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On the Bowen fluorescence mechanism in the helium–oxygen plasmas

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Abstract. The dependence of the radiation intensity from the 2p3d $^3P^o_{2,1,0}$ doubly ionized oxygen (O III) levels on the He/O density ratio has been investigated in optically thin laboratory plasmas. A clear contribution of the astrophysically important Bowen mechanism to the most intensive 313.279 nm O III line radiation has been found in the primary O III Bowen cascade. We have found that in plasmas with electron temperatures of about 50 000 K and electron densities higher than 10^{22} m^{-3}, the 312.163 nm O III spectral line also shows a fluorescence tendency caused by the Bowen mechanism. On the basis of the established dependence of the fluorescence efficiency on the He/O density ratio we recommend the I(313.279 nm)/I(311.567 nm) and I(312.163 nm)/I(311.567 nm) O III line intensity ratios as a measure of the presence of the helium/oxygen density ratio in astrophysical plasmas. The line intensity ratio related to the 344.405 nm and 342.863 nm O III lines (which also belong to the primary cascade in the Bowen fluorescence mechanism and originate in the same energy level) has also been monitored in pure oxygen and helium–oxygen plasmas. We have found a good agreement with the results of previous astrophysical observations and recently published theoretical predictions. We have also found that the I(344.405 nm)/I(342.863 nm) line intensity ratio does not depends on the helium presence in plasmas and thus, it represents a convenient value in plasma spectroscopy.

Key words. plasmas – atomic data

1. Introduction

In the Bowen mechanism (Bowen 1934; Kallman & McCray 1980; Saraph & Seaton 1980) the 2p3d $^3P^o_2$ doubly ionized oxygen (O III) level (with 40.85 eV excitation energy) is populated through pumping by the ultraviolet He II Ly$_\alpha$ resonance line at 30.378 nm. The excited state then decays through a series of primary, secondary and tertiary cascades (Figs. 1 and 2 in Saraph & Seaton 1980 and Fig. 1 in Kallman & McCray 1980). Some of these lines have been observed in optical spectra of nebulae (Aller et al. 1966; Liu & Danziger 1993; Shrader et al. 1997) and others have been observed with the International Ultraviolet Explorer (IUE) satellite (Harrington et al. 1981). It is to be expected that these O III lines have higher intensities than the population processes provide, based on the LTE model, especially in the case of the 313.279 nm, 344.405 nm and 342.863 nm lines in the primary cascade which originates in the pumped 2p3d $^3P^o_2$ level. The intensity of the fluorescence must depend on the density of the He II Ly$_\alpha$ photons. Therefore, plasma composition and conditions (i.e. electron temperature (T) and density (N)) clearly determine this mechanism. As a measure of the presence and efficiency of the Bowen fluorescence mechanism, spectral line intensity ratios within O III spectral lines could be used. One of them comes from the Bowen cascades and the second is out of the cascades.

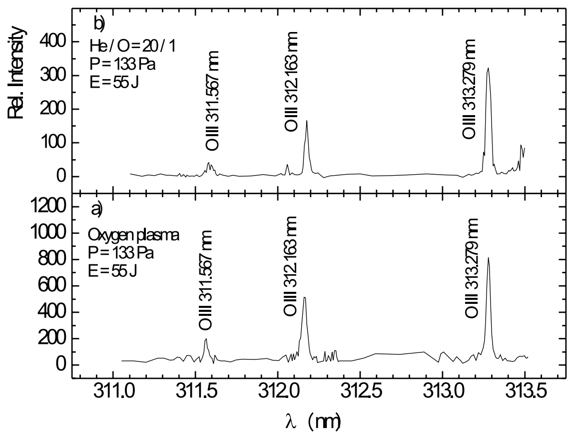

Fig. 1. Recorded O III lines at various plasma compositions recorded at 5th μs **a)** and 10th μs **b)** after the beginning of the discharge. P and E denote discharge pressure and bank energy, respectively.

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The aim of this work is to present, for the first time, the dependence of the efficiency of the Bowen fluorescence mechanism in the O III spectrum on the He/O abundance ratio and plasma parameters (T and N) on the basis of the measured O III line intensity ratios. As a pilot line, we have chosen the most intensive 313.279 nm O III line origins from the pumped 2p3d $^3P^o_2$ O III level (with 40.85 eV excitation energy) for which the Bowen mechanism has shown and confirmed. The 312.163 nm (from the 2p3d $^3P^o_1$ level with 40.86 eV energy) and 311.567 nm (from the 2p3d $^3P^o_0$ level with 40.87 eV energy) lines which come from the mutually very close energy levels in the same transition have also been included in investigation. Also, we have monitored the spectral line intensity ratio related to the 344.405 nm and 342.863 nm O III lines which also belong to the primary Bowen cascade (both arise from the 2p3d $^3P^o_2$ level) in pure oxygen plasma and also in helium–oxygen plasmas. Their existing experimental (Aller et al. 1966; Liu & Danziger 1993) and theoretical (Saraph & Seaton 1980; NIST 2003, and references therein) values show high internal scatter up to a factor of 2.

2. Experiment

A modified version of the linear low pressure pulsed arc (Djeniže & Bukvić 2001; Djeniže et al. 2002a–c; Milosavljević & Djeniže 2002) has been used as an optically thin plasma source. A pulsed discharge was performed in a pyrex discharge tube (with quartz windows) of 5 mm inner diameter and plasma length of 14 cm. The working gases were pure oxygen and various helium–oxygen mixtures (He/O: 0.9, 5 and 20) at 133 Pa pressure in flowing regime. The He/O density ratio includes neutrals and all other ionization stages. The capacitor of 14 μF was charged up to 2.8 kV. The complete line profile and intensity (I) recording procedures together with the experimental set–up used have been described in Djeniže et al. 2002a,b, 2003). As an example, the recorded 313.279, 312.163 and 311.567 nm O III line profiles are presented in Fig. 1 for two different plasmas.

The electron temperature was determined from the ratios of the relative intensities (Saha equation) of O III (326.08 nm, 326.53 nm and 326.72 nm) and O II (327.08 nm and 327.34 nm) spectral lines with an estimated error between ±8% and ±12%, assuming the existence of LTE, according to the criterion from Griem (1964) and Rompe & Steenbeck (1967). The mentioned O III lines are out of the Bowen cascades and their parent energy levels (with about 40.25 eV excitation energy) are populated according to the predictions made by the LTE model. In our experiments, the electron densities are about 5×10^{22} m^{-3} (in the 10th μs after the beginning of the discharge; see Fig. 2 in Djeniže et al. 2003) satisfying the criterion for the existence of the LTE. This criterion (Rompe & Steenbeck 1967) support the LTE at $N > 2.4 \times 10^{22}$ m^{-3} (at 50 000 K electron temperature) for the O III lines used. The necessary atomic data are taken from NIST (2003). The obtained electron temperatures were about 50 000 K (within ±8%) in the case of helium–oxygen plasmas. The electron density decay was measured using the well–known single laser interferometry technique for the 632.8 nm He–Ne laser wavelength with an estimated error of ±6%. In the case of helium–oxygen plasmas they are higher than 10^{22} m^{-3} from the 4th μs up to the 45th μs after the beginning of the discharge when the line intensity ratios have been monitored. We have monitored the chosen O III spectral line intensities during the whole plasma decay period together with the He II Pα (468.6 nm) spectral line intensity. The moment of realization of the He II Pα line intensity maximum is also the moment when the concentration of the He II ions is at its maximum. We expect that the presence of the 30.378 nm He II resonance photon density, essential for the Bowen fluorescence mechanism, also has its maximum at this moment. At this moment the efficiency of the Bowen fluorescence must have its maximum. We expect that this efficiency depends on the He/O density ratio.

Table 1. Characteristics of the investigated O III transitions. J_f and J_i are the inner quantum numbers of the final (f) and initial (i) state of the transition. E_i and g_i represent initial energy levels and their statistical weights. Atomic data are taken from NIST (2003).

Multiplet $J_f - J_i$	λ (nm)	E_i (eV)	g_i
3p ^{3}S – 3d ^{3}P^o			
1 – 2	313.279	40.85	5
1 – 1	312.163	40.86	3
1 – 0	311.567	40.87	1
3p ^{3}P – 3d ^{3}P^o			
1 – 2	342.863	40.85	5
2 – 2	344.405	40.85	5

3. Line intensity ratio

When two spectral lines (index 1 and 2) arise from the mutually very close upper energy levels (see Table 1) their relative line intensity ratio (practically independent of the electron temperature) is given as (Griem 1964):

$$I_1/I_2 = A_1 g_1 \lambda_2 / A_2 g_2 \lambda_1 \quad (1)$$

where A, g and λ denote transition probability, statistical weight and the wavelength of the transitions. $g_1 = g_2$ for the same parent energy levels. The knowledge of these atomic data (NIST 2003) enables the comparison between the experimental and theoretical line intensity ratios. The characteristics of the investigated O III transitions are presented in Table 1.

4. Results

Our measured O III line intensity ratios during the whole plasma decay interval are presented in Fig. 2 for various plasma compositions together with the normalized He II 468.6 nm line intensity decays.

Our line intensity ratios related to the 344.405 nm and 342.863 nm O III lines are presented in Table 2 together with the results of other authors.

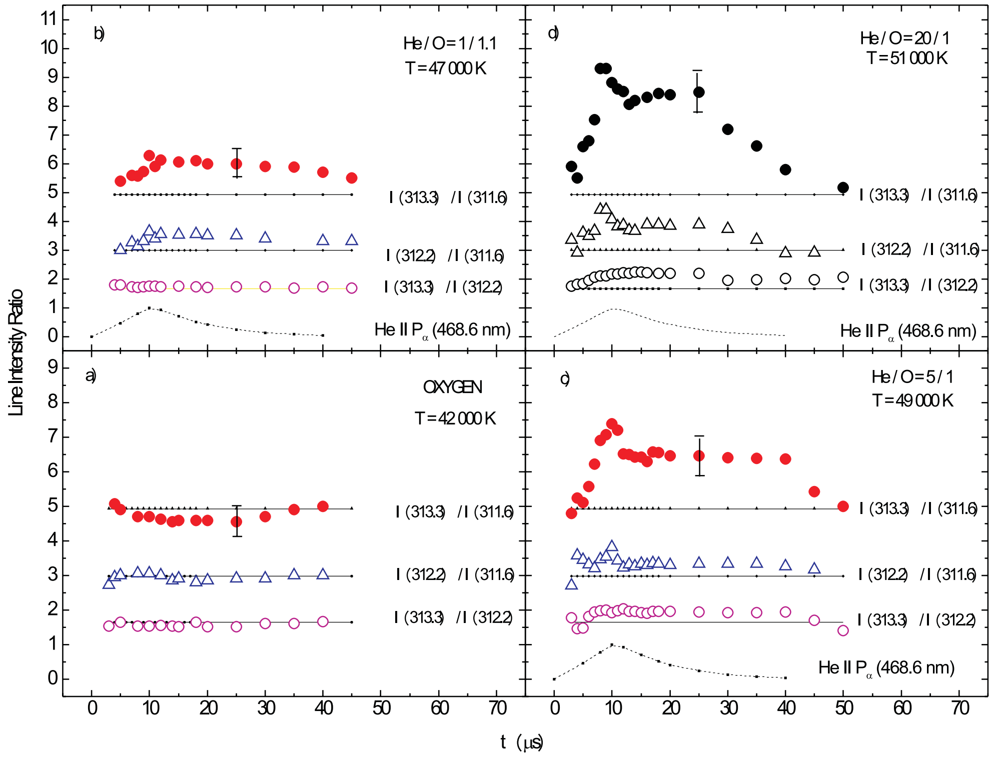

Fig. 2. O III line intensity ratios during the plasma decay in various **a)–d)** plasma compositions. Symbols •, Δ and ∘ correspond to the I(313.3)/I(311.6), I(312.2)/I(311.6) and I(313.3)/I(312.2) O III line intensity ratios, respectively. Full lines represent line intensity ratios calculated on the basis of Eq. (1) using transition probabilities tabulated in NIST (2003). Dashed lines denote normalized experimental line intensity maximum of the He II Pα (468.6 nm) spectral line. Electron temperature (T) is related to the 10th μs after the beginning of discharge when the Pα line has its intensity maximum and the Bowen mechanism comes up to its maximum. Error bar represents estimated uncertainties of ±8%.

Table 2. The I(344.4)/I(342.9) O III line intensity ratios. Symbols: Tw(O), Tw(He/O = 0.9) denote our values obtained in oxygen and helium–oxygen mixture within ±8% uncertainties. Results from other data sources are given with: A (Aller et al. 1966); LD (Liu & Danziger 1993); FF (Froese Fischer 1994); AG (Aggarwal et al. 1997); KB (Kastner & Bhatia 1990); BK (Bhatia & Kastner 1993); SS (Saraph & Seaton 1980); N (NIST 2003).

Tw(O)	Tw(He/O)	A	LD	FF	AG	KB	BK	SS	N
6.50	5.95	6.40	5.40	6.53	5.23	6.10	5.52	2.98	2.95

5. Discussion

5.1. Oxygen plasma

In case of pure oxygen plasma we have found line intensity ratios (see Fig. 2a) which agree very well (within 8% experimental accuracy) with the theoretical ones based on the transition probabilities tabulated by NIST (2003). This also implicitly confirms the validity of predicted transition probability ratios for the chosen 313.3, 312.2 and 311.6 nm O III spectral lines. Moreover, using the method (Djeniže & Bukvić 2001) for the test of the self–absorption we can conclude that our investigated O III lines are not absorbed. Our line intensity ratio related to the 344.4 nm and 342.9 nm O III lines (Table 2) agree with values presented by Aller et al. (1966), obtained in astrophysical observations, and with theoretical predictions made by Froese Fischer (1994) and Kastner & Bhatia (1990). Tolerable agreement was found (within the experimental accuracy and theoretical uncertainties) with the values presented by Liu & Danziger (1993) (from observations of Bowen fluorescence mechanism and charge transfer in planetary nebulae); Aggarwal et al. (1997); Bhatia & Kastner (1993). Line intensity ratios presented by Saraph & Seaton (1980); NIST (2003) are about half the size of the others.

5.2. Helium–oxygen plasmas

The helium ions presence in the plasma verifies the role of the Bowen fluorescence mechanism. It is clear in the case of the 313.279 nm O III line which origins from the pumped 2p3d^{3}P$^o_2$ energy level with 40.85 eV excitation energy (NIST 2003). Namely, one can conclude that the I(313.3)/I(311.6) line intensity ratio begins up with the increasing of the He/O density ratio in plasma (see Figs. 2b,c,d). It turns out that the 311.6 nm O III line arises from the level 2p3d ^{3}P$^o_0$ with 40.87 eV (NIST 2003) excitation energy, which is higher than the pumping He II photon energy. Therefore, this energy level remains without extra population processes due to the He II Ly$_\alpha$ photon absorption. The mentioned line intensity ratio depends on the

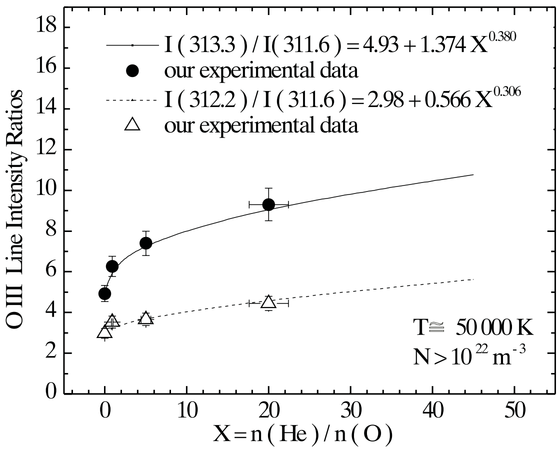

Fig. 3. O III line intensity ratios versus $X = n(\mathrm{He})/n(\mathrm{O})$ density ratio at about 50 000 K electron temperature and electron densities higher than 3×10^{22} m^{-3}. The line intensity ratios are obtained in the 10th μs after the beginning of the discharge. The symbols • and Δ are related to the measured I(313.3)/I(311.6) and I(312.2)/I(311.6) O III line intensity ratios. The full and dashed lines denote their calculated values on the basis of the established Eqs. (2) and (3).

He II ion concentration and has its maximum at the moment when the He II (468.6 nm) line intensity reaches its maximum.

Similar behavior was found in case of the I(312.2)/I(311.6) line intensity ratio (see Figs. 2b,c,d) which was not expected and observed up to now. It turns out that the 312.2 nm O III line arises from the level 2p3d $^3\mathrm{P}^\mathrm{o}_1$ with 40.86 eV (NIST 2003) excitation energy. This level lies above the energy of the pumping photons and in the case of rare plasmas (with $N < 10^{13}$ m^{-3}) it is not included in the Bowen mechanism. We think that in the plasmas with $N > 10^{22}$ m^{-3} electron density this level is broadened by the influence of an external micro-field created by electrons and ions (Griem 1974) and thus it is attainable for the pumping He II photons. In our experiment the electron density was higher than 2×10^{22} m^{-3}. So, we found an extra population tendency also in the case of the 2p3d $^3\mathrm{P}^\mathrm{o}_1$ O III level. The Bowen fluorescence mechanism has in this case a smaller role than in the case of the 2p3d $^3\mathrm{P}^\mathrm{o}_2$ level (see also the I(313.3)/I(312.2) line intensity ratios in Figs. 2b,c,d). On the basis of the found dependence of the line intensity ratios on the $X = n(\mathrm{He})/n(\mathrm{O})$ density ratio (see Fig. 3) we have established the relationships between them.

They are:

$$I(313.3)/I(311.6) = 4.93 + 1.374X^{0.380} \quad (2)$$

and

$$I(312.2)/I(311.6) = 2.98 + 0.566X^{0.306} \quad (3)$$

obtained with high correlation factors of fitting (0.99).

Equations (2) and (3) can be used for calibration purposes in astrophysical and laboratory plasmas in the range of the cited plasma parameters.

In the case of the I(344.4)/I(342.9) line intensity ratio we have found agreement with the value obtained in pure oxygen plasma (see Table 2) within our experimental accuracy of ±8%. Taking into account that both the lines arise from the same energy level (2p3d $^3\mathrm{P}^\mathrm{o}_2$) one can conclude that the presence of the Bowen mechanism does not influence their radiation probability ratio. Because this line intensity ratio does not depend on the helium presence in plasmas, it represents a convenient value in astrophysical plasma diagnostics.

6. Conclusion

We have found that in helium–oxygen plasmas with $N > 10^{22}$ m^{-3} and $T \sim 50\,000$ K, the 312.163 nm O III line also shows a fluorescence tendency caused by the Bowen effect. We recommend the I(313.379 nm)/I(311.567 nm) O III line intensity ratio as a measure of the He/O density ratio in plasmas with $N < 10^{23}$ m^{-3} and $T < 50\,000$ K. Our method is not sensitive to the presence of the helium ions and also to the possible self–absorption of the He II Pα line used offer for astrophysical plasma diagnostic purposes. We have also found that the I(344.405 nm)/I(342.863 nm) O III line intensity ratio, in the primary Bowen cascade, not dependent on the helium presence in plasma. On the basis of our results and those of other authors its proposed value is 5.94 ± 14%.

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