intensity of the KU continuum after passing the Normtemperature (see Fig. 4) decreases, while the observed continuum, as shown in Fig. 2, grows further. The calculations, made by Schlüter [5], only cover a temperature range from 8000 to 14 000 K. These calculations show a greater dependence on the temperature of the ξ-factor just in that wavelength range, in which also a greater dependence of the temperature has been established in our work.

B) Investigation of the Nitrogen Continuum

As can be seen, the dependence of the continuum intensity from the wavelength and the temperature (Fig. 6), has a similar dependence as in the case of the Argon plasma. It cannot be described by the KU-theory with sufficient precision.

As above we have plotted the ξ-factor in Fig. 7 as function of T and λ as parameter. The Maecker-Peters formula (2) describes the real coefficient only fairly well in the temperature range from 24 000 to 26 000 K and for $\lambda = 3800$ to 4380 Å. In this narrow range we have $\xi \approx 1$. Otherwise ξ varies from 0.02 to 10. According to formula (2) the real coefficient is composed of radiation from different particles (for example N_{II}, N_{III} and N_{IV}). Due to our method of measurements, the corresponding correction factors ξ_{II}, ξ_{III}, ... cannot be separated clearly. Only in a narrow temperature range an approximation is possible. This can be discussed by means of Fig. 8 which shows the particle densities depending on the temperature in the case of LTE.

From $T = 18\,000$ K to approximately 28 000 K, the density of the single ionized particles N_{II} is prevailing, and therefore the continuum emission coefficient can be written as

$$\varepsilon_k = \frac{5.443 \cdot 10^{-39}}{(k\,T)^{1/2}}\, n_e \cdot n_{II} \cdot \xi_{II}\, \frac{c}{\lambda^2}\,. \quad (4)$$

For this temperature range the relation [18]

$$\varepsilon_{bf}/\varepsilon_{ff} = \exp\{h\,c/k\,T\,\lambda\} - 1 \quad (5)$$

assumes values from 3.9 to 1.8 for $\lambda = 5050$ Å. Consequently the measured deviation from the theory is caused by free-bound transitions mainly, and ξ_{II} can be written as ξ_{II}^{fb}. Besides, in this temperature range ξ_{III}, ξ_{IV} and ξ_{V} can be neglected.

In the temperature range from $T = 32\,000$ K to 45 000 K the density of the N_{III} ions (see Fig. 8) is predominant. Since according to Eq. (5) the fraction $\varepsilon_{bf}/\varepsilon_{ff}$ is approximately one, the total emission coefficient according to Eq. (2) is composed of free-free and free-bound radiation at equal parts. Therefore by measuring the deviation ξ_{III} the terms ξ_{III}^{ff} and ξ_{III}^{fb} cannot be determined separately.

Since for the complex structure of the ionized nitrogen atoms the recombination cross sections can be hardly calculated, one has to take the experimentally found values of the real continuum coefficient.

To apply the experimentally found correction factors, we produced a hot plasma by focusing a Q-switched Nd: glass laser, and investigated the plasma parameters T, n_e, p [19]. In the case of a laser

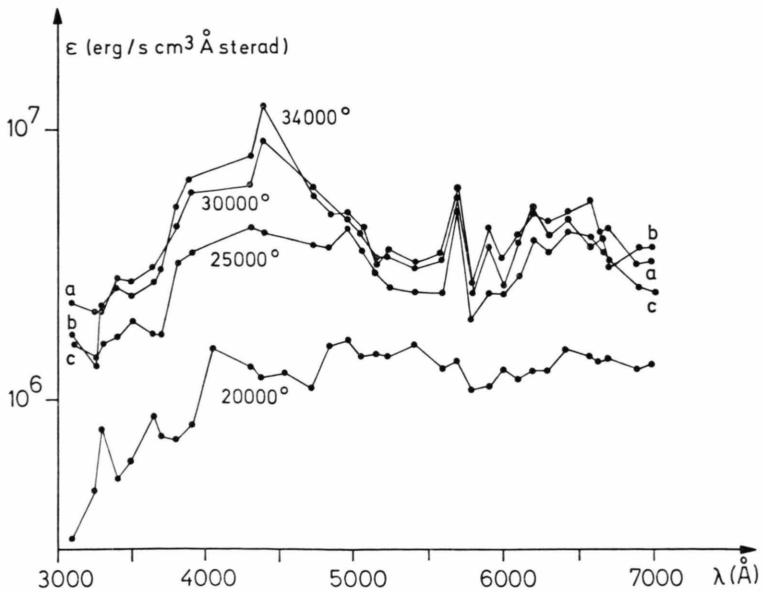

Fig. 6. The measured continuum coefficient in a nitrogen plasma in the temperature range from 20 000 K to 34 000 K.

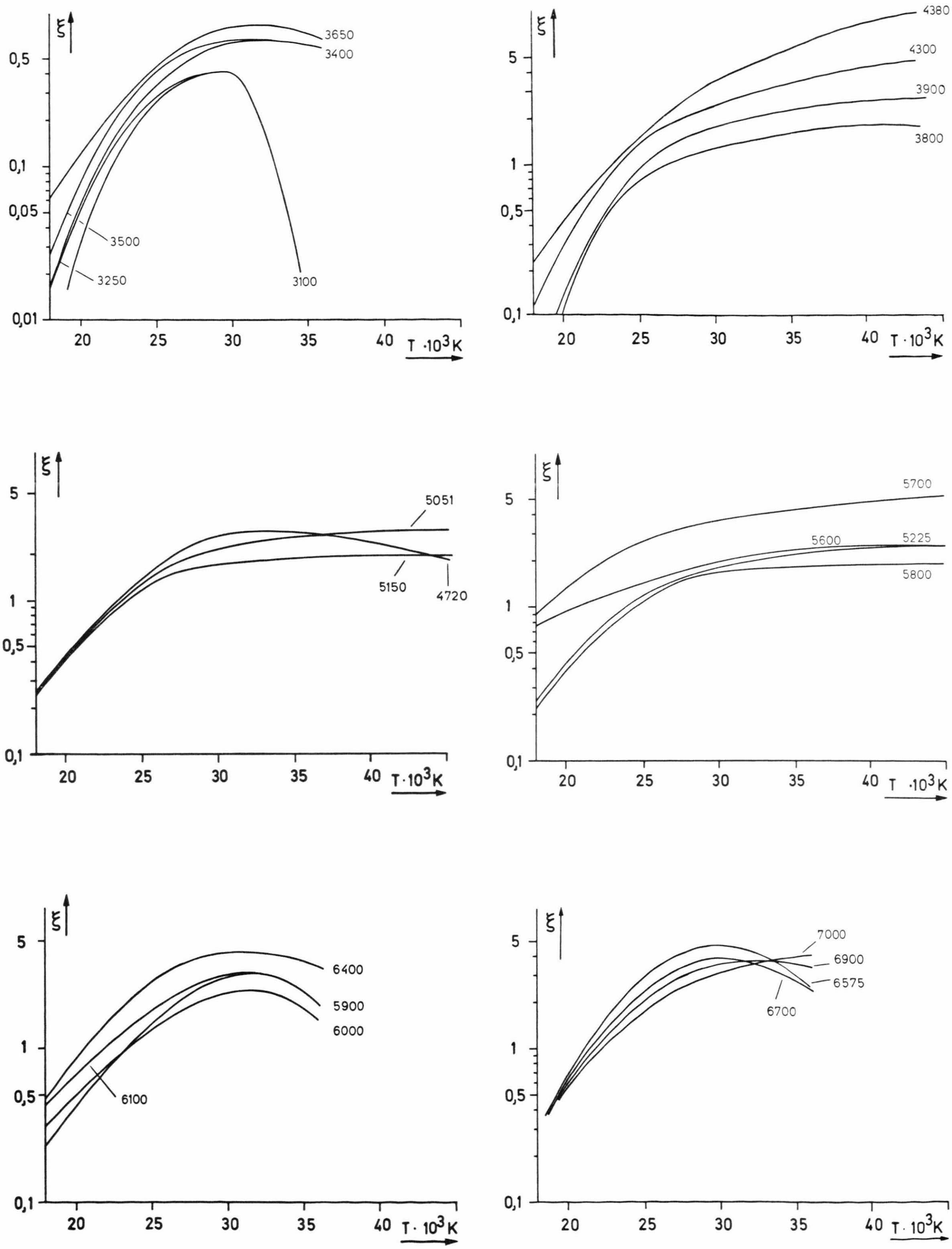

Fig. 7. The measured correction factor as function of the temperature with the wavelength as parameter.

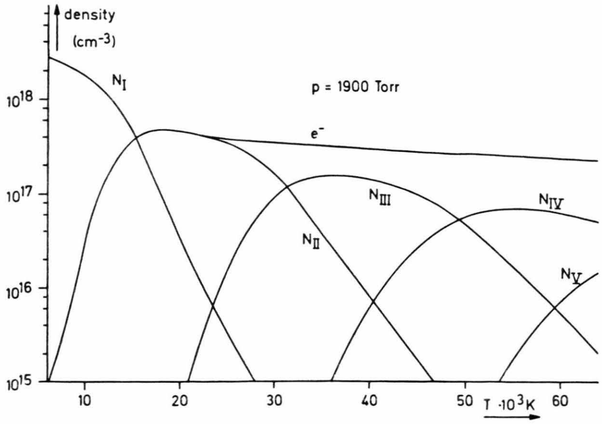

Fig. 8. The plasma composition as function of the temperature with the pressure as parameter.

induced spark, a strong continuum radiation can be observed. We used two methods to determine the plasma parameters:

(i) Using the experimentally found correction factor ξ for $\lambda = 5050$ Å (see Fig. 7), we have evaluated the plasma parameters with help of the theoretical emission coefficient according to Equation (3).

(ii) We have determined the plasma parameters by measuring the emitted light of the line group at 5000 Å and the line group at 5176 Å using Equation (1).

The temperatures, found with help of these two methods agree within an accuracy of 10%. So the measured ξ-factors are checked in a plasma quite different from such, produced in an electrical discharge, and seem to be reasonable.

We can conclude that the KU theory can only be taken as a rough approximation to describe the continuum emission in nitrogen and argon. Regarding the measured ξ-factors, it is possible to use the continuum emission fairly well for plasma diagnostics on laser plasmas too.

Acknowledgements

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