Chapter 4

Spectra of the gaseous nebulae and their interpretation

The spectrum of a gaseous nebula consists of weak continuous emission spectrum superposed by numerous emission lines. Several thousands of spectral lines have been recognized but only about 200 of them can be measured with sufficient exactness and used for analysis of physical conditions in nebulae. The spectral lines of atoms and ions of almost all chemical elements from H to Ni and more heavy elements (see Balateau et al. (1995), Pequignot & Balateau (1994)) have been detected. Intensity of the continuous spectrum has been measured for comparatively small number of nebulae.

The emission lines observed in nebulae depending on the mechanism of their formation can be divided in two main types: 1) the recombinational and 2) the collisional lines. The list of main spectral lines specified in the ultraviolet, visible and infrared spectral regions, is given in Table 25. The values of wavelengths and transition probabilities for these lines are also presented in Table 25.

4.1 Recombination line intensities

In the spectra of nebulae there are observed the spectral lines of allowed transitions between excited states of H, He, C, N and O. Some lines of such types are detected for the ions having lower abundances (see Table 25), say for Ne, Si and Mg. The main mechanism of formation of these lines is recombination: the photorecombination or (and) dielectronic recombination (for He, C, N, O) of the excited states of ion $\mathrm{X}^{\mathrm{i+1}}$ followed by the cascade transitions to the ground state of ion X^{i}. Definite contribution to the formation of some recombination lines give also the collisional excitation processes.

At the present time only the recombination spectra of H and He have been investigated in detail. The most complete data concerning the theoretical recombination line intensities of H, HeI and HeII are given in the papers by Brocklehurst (1971, 1972), Hummer & Storey (1987), Martin (1988) and Ilmas & Nugis (1982). Somewhat less have been studied the recombinational spectra of C, N and O. The difficulties of these calculations are caused by the complicity of the structure of their atomic energy levels and by inaccuracy of the values of transition probabilities, which determine the state populations. The references on the recombination spectra of C, N and O ions have been compiled by Nikitin et al. (1988), Hummer & Storey (1987) and Escalante & Victor (1990, 1992).

In the most cases gaseous nebulae are transparent for the emission in the recombination lines. Thus, the energy irradiated by a nebula in recombination line with wavelength λ_{jk} is

$$E(\lambda) = 4\pi j(\nu) = \int n_j n(X^i) A_{jk} h\nu_{jk} dV = \int n_{\mathrm{e}} n(X^{i+1}) \alpha^{\mathrm{eff}}(\lambda) h\nu_{jk} dV \,, \qquad (4.1)$$

where n_j is the population of the level j of ion X^{i}, the quantity A_{jk} is the corresponding spontaneous transition probability, further, $h\nu_{jk}$ is the photon energy of the transition, n_{e} is the electron number density, $n(\mathrm{X}^{\mathrm{i}+1})$ is the number density of recombining ion and α^{eff} is the effective coefficient of recombination, which has been defined as the total recombination coefficient due to all recombination acts plus the contribution of the cascade processes. The integration covers whole volume of a nebula.

The populations of levels n_j can be found from the equation of statistical equilibrium

$$n_m \sum_{k=1}^{m-1} A_{mk} = n_{\mathrm{e}} n(\mathrm{X}^{\mathrm{i}+1}) \alpha_m(T_{\mathrm{e}}) + \sum_{k=m+1}^{k_{max}} n_k A_{km} \quad (m = 2, 3, 4...) \tag{4.2}$$

for the Menzel A case if the optical depth in the resonance line series ($\tau_{1n} \ll 1$). Here k_{max} is the index of the highest state considered. For Menzel B case ($\tau_{1n} \gg 1$) we have

$$n_m \sum_{k=2}^{m-1} A_{mk} = n_{\mathrm{e}} n(\mathrm{X}^{\mathrm{i}+1}) \alpha_m(T_{\mathrm{e}}) + \sum_{k=m+1}^{k_{max}} n_k A_{km} \quad (m = 3, 4, 5...). \tag{4.3}$$

In these equations a_m (T_{e}) is the total electron recombination rate onto level n of ion $\mathrm{X}^{\mathrm{i}+1}$.

It must be mentioned that models A and B simplify essentially the problem of radiative transfer in recombination spectral lines. For intermediate case if at different values of n the optical depth τ_{1n} is in the range of between the Menzel A and B cases, we have to use some approximations to solve the transfer problem for the first series lines. In gaseous nebulae the optical depth in resonance line series of most abundant elements (H, He, C, N, O) is $10 - 10^5$. The calculation of recombination spectra for HI in the case of the finite optical depth in the L_α for the stationary nebulae presented by the plane-parallel layers has been carried out by Grinin (1969). In the most cases one can use the standard Sobolev (1947) approximation. This approximation has been used by several authors (see, e.g., Rublev (1969), Ilmas (1986), Ilmas & Nugis (1982)).

The level populations of atoms and ions practically in all nebulae can be treated as the time independent quantities. Only in the case if there happens a rapid change of ionizing radiation it is inevitable to use the equations describing the time dependency of level populations.

The level population of atoms and ions having low excitation potentials can also be influenced by collisions with electrons or other particles. In this case to the right-hand part of Eq.(4.2) and Eq.(4.3) must be added the term $n_1 n_{\mathrm{e}} q_{1n}$ which takes into account the excitation processes from the ground state.

¿From Eq.(4.2) or Eq.(4.3) we can find the quantities $n_k/(n_1(\mathrm{X}^{\mathrm{i}+1})\, n_{\mathrm{e}})$ and thereafter to calculate the recombination line intensities

$I_{kj} \propto n_k A_{kj} h\nu_{jk}$.

Due to large numbers of quantum states and of corresponding equations for nebulae the system of equations turns out to be very bulky one (about 10000 states for planetary nebulae). The needed values of A_{kj} and a_n are often badly known. Therefore it is reasonable to simplify the problem considering moderate number of states (about 100) and to take the contribution of higher states into account by correction coefficients (e.g., Nikitin et al. (1986)). Using the

Menzel parameters b_m the level populations n_m can be expressed in the form

$$n_m = \frac{g_n\, h^3\, n_\mathrm{e}\, n(\mathrm{X}^{\mathrm{i}+1})}{g^+\, 2(2\pi m k T_\mathrm{e})^{3/2}}\, b_m(T_\mathrm{e})\, e^{I_\mathrm{m}/kT\mathrm{e}} = 2.071\, 10^{-16} \frac{g_n\, n_\mathrm{e}\, n(\mathrm{X}^{\mathrm{i}+1})}{g^+\, (T_\mathrm{e})^{3/2}}\, b_m(T_\mathrm{e})\, e^{I_\mathrm{m}/kT\mathrm{e}}\,, \qquad (4.4)$$

where level n, g_+ is the statistical weight for the ground state of ion $\mathrm{X}^{\mathrm{i}+1}$. The coefficients b_m, express the deviations of the level population n_m of ion X^{i} from its value at the local thermodynamical equilibrium, and the quantity I_m is the ionization potential for level m.

The system of statistical equilibrium equations for atoms and ions of H, He, C, N and O has been solved by numerous authors, who have taken into account the transition probabilities due to different processes populating and depopulating the levels. Here we shall refer to the results of most complete computations. For hydrogen levels the values of parameters $B_n = b_n e^{x_n} = b_n\, \exp(I_n/kT_\mathrm{e})$, which are indispensable for calculation of $E(\mathrm{H}_\beta)$ and the intensity ratios of HI, HeI and HeII recombination lines have been computed by Brocklehurst (1971, 1972) for different values of n_e and T_e with due account of most important processes. The results we reproduce in our Tables 26 – 28. In these tables there are given also the numerical values of expressions $Q = E(\lambda)/n(\mathrm{X}^{I+1})n_\mathrm{e}$ and $\alpha^{\mathrm{eff}}(\lambda)$. The theoretical values of the recombination line intensities of HeI and HeII for the Menzel B model can be taken from a paper by Hummer & Storey (1987). These line intensities have been computed taking into account the collisions with electrons for wide range of values for n_e, T_e and for the principal quantum number n. The logarithms of total line intensities have been stored on microfiches in the same journal as the main paper, where also the effective collision strengths γ(HeII) for quantum levels n=1, 2, 3 have been tabulated. Martin (1988) has calculated the HI recombination spectra in the case of extremely low temperature $T_\mathrm{e} \leq 500\,\mathrm{K}$. Special interest presents the transitions between higly-excited states of atoms (Rydberg states) forming the radiolines. Short review of the problem and numerous references have been presents by Gulaev (1990).

Ferland (1980) has approximated the radiation coefficient of the H_β line (in erg cm^3/s) with an error less than 10% by the expression

$$4\pi j(\mathrm{H}_\beta) = \begin{cases} 2.53 \cdot 10^{-22}\, T_\mathrm{e}^{-0.833}, & \text{for } T_\mathrm{e} \leq 2600\,\mathrm{K}, \\ 1.12 \cdot 10^{-22}\, T_\mathrm{e}^{-1.20}, & \text{for } T_\mathrm{e} > 2600\,\mathrm{K}. \end{cases} \qquad (4.5)$$

In Table 29 are given the relative intensities of recombination lines of some C, N and O ions, computed by Nikitin & Kholtygin (1986), Bogdanovich et al. (1985b) and Nikitin et al. (1994) for Menzel A and B cases at T_e=10 000K and T_e=20 000K.

For many recombination lines the contribution of dielectronic recombination in the total line intensity is important. Its contribution (Nussbaumer & Storey (1984, 1986, 1987)) at low electron temperatures has been presented by

$$\alpha_{ik}^{\mathrm{di}}(T_\mathrm{e}) = (\frac{a}{t} + b + ct + dt^2)\, t^{-3/2}\, \exp(-f/t)\, 10^{-12} \quad \mathrm{cm}^3/\mathrm{s}\,. \qquad (4.6)$$

The numerical values of parameters a, b, c, d and f are given in Table 30. The value of total recombination coefficient includes the contribution of both the photorecombination and the dielectronic recombination:

$$\alpha_{ik}^{\mathrm{R}} = \alpha_{ik}^{\mathrm{eff}} + \alpha_{ik}^{\mathrm{di}}\,.$$

In Table 31 we have compiled the values of a_{ik}^{eff},a_{ik}^{di} and a_{ik}^{R} for main spectral lines of ions of C, N and O, which have been taken from the paper by Nikitin et al. (1994). Many values of α_{ik}^{eff} for recombination lines of C, N and O ions were calculated in hydrogen-like approximation by Pequignot et al. (1991). Most of the given in this paper values are close to those presented in table 31.

The observed intensities of spectral lines in nebulae are usually expressed in duly calibrated units of Balmer lines as shown above − usually of H_β, but sometimes also of H_α, H_γ or H_δ.

The effect of electron collision processes on intensities of recombination lines of H and He has been discussed by Ferland (1986), Hummer & Storey (1987), Peimbert & Torres-Peimbert (1987a,b), Clegg (1987), Giovanardi et al. (1987), Storey & Hummer (1988). The effect of electron collisions for the recombination lines is low.

4.2 Collision-excited lines

In the spectra of gaseous nebulae a large number of forbidden lines of atoms and ions of C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Ar, Ca, K and of some other elements have been observed. These lines are generated due to transitions from the metastable states of corresponding ions X^{i}. The lines of highest intensity among them belong to the visible spectral region. During the last decade a lot of forbidden spectral lines in the ultraviolet and infrared spectral regions have been detected.

The term structure and the types of forbidden transitions for configurations with the external shell p, p^2, p^3, p^4 and p^5 are shown in Fig. 2.1. Drawn values of wavelenghts are given for ions OI - OIII. The ground term of configurations p^1 and p^5 is splitted, the transitions between its levels give spectral lines observed in the infrared spectral region. The transitions between two higher terms of configurations p^2, p^3 and p^4 are named the auroral (A), the transitions between the middle and the lowest terms give nebular (N) lines and the transitions between the highest and the lowest terms give the transauroral (TA) spectral lines. Thus, the transitions D–P in configurations p^2 and p^4 give the nebular lines, but to transitions S–D and S–P correspond the auroral and the transauroral spectral lines, respectively. In configuration P^3 the nebular lines correspond to transitions D–S, the auroral lines to P–D transitions and the transauroral ones to P–S transitions.

The intercombination lines (I) are forming in dipole transitions between the levels of different multiplicity ($\Delta s \neq 0$). They are observed mainly in the ultraviolet spectral region of nebulae. The list of the spectral lines, included the intercombinational ones observed in the ultraviolet, visible and infrared spectral regions is given in Table 25. The main mechanism of the formation of the forbidden and intercombinational lines is the collision with protons and electrons. The collisions with the neutral atoms (atoms H et al.) are less effective. In most cases contribution of recombination processes into the intensities of forbidden and intercombinational spectral lines of nebulae is negligible.

The energy, emitted in a forbidden or intercombinational line in nebulae is expressed by Eq.(4.1). In order to determine the level populations n_j we must solve the equations of statistical equilibrium

$$\sum_{j\neq i} n_j n_e q_{ji} + \sum_{j>i} n_j A_{ji} = \sum_{j\neq i} n_i n_e q_{ij} + \sum_{i>j} n_i A_{ij}\,. \qquad (4.7)$$

where the quantities q_{ij} are the coefficients of collisional excitation if $i < j$ and of collisional deactivation if $i > j$. The quantities q_{ij} can be expressed via the effective collision strengths (see Eq.(3.8)).

For finding the level populations of atoms and ions we need the large number of transition probabilities A_{ij} and effective collision strengths $\gamma_{ij}(T_e)$. These values, which are taken basically from compilation (Mendoza (1983)), are given in Tables 16,17 and 25.

4.3 Selective mechanisms of the line excitation

Recombination and collisional excitation are the main mechanisms preceding to the line formation in the spectra of low-density plasma targets such as the gaseous nebulae and stellar coronae. Besides that there are the selective line excitation mechanisms which are responsible for enhancement of intensity of the selective lines in the spectra.

The most important selective mechanisms are:

photoionization,
excitation in the result of Auger ionization,
photoexcitation by the continous spectrum,
excitation by the light emited in the selective lines (Bowen fluorescence),
excitation in charge transfer reaction.

These excitation mechanisms have been treated in detail by Rudzikas et al. (1990).

First of the mentioned mechanisms leads mainly to the enhancement of the resonance or forbidden and intercombination line intensities in the spectra of the gaseous nebulae relative to the intensities determined by electron impacts (see, for example, Ferland (1986)). The photoinization mechanism appears to be effective for relatively low electron temperatures ($T_e \leq 8 \cdot 10^3$ K).

The Auger ionization is accompanied by formation of the auotoionization states. The radiative stabilization of such states results in generation of the excited states of the high-stripped ions and of numerous lines due to the cascade transitions from these states.

Photoexcitation by the continuous radiation (non-resonant fluorescence) has been discussed by Nikitin et al. (1990). This kind of excitation can increase the intensity of the weak recombination lines of C, N and O ions (see, e.g. Grandi (1976)). The increase is commonly not high. On the contrary, the Bowen (resonance) fluorescence (often treated as the laser action) enhances significantly the intensity of the selective lines. The most famous example of the Bowen fluorescence is the pumping of the $2p3d\,^3P_{1,2}$ of OIII by the HeII L_α photons (Aller (1984), Harrington et al. (1982), O'Dell et al. (1992), Liu & Danziger (1994)). Florescent excitation of the OI and NeII lines has been considered by Sarazin (1986).

Charge transfer process also leads to the additional population of the excited levels. An example of such process is the charge transfer

$$\text{OIV} + \text{H} \rightarrow \text{OIII}\ (2p3d) + \text{H}^+\,.$$

The excited states ^1D, ^3P and ^1D of ions OIII are formed in the result of this process (see, for example, Dalgarno & Sternberg (1982)).

4.4 Plasma diagnostics for $n_{\rm e}$ and $T_{\rm e}$

In the first approximation the emission power of the plasma depends on the mean values of electron temperature $\overline{T}_{\rm e}$ and on the mean electron number density $\overline{n}_{\rm e}$. The intensities of the emission lines excited by electron collisions are strongly sensitive to the values of $\overline{T}_{\rm e}$ and $\overline{n}_{\rm e}$. The ratio of the intensities of such lines depends on $\overline{T}_{\rm e}$ and $\overline{n}_{\rm e}$:

$$R_{ki;\,mn} = \frac{I(\lambda_{ki})}{I(\lambda_{mn})} = R(\overline{T}_{\rm e}, \overline{n}_{\rm e})\,. \tag{4.8}$$

If the upper levels of transitions $k \to i$ and $m \to n$ in Eq.(4.8) have a great energy difference then the ratio $R(\overline{T}_{\rm e}, \overline{n}_{\rm e})$ depends mainly on $\overline{T}_{\rm e}$ (see, for example, Fig 4.1). So, if $\overline{n}_{\rm e}$ is approximately known, the mean electron temperature $\overline{T}_{\rm e}$ can be found by using the function $R(\overline{T}_{\rm e}, \overline{n}_{\rm e})$ and the observed line intensity ratio.

On the contrary, for lines with small energy difference of the upper levels (mostly for the lines of the same multiplet) the ratio of their intensities predominantly depends on the value of $\overline{n}_{\rm e}$, see Fig.4.2. Lines of such type are often used for the mean electron number density determinations.

Numerous references on the recent calculations of the collision line intensities can be found in book by Rudzikas et al. (1990) and in review by Kholtygin (1990).

In general case the line ratios depend on both $\overline{n}_{\rm e}$ and $\overline{T}_{\rm e}$. For determination of both the values, not less than two observed line ratios must be known. The method of line pairs (see, for detail, Aller (1984), Pottash (1984)) can be used.

Different pairs of lines in the spectra of a nebula give slightly different values of both $\overline{n}_{\rm e}$ and $\overline{T}_{\rm e}$. This difference gives evidence about the temperature and density fluctuations (or clumps) in the nebulae. The method of diagnostics of the temperature fluctuations following Peimbert (1967) has been proposed by Kholtygin and Feklistova (1992 a,b). Joint study of both the temperature and the electron number density fluctuations has been carried out by Kholtygin (1996).

The recombination line intensities do not show significant dependence neither on $\overline{n}_{\rm e}$ nor $\overline{T}_{\rm e}$ and thus they cannot be used for $n_{\rm e}$ and $T_{\rm e}$ diagnostics. Paschen lines can be an exception of the rule. The intensities of these lines depend significantly on the mean electron number density (see Table 26).

In the presence of the strong external X-ray radiation field the intensity of the collisionlly excited lines can be strongly distorted by the post-Auger ionization and excitation (Aldrovandi & Gruenwald (1985)) and thus they cannot be used for $n_{\rm e}$ and $T_{\rm e}$ diagnostics.

4.5 Chemical abundance determination

The total flux emitted by a nebula in a spectral line can be found if we know the distance to the nebulae. The relative ion abundancies can be found from observed line intensities by

$$\frac{n(\mathrm{X^i})}{n(\mathrm{H^+})} = \frac{\lambda(\mathrm{X^i})}{\lambda(\mathrm{H}_\beta)} \frac{\alpha^{eff}(\mathrm{H}_\beta)}{\alpha^{eff}(\lambda)} \frac{I(\lambda)}{I(\mathrm{H}_\beta)} = \mathrm{X}(T_\mathrm{e}) \frac{I(\lambda)}{I(\mathrm{H}_\beta)} \,. \tag{4.8}$$

This formula follows from (4.1) if we make use of averaged effective recombination coefficients.

Using the effective recombination coefficients found by Brocklehurst (1971, 1972) for HeI and HeII lines we can write the following formula for finding the relative ion number densities

$$\frac{n(\mathrm{HeII})}{\mathrm{n(HII)}} = (a_i + b_i t + c_i t^2) \cdot \frac{I(\lambda_i \mathrm{HeI})}{I(\mathrm{H}_\beta)} = \begin{cases} (3.98 + 0.33t - 0.01t^2)\, I(\lambda 4026\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (98.3 - 58.0t - 14.0t^2)\, I(\lambda 4120\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (27.6 + 2.13t - 0.068t^2)\, I(\lambda 4123\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (14.8 + 1.8t - 0.16t^2)\, I(\lambda 4388\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (274 - 153t - 36.7t^2)\, I(\lambda 4437\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (1.73 + 0.37t - 0.06t^2)\, I(\lambda 4471\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (6.36 - 1.54t - 0.23t^2)\, I(\lambda 4921\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (0.493 + 0.305t - 0.059t^2)\, I(\lambda 5876\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (5.64 + 2.13t - 0.35t^2)\, I(\lambda 6678\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (31.3 - 18.0t + 4.38t^2)\, I(\lambda 7065\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \\ (148 - 93.4t + 23.4t^2)\, I(\lambda 7281\,\mathrm{HeI})/\mathrm{I(H_\beta)}, \end{cases}$$

and

$$\frac{n(\mathrm{HeIII})}{n(\mathrm{HII})} = (0.0653 + 0.0238t - 0.052t^2)\, I(\lambda 4686\,\mathrm{HeII})/I(\mathrm{H}_\beta),$$

where $t = T_\mathrm{e}/10^4\mathrm{K}$.

The coefficient $\mathrm{X}(T_\mathrm{e})$ in Eq.(4.8) for many ion species can be expressed by

$$\mathrm{X}(T_\mathrm{e}) = \chi_0\,(t)^\eta \,. \tag{4.9}$$

The numerical values of the fitting parameters χ_0 and η for the C, N and O ion spectral lines are given in Table 32. They were derived based on the effective recombination coefficients, given in Table 31.

In monograph by Aller (1984) there are given the expressions, connecting the relative abundances of ions with corresponding ratios of ultraviolet line intensities:

$$\frac{N(\mathrm{X^i})}{N(\mathrm{HII})} = A_{\lambda i}\, E^0_{4,2}\, t^{1/2} e^{-d/t} \frac{I(\lambda)}{I(\mathrm{H}_\beta)} \,, \tag{4.10}$$

where the coefficient $E^0_{4,2}$ for line H_β has for the Menzel B case the following form

$$E^0_{4,2} = \alpha^\mathrm{eff}(\mathrm{H}_\beta)\, 10^{25} = 1.387\mathrm{t}^{-0.983} \cdot 10^{-0.0424/\mathrm{t}} \quad \mathrm{erg/cm^3s} \tag{4.11}$$

The needed values of $A_{\lambda i}$ and d are given in Table 33.

4.6 The continuous spectrum of nebulae

Gaseous nebulae emit the weak continuous spectrum, which is observed in ultraviolet, visible, infrared and radio wave regions. The continuous spectrum of nebulae has been caused by the free-free, free-bound and two-quantum transitions 2s–1s of H, He atoms and of the ion He^+.

The computations of the two-quantum transitions have been first carried out by Kipper (1950, 1952) and by Spitzer & Greenstein (1951). In the far infrared spectral region the main contribution in the total continuum emission is provided by the emission of dust and by the HI free-free transitions.

The energy emitted by gas in the unit volume is

$$E_\nu d\nu = N(\mathrm{X}^{\mathrm{i+1}})\,\mathrm{n_e}\,\gamma\,\mathrm{d}\nu\,, \tag{4.12}$$

where the emission coefficient

$$\gamma = \gamma(\mathrm{HI}) + \gamma(\mathrm{2q,HI}) + \gamma(\mathrm{HeI})\frac{\mathrm{N(HeII)}}{\mathrm{N(HII)}} + \gamma(\mathrm{HeII})\frac{\mathrm{N(HeIII)}}{\mathrm{N(HII)}}\,, \tag{4.13}$$

In this expression $\gamma_\nu(\mathrm{X^i})$ is the emission coefficient due to free-free and free-bound electron transitions in HI, HeI or HeII, the quantity $\gamma(2q,\mathrm{HI})$ is the two-photon emission coefficient of H atoms. The values of these coefficients are given in Table 34.

The values of $\gamma(2q,\mathrm{HeI})$ can be found in the monograph by Pottash (1984). Two-photon transitions from singlet and triplet metastable states of helium-like ions have been studied in the paper by Drake et al. (1969), where the corresponding values of $\gamma(2q,\mathrm{X^i})$ have been given. Due to relatively low helium abundance in nebulae the processes, however, can be neglected.

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