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Abstract

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V. G. GORBATSkii

ON THE ORIGIN OF THE [OI] LINES IN THE SPECTRA OF SUPERNOVAE

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As is known, the only lines identified with sufficient confidence in the spectra of type I supernovae are the forbidden lines (OI) $\lambda\lambda$ 6300, 6364 Å. In the case of the supernova IC 4182 they became noticeable 180 days after maximum light, and their intensity changed little during the subsequent 150 days (^{1}). Clarification of the causes producing emission in these lines may contribute to a fuller understanding of the process of a type I supernova outburst.

Using data on the intensity of the [OI] lines, I. S. Shklovskii (^{2}) found that the mass of the envelope of the supernova in IC 4182 is of the order of $0.1\,M_\odot$. It was assumed in this that the oxygen in the envelope is predominantly in the neutral state, while the electron temperature in it is about $10^4\,^\circ$K. It is obvious that the degree of ionization of hydrogen in the envelope at that time could not have been high. The question of how, over a long time, a sufficiently high electron temperature could be maintained in the stellar envelope remained open. For $T_e = 10^4\,^\circ$K and $M_{\text{env}} \approx 0.1\,M_\odot$, the total energy of free electrons (even if complete ionization of H is assumed) is $2 \cdot 10^{44}$ erg, whereas about $4 \cdot 10^{45}$ erg was radiated in the [OI] lines during the time they were observed. In this note we show that the indicated contradiction finds an explanation if it is assumed that the emission of the supernova envelope in the [OI] lines arose in the same way as the emission of nova envelopes in these lines, namely during fluorescence.

In a fluorescing layer of hydrogen that was initially in a state of high ionization, the electron temperature decreases much more slowly than the degree of ionization falls. The maintenance of a temperature of order $10^4\,^\circ$K is provided, as shown in (^{3}), by the energy of L_α quanta. If the layer is sufficiently extended and the initial concentration of atoms in it is $n_H \gtrsim 10^9$ cm^{-3}, the L_α radiation produced during recombinations proves to be trapped. Its energy is gradually converted into the kinetic energy of free electrons in ionizations from excited states and in collisions of the second kind. In this way more than half of the entire ionization energy must be transformed into the kinetic energy of the electrons.

The fall in the degree of ionization of oxygen accompanying fluorescence leads to an increase in the concentration of neutral atoms and, consequently, at a slowly varying value of T_e, to an increase in the total number of excitations of them into the metastable state. Since the electron concentration and, correspondingly, the rate of deactivation of excited OI atoms decrease at the same time, the intensity of the radiation in the [OI] lines after the beginning of fluorescence should increase rapidly.

For the energy $E_{2\to1}$, emitted by a volume V in the lines $\lambda\lambda$ 6300, 6364 Å, corresponding to the transition from the level ^1D to the level ^3P, the following expression was obtained in (^{4}):

$$E_{2\to1} = \frac{g_2}{g_1}\, p n_H V A_{21}\, \frac{(1 - n_e/n_H) q_{21} n_e}{A_{21} + q_{21} n_e}\, h\nu_{12} e^{-h\nu_{12}/kT_e}, \tag{1}$$

where p is the abundance of oxygen atoms relative to hydrogen;

n_H is the total concentration of hydrogen atoms; g_{21} is the coefficient of deactivation of OI atoms from the state ^1D; A_{21} is the probability coefficient of the corresponding spontaneous transition; ν_{12} is the mean frequency of the lines $\lambda\lambda$ 6300; 6364 Å. By means of formula (1), a quantitative interpretation was given of measurements of the intensity of the [OI] lines in the spectra of Nova Lacertae 1950 and Nova Herculis 1934.

A supernova outburst is accompanied by the ejection of an envelope more massive than in the case of a nova. Let us consider the process of its afterglow (i.e., the decrease of the degree of ionization of hydrogen in it), assuming that it begins when the envelope is already transparent to radiation in the Balmer and higher continua.

Let the envelope be a spherical layer with volume V, and let the velocity of its motion be constant. Then the radius of the envelope changes proportionally to time. Since the thickness of the envelope must also increase proportionally to time as a result of the expansion of the layer with a velocity of the order of the speed of sound, the volume of the envelope V increases proportionally to t^3:

$$V/V_0 = (t/t_0)^3. \tag{2}$$

The velocities of motion of the envelopes of type I supernovae are of the order of 10^8 cm/sec, and, as far as can be judged from the width of the [OI] lines in the spectrum, for the supernova in IC 4182 it was about 1500 km/sec. The mean concentration of atoms in the envelope at the moment of appearance of the [OI] lines, if the envelope is regarded as a homogeneous sphere and its mass is taken to be $0.1\,M_\odot$, is $2 \cdot 10^9$ cm^{-3}. If, however, its thickness is several times smaller than the radius, as is the case for novae, then $n_H \approx 10^{10}$ cm^{-3}.

The envelopes of novae are usually already transparent in visible frequencies and in the Balmer continuum 10 days after outburst (for masses of the order of

$10^{-4}M_\odot$). Consequently, it may be assumed that 180 days after the outburst of a star, an envelope with a mass three orders of magnitude greater and moving at the same time 2-3 times faster will also be transparent at the frequencies of the Balmer continuum. Therefore, provided that hydrogen is the principal component of the envelope, the change in the total number of free electrons in the envelope N_e is determined by the equation

$$dN_e/dt = -CN_en_e, \tag{3}$$

where C denotes the sum of the recombination coefficients to all levels of the hydrogen atom, beginning with the second.

Taking into account that the quantity N_e is related to the electron concentration by the relation

$$N_e = Vn_e, \tag{4}$$

we have the equation

$$dN_e/dt = -CN_e^2/V. \tag{5}$$

Integrating this equation with allowance for (2) and under the condition $t = t_0,\ N_e = N_e^0$, we obtain

$$N_e = N_e^0/[1 + \tfrac{1}{2}Cn_e^0t_0(1 - t_0^2/t^2)], \tag{6}$$

whence, for the electron concentration n_e, we find the expression

$$n_e = n_e^0 \Big/ \left[\left(\frac{t}{t_0}\right)^3 + \tfrac{1}{2}Cn_e^0t_0\frac{t}{t_0}\left(\frac{t^2}{t_0^2} - 1\right)\right]. \tag{7}$$

As is seen from (6), the quantity N_e, equal to the total number of ionized atoms in the envelope, as $t \to \infty$ tends to the finite limit

$$N_e \xrightarrow[t\to\infty]{} N_e^0/(1 + \tfrac{1}{2}Cn_e^0t_0). \tag{8}$$

Here we are dealing with an effect analogous to the well-known phenomenon of "quenching" in gas dynamics (see, for example, ([5]))*. Expansion of the envelope leads to recombinations proceeding more slowly than would be the case for the illumination of a stationary envelope, and the gas flies apart to infinity partially ionized. The fall of the electron concentration at $t \gg t_0$ occurs almost exclusively because of the expansion of the envelope. It is not difficult to show that, also in the case of expansion of the envelope according to the law $V \sim t^2$, i.e., without an increase in its thickness, a similar effect also exists.

Let us now substitute the quantities N_e and n_e, determined from (6) and (7), into formula (1). Assuming that at the initial moment the envelope was completely ionized, i.e. taking at $t = t_0$, $N_e^0 = N_H^0$, and taking into account that $n_e/n_H = N_e/N_H$, $N_H = Vn_H$, we have

$$E_{2\to1} = Ba(1 - 1/z^2)/[1 + a(1 - 1/z^2)][z^3 + az(z^2 - 1) + b], \tag{9}$$

where it is denoted

$$\frac{t}{t_0} = z, \qquad \frac{1}{2}Cn_e^0 t_0 = a, \qquad \frac{q_{21}}{A_{21}} n_e^0 = b \tag{10}$$

and B is a coefficient depending only on T_e and the relative oxygen abundance.

For $a \gg 1$ the quantity $E_{2\to1}$ very quickly reaches a maximum at the value $z = z^*$, where

$$z^* \approx 1 + 1/2a. \tag{11}$$

After this, $E_{2\to1}$ at first decreases very slowly—by a factor k at the value z_k, determined from the equation

$$z_k^3 - z_k = \frac{b}{a}(k - 1), \tag{12}$$

and then ever more rapidly, and for $z \gg 1$ the quantity $E_{2\to1} \sim z^{-3}$. Thus, during the time interval from $t_0 z^*$ to $t_0 z_{10}$, the quantity $E_{2\to1}$ decreases by an order of magnitude.

The quantity b/a does not depend on the electron concentration at the initial moment n_e^0

$$\frac{b}{a} = \frac{2q_{21}}{CA_{21}} \frac{1}{t_0}. \tag{13}$$

Using the values $q_{21} = 6.7 \cdot 10^{-3}$, $A_{21} = 9.1 \cdot 10^{-3}$, $C = 3 \cdot 10^{-13}$, we find $b/a = 5 \cdot 10^6/t_0$.

For the conditions of the envelope of supernova IC 4182, as shown above, $n_H^0 \gg 2 \cdot 10^9$, and consequently the maximum of the absolute intensity of the [OI] lines should have been reached very quickly. Since the [OI] lines appeared approximately $1.5 \cdot 10^7$ sec after the outburst of the star, $z^* - 1 \lesssim 2 \cdot 10^{-4}$, and therefore they became visible almost immediately after the beginning of illumination. As for the time over which $E_{2\to1}$ decreases by a factor of 10, from (12) we find $z_{10}^3 - z_{10} = 3$ and $z_{10} = 1.7$, and hence $t_{10} - t^* \approx 10^7$ sec.

It is known from (1) that the [OI] lines in supernova IC 4182 were observed approximately over $1.2 \cdot 10^7$ sec, and during the last 80–90 days their relative intensity, insofar as can be judged from reproductions of microphotograms, if it increased, did so slowly. At the same time, the photographic brightness of the star decreased approximately by a factor of two every 50 days. Therefore it may be considered that over a time of $1.2 \cdot 10^7$ sec the absolute intensity of the lines decreased by an order of magnitude, and one may state

* This case differs from those considered earlier in that the disturbance of the ionization-recombination equilibrium is connected with illumination, and not with the expansion of the gas.

good agreement between the observed fading time and the theoretical estimate.

Let us note that for the case of Nova Herculis the corresponding time is $t_0 \approx 10^6$ sec. Accordingly, $b/a = 5$ and $z_{10} = 3.7$, which gives, for the duration of the decrease in the intensity of the [OI] lines, a time of about 30 days; whereas the observed duration of the decrease in the intensity of the [OI] lines is of the order of 50 days (6). Thus, in this case as well, the theory agrees with the observations.

In the case of the supernova in IC 4182, observers drew attention to the absence of the [OI] line $\lambda 5577$ Å, produced in the transition $^1S \to {}^1D (3 \to 2)$. This fact has a simple explanation. The ratio of the line intensities is determined by formula (4)

$$\frac{E_{3\to2}}{E_{2\to1}} = 32 e^{-25800/T_e} \frac{1 + 8.4 \cdot 10^5 n_e^{-1}}{1 + 1.67 \cdot 10^8 n_e^{-1}}. \tag{14}$$

During the period when the lines $\lambda 6300, 6364$ had their greatest relative intensity, several tens of days after the moment t_0, the value of n_e should not have exceeded 10^5 cm^{-3}. Accordingly, as is seen from (14), the line $\lambda 5577$ Å differed in intensity by two orders of magnitude from the lines $\lambda 6300, 6364$ Å, and therefore it was impossible to notice it in the complex spectrum of the supernova.

Thus, on the basis of the assumption made above concerning the character of the emission of the envelopes of supernova stars in the [OI] lines, the observational facts are successfully explained, and we arrive at the conclusion that the degree of ionization in the bulk of the envelope of a supernova decreases sharply approximately 180 days after maximum light. Since the release of the energy initially contained in the envelope must end much earlier—in the epoch of maximum light (7)—the appearance of [OI] lines in the spectrum indicates a sharp decrease in the effectiveness of the factors responsible for the ionization of hydrogen. In the case of novae, such a factor is either the energy of corpuscular streams transformed into radiation—as, for example, in Nova Herculis 1934—or the short-wavelength radiation of the star, as in Nova Lacertae 1950. In supernova stars, in addition to this, other circumstances may also play a significant role in ionization, for example the synchrotron radiation of relativistic electrons and the radiation accompanying the radioactive decay of transuranic elements.

Leningrad State University
named after A. A. Zhdanov

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Note: Figure translations are in progress. See original paper for figures.