THE EXCITATION MECHANISM OF METASTABLE LEVELS AND VARIABILITY OF OXYGEN FORBIDDEN LINES 4959+5007 Å [OIII] IN THE SEYFERT NUCLEI

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ABSTRACT. In high density gas $n(H) \sim 10^9 cm^{-3}$ the electron impact and charge transfer $OIV+HI \rightarrow OIII+HII$ secure high emissivity of gas in [OIII] lines only with low hydrogen and helium ionization, when $n_e \sim n(OIII) \sim 10^6-10^7 cm^{-3}$. Such condition is possible in HI-zones where oxygen is ionized by soft X-ray (Auger effect). It is shown, that the observed luminosity of NGC 1275 nucleus in 4959+5007 Å [OIII] lines can be explained by the electron impact in gas with hydrogen concentration $n(H) \sim 10^{12} cm^{-3}$ and does not contradict to a possibility of lines variations within several days.

The variability of continuum and permitted lines with the intrinsic time of days or months is widely accepted now and provokes no doubts, which is not so in case of forbidden lines. Numerous observations of [OIII]/Hβ and [NII]/Hα variations, or changes of the equivalent width of [OIII] line are being explained only by the variations of hydrogen lines and continuum. The difficulty in interpreting the forbidden lines variations in the spectra of Seyfert nuclei is due to the fact, that a tiny gaseous region ($r \sim 10^{15}-10^{16}$ cm) inferred from the time of lines variation cannot provide the observed luminosity of nuclei in [OIII] lines at n_e less than $10^6 - 10^7 cm^{-3}$. The required density of the ionized gas ($n_e \sim 10^9 cm^{-3}$) provides nucleus luminosity in Hβ line of the

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order of 2-3 higher than that of [OIII] line, which contradicts to the observations. But this obstacle can be overcome if we assume, that the ions of OIII belong to the region of neutral hydrogen, where $n_e \sim n(\mathrm{OIII}) \sim 10^6$-$10^7 \mathrm{cm}^{-3}$. Such condition might occur in the nuclei with strong X-ray emission at region of about 1 kev energies.

Population mechanism of metastable levels

The metastable levels of OIII atoms are mainly populated by means of electron impact, their number being proportional to n_e and the number of OIII atoms at a ground state. At a very high n_e the population of metastable levels is restricted by deactivation due to electron impacts of the secondary order. Spontaneous transitions to lower levels accompanied by forbidden lines emission always exist independently on the value of dense gas, but the percentage of such transitions from the total number of deactivations is strongly dependent on the electron density (see Table I).

TABLE I

Percentage of spontaneous transitions from $2p\,^1D_2$ level from the total number of deactivations

n_e cm^{-3}	10^4	10^5	10^6	10^7	10^8	10^9
$\varkappa$ %%	98,5	86,6	39,4	6,1	0,64	0,065

As a result of very short lifetime of OIII atoms in highly excited states, no emission flux density can essentially affect the redistribution of population of the ground and metastable levels of OIII atoms.

The population of the second level in respect to that of the ground one is determined by three processes: electron excitation, spontaneous downward transitions and electron impacts of the secondary order. They determine the balance of level population which in zero approximmation is expressed as:

$$n_1 n_e q_{12} = n_2 A_{21} + n_2 n_e q_{21} \qquad (1)$$

where n_1 and n_2 are the populations of the first and second levels of OIII ions, A_{21} is the probability of spontaneous transitions, q_{12} and q_{21} are the probabilities of excitation and deactivation by electron impacts.

$$q_{21} = 8{,}63\cdot 10^{-6}\frac{\Omega_{21}}{\omega_2 T_e^{1/2}}\ cm^3/s \quad , \quad q_{12} = q_{21}\frac{\omega_2}{\omega_1}\, e^{-\frac{h\nu}{kT_e}}\ cm^3/s \qquad (2)$$

TABLE II. Lower levels population n_2/n_1 for OIII ions at different T_e and n_e

n_e cm^{-3} / $T_e 10^{-4}$K	10^4	10^5	10^6	10^7	10^8	10^{10}
1	0.48 10^{-3}	0.42 10^{-2}	0.019	0.030	0.032	0.032
2	1.43	1.30	0.068	0.122	0.132	0.133
3	1.89	1.75	0.100	0.193	0.212	0.214
4	2.07	1.94	0.118	0.240	0.268	0.272
5	2.15	2.02	0.128	0.274	0.309	0.313
8	2.10	2.00	0.137	0.328	0.382	0.389
10	2.03	1.94	0.136	0.346	0.408	0.416
20	1.66	1.60	0.123	0.373	0.467	0.481
50	1.14	1.11	0.094	0.359	0.501	0.524
100	0.83 10^{-3}	0.82 10^{-2}	0.072	0.327	0.507	0.540

According to (1) at high electron concentrations ($n_e \gg \frac{A_{21}}{q_{21}} \sim 10^6\ cm^{-3}$) the ratio n_2/n_1 does not depend on n_e and at T_e=10^4 °K equals to 0.0318 (see Table II). With the increase of T_e the ratio n_2/n_1 tends to increase very sharply and at $T_e \sim 30000$ °K it equals to 0.21. With the further rise of T_e at all values of $n_e \gg 10^6$ from (1), follows Boltzmann distribution :

$$\frac{n_2}{n_1} \rightarrow \frac{q_{12}}{q_{21}} = \frac{\omega_2}{\omega_1}\, e^{-\frac{h\nu}{kT_e}} \sim \frac{\omega_2}{\omega_1} = 0{,}55 \qquad (3)$$

At a very high T_e high levels are being populated followed by cascade downward transitions that lead to metastable levels population. The excitation of high levels of OIII by electron impact at $T_e = 2\text{x}10^5$ °K and $n_e = 10^7 \text{cm}^{-3}$ is computed by Kato et al., [1]. They obtained $n_2/n_1 = 0.37$ that almost coinsides with the corresponding value in Table II.

Recombinations of free electrons by OIV ion lead to the population of lower levels of OIII ion being proportional to their statistical weight. Since the recombination time $t_{rec} = (n_e \cdot 5{,}1 \cdot 10^{-12})^{-1}$ sec is much longer than the time between two sequential excitations $t_{exc} = (n_e \cdot 1{,}34 \cdot 10^{-9})^{-1}$ sec, the efficiency of metastable levels population by recombination is always lower than that of impact mechanism independently of gas density. But since the recombinations OIV OIII are faster than OIII→OII, at extremely nonstationary conditions in galaxies nuclei when the source of ionizing emission is being "switched off", a temporal increase of OIII ion number is possible, hence, the increase of brightness in 4959+5007 [OIII] lines. The minimal time of such a flare and a consequent decrease may range from several days to hours respecting n_e.

In analogy to recombination, the charge transfer OIV+HI → OIII+HII also leads to OIII ions formation with the population of lower levels proportional to their weights [2] . The probabilities of charge transfer with first and second levels population of OIII ion, are $k_2 = 1.2\ 10^{-9} \text{cm}^3/\text{s}$ and $k_3 = 2\ 10^{-10} \text{cm}^3/\text{s}$. Thus, the number of charge transfers leading to the population of the second level of OIII ion at a unit of volume for 1 second is:

$$n(\text{OIV})\ n(\text{HI}) \cdot 1{,}2 \cdot 10^{-9}\ \text{cm}^3/\text{s} \qquad (4)$$

The coefficient characterizing the charge transfer velocity is the same as q_{12} coefficient in (1). The conventional condition , when the charge transfers are compatible or exceed the number of excitations by electron impact, can be expressed as :

$$\frac{n(\text{OIV})}{n(\text{OIII})} \; \frac{n(\text{HI})}{n_e} \geqslant \frac{1{,}34 \cdot 10^{-9}}{1{,}2 \cdot 10^{-9}} \sim 1 \qquad (5)$$

In gaseous nebulae the latter expression is always $\ll 1$ due to high ionization of hydrogen. Hydrogen ionization in dense gas is the main reason why the ratio I [OIII]/$I_{H\beta}$ is low, even at sufficiently high ionization of oxygen. Hence the most advantageous conditions for the effective [OIII] line emission and high ratio I [OIII]/$I_{H\beta}$ arises at dence zones of neutral hydrogen and helium, when $n_e \sim n(\mathrm{OIII}) \sim 10^6 - 10^7$ cm^{-3} in spite of $n(H) \sim 10^9$. In this case the number of excitations of [OIII] by impact at a unit of volume for 1 sec is :

$$n_1(\mathrm{OIII})\, n_e\, 1{,}34 \cdot 10^{-9} \sim 10^{3}\, \mathrm{cm}^{-3}/\mathrm{s}\,, \quad n_1(\mathrm{OIII}) \sim n_e \sim 10^{6} \qquad (6)$$

and the number of the second level population due to charge transfer is

$$n(\mathrm{OIV})\, n(\mathrm{HI}) \cdot 1{,}29 \cdot 10^{-9} \sim 10^{5}\, \mathrm{cm}^{-3}/\mathrm{s} \quad \text{if} \quad n(\mathrm{OIV}) \sim 10^{5},\ n(\mathrm{H}) \sim 10^{9} \qquad (7)$$

Charge transfers make a significant contribution to the [OIII] line excitation even if hydrogen is being partially ionized. An essential status for charge transfer at stationary conditions is the reverse process - ionization of OIII atoms. It might be due to photoionization by quanta with $\lambda \leqslant 100$ Å, that are no longer absorbed by hydrogen or helium. The ions of OIII are being formed as a result of OI ionization by soft X-ray emission (Auger effect). The ionization of K-shell of atoms of heavy elements by soft X-ray emission is noteworthy, because the galaxies nuclei are the sources of soft X-rays with $E \gtrsim 1$ kev. The presence of such a mechanism of ionization of heavy elements atoms leads to emission in very dense gas of neutral hydrogen. The threshold of K-shell ionization of OI atoms constitutes approximately 550 ev. The efficiency of cross-section ionization and its dependence on quantum energy E is given in [3] . For preliminary calculations one may adopt $\sigma_\nu \sim 10^{-19}\left(\frac{E_0}{E}\right)^3 \mathrm{cm}^2$, where E_0 = 550 ev. At stationary conditions the number of ionizations OI OIII must be equal to the number of recombinations OIII+e→OII :

$$n(\mathrm{OI})\int \frac{F_\nu}{h\nu}\,\sigma_\nu\,d\nu = n(\mathrm{OIII})\cdot n_e\cdot 2\cdot 10^{-12} \qquad (8)$$

and a number of recombinations OII+e → OI is :

$$n(\mathrm{OI})\int \frac{F_\nu}{h\nu}\,\sigma_\nu\,d\nu = n(\mathrm{OII})\cdot n_e\cdot 3\ 10^{-13} \qquad (9)$$

The number of ionizations depends on the emission flux in the region of soft X-rays, spectral index α , and the distance to the central source. For the averaged spectrum with $\alpha \sim 1$ and $F_{\lambda=20\text{Å}} = 6\cdot 10^{-6}$ erg/cm^2·s·Hz at the distance $r \sim 3\cdot 10^{15}$cm from the source (three light days), we have obtained the following ratios using (8) and (9) : n(OIII)/n(OII) = 0.15 and n(OII)/n(OI) = $2\ 10^{14}/n_e$. Thus, in case of oxygen ionization by X-rays, 13% of oxygen atoms are in the state of OIII and 85% - in OII state. The number of OI atoms is negligible. The account on charge transfer OIII+HI → OII+HII would change this relation towards the increase of OII and OI ions. In case of nonstationary state each X-ray burst or rather sharp increase of intensity must be followed by an instantaneous increase of OIII line emission. After 5 or 10 days (respecting the gas density) the number of OIII ions would decrease to 13% and line intensities would drop twofold. Therefore, any observed correlation between soft X-ray variations and [OIII] line intensity might be considered as an evidence in favour of Auger effect in the nuclei of galaxies.

Can the intensity of forbidden lines N_1+N_2 [OIII] in galaxies nuclei markedly vary within several days?

A positive answer to this question would signify, that the emission region must have a dimension of about 10^{16}cm. This region in its turn must provide N_1+N_2 [OIII] lines luminosity of about 10^{42} erg/sec (all given parameters are adopted for NGC 1275). If $L_{obs} = 3\ 10^{41}$ erg/sec Hz [4] , then after absorption reduction we yield $L(N_1+N_2) = 9\ 10^{41}$ erg/sec. As follows from the observational data [5, 6], at the distance $3\ 10^{15}$cm from the central source in NGC 1275, the flux in Lyman discontinuity is F_ν (912Å) 2 10^{-4} erg/cm^{2}sec Hz. To keep hydrogen neutral its density must exceed 10^8. We have estimated the intrinsic time of variations at two values of density : $n(H) \sim 10^9$ and $n(H) \sim 10^{12}$ cm^{-3}. Relative abundance of oxygen is adopted to be $O/H = 10^{-3}$ and $n(OIII)/n(O) = 0.13$. Taking into account, that besides oxygen other heavy elements might be also ionized, we adopted $n_e \approx 10^7$. Assuming that only 6 % of OIII atoms of the second level would leav it as a result of spontaneous transitions ($\text{æ} = 0.06$), we obtain for [OIII] emissivity :

$$\varepsilon(N_1 N_2) = n(\mathrm{OIII})\, n_e\, q_{12}\, \text{æ}\, A_{21}\, h\nu_{21} \approx 2\ 10^{-11}\ \mathrm{erg/s}$$

The volume and the dimension of gas cloud would be respectively $V = E(N_1\ N_2)/\varepsilon(N_1\ N_2) = 50\ 10^{51}$ cm^3, $r = 4\ 10^{17}$ cm. Such dimension of gaseous region would provide the variability of lines with the intrinsic time of about 1 month. For $n(H) = 10^{12}$ cm^{-3}, $n(O) = 10^9$, $n(OIII) = 1.3\ 10^8$ cm^{-3}, $n_e = 3\ 10^9$ and $\text{æ} = 0.02$ we obtain the following values : $V = 9\ 10^{47}$ cm^3 and $r = 10^{16}$ cm. Considering oxygen ionization by X-rays and the emission of OIII ions in the region of neutral hydrogen we assume, that $T_e = 10^4$ °K. Such a temperature must be set up very quickly as a result of neutral hydrogen cooling. But however it means, that hydrogen would emit in lines. The profiles of hydrogen lines in this gas must be identical to the contour of OIII lines.

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