ON THE ORIGIN OF ABSORPTION LINES OF THE BALMER SERIES OF HYDROGEN IN THE SPECTRA OF GALAXIES

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Abstract

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G. A. GURZADYAN

ON THE ORIGIN OF ABSORPTION LINES OF THE BALMER SERIES OF HYDROGEN IN THE SPECTRA OF GALAXIES

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As is known, in the spectra of some galaxies there are absorption lines of the Balmer series of hydrogen of rather high intensity. The well-known irregular galaxy M82 may serve as an example ([1,2]). Proceeding from this fact, one would have to conclude that in such galaxies the stellar population of the first type predominates, for which a small value of the color index—of the order of $+0^m.3$—is characteristic. Meanwhile, in the case, for example, of the galaxy M82, the color index is of the order of $+0^m.8$ ([3–5]), which, on the contrary, indicates the predominance in it of the stellar population of the second type. In other words, the spectrum of the galaxy indicates its belonging to an early spectral type, while the color indicates a late spectral type. This discrepancy between the color and the spectrum of the galaxy apparently cannot be regarded as accidental, and it is, in all probability, connected with the specificity of the physical conditions in it.

If the Balmer lines of hydrogen in the spectrum of a galaxy are not of stellar origin, then they must have an interstellar origin—in relation to the given galaxy. In this case the optical thickness of the interstellar medium (hydrogen) over the entire depth of the galaxy in the lines of the Balmer series must be of the order of, or greater than, unity. For given dimensions of the galaxy and density of hydrogen atoms in it, there exists a certain minimum concentration of hydrogen atoms in the second energy state n_2 at which the indicated condition will be fulfilled. The problem is to determine n_2 and to indicate the mechanism of excitation of the second state of hydrogen atoms to the required extent.

We have considered the following schemes: a) all the interstellar hydrogen in the galaxy is in the neutral state; b) a model of our Galaxy; c) the galaxy consists mainly of stars of types B_1–B_2; d) the hydrogen is completely in the ionized state. In none of these schemes, as quantitative analysis shows, is a positive solution obtained regarding the possibility of the occurrence of Balmer absorption lines in the spectra of these galaxies. However, in one case—when the interstellar hydrogen is ionized very weakly, and the ionization is due to short-wavelength radiation of synchrotron origin—the formation of Balmer absorption lines in the spectrum of the galaxy is possible. In the present article the principal results obtained on this question are presented.

Let I_{if} denote the intensity of the i-th Balmer absorption line of hydrogen, and I_{ie} the intensity of the emission line of the same number; in both cases the intensity refers to the outer boundaries of the galaxy. In order that, in the integral spectrum of the galaxy, the given hydrogen line i be observed in absorption, it is necessary that

$$I_{if} > I_{ie}. \tag{1}$$

If H_i is the flux of radiation in the continuous spectrum of the given galaxy at its outer boundaries near the hydrogen line i, and W_i is the equivalent width in frequency units of this line, then we can write for I_{if}

$$I_{if} = W_i H_i. \tag{2}$$

Writing I_{if} in this form, we in effect liken the whole galaxy to a reflecting layer of the Sun, with the only difference that the sources of continuous radiation are the stars of the galaxy, while the selective scattering is caused by the interstellar hydrogen atoms of this same galaxy.

For W_i we have, in the case when the broadening of the absorption line is caused by the Doppler effect of the thermal motions of the atoms:

$$W_i = 2t_i \Delta\nu_D \varphi(t_i), \tag{3}$$

where

$$\varphi(t_i) = \int_0^\infty \frac{dp}{e^{p^2} + t_i}, \qquad \Delta\nu_D = \frac{\nu_i}{c}\sqrt{\frac{2kT}{m}}; \tag{4}$$

t_i is the optical thickness of the galaxy at the frequency of the given Balmer line i; $t_i = n_2 s_{iD}$, where s_i is the coefficient of selective absorption of hydrogen in line i; D is the linear size of the galaxy.

Substituting (3) into (2), we shall have for the intensity of the absorption line

$$I_{if} = 2t_{iH} i\varphi(t_i). \tag{5}$$

For the intensity of the emission line of the same number i we have:

$$I_{ie} = \frac{\varepsilon_i}{\alpha_i}(1 - e^{-t_i}), \tag{6}$$

where $\alpha_i = s_{in}2$ is the volume absorption coefficient, and ε_i is the volume emission coefficient, equal to $\varepsilon_i = n_{iA_{i2}} h\nu_i = n^+ n_{ez} i(T_e) A_{i2} h\nu_i$, where $z_i(T_e) = n_i/n^+ n_e$, n^+ and n_e are the concentrations of protons and free electrons in the medium. From (6) it follows that, for $t_i \gg 1$,

$$I_{ie}^{\max} = \varepsilon_i/\alpha_i = \varepsilon_i/n_2 s_i, \tag{7}$$

i.e., for a given concentration of hydrogen atoms in the second state n_2 there exists a maximum value of the emission-line intensity, greater than which it cannot be even for arbitrarily large dimensions of the galaxy. In contrast to this, the intensity of the absorption line, as follows from (5), will be the greater the larger the extent of the galaxy in the given direction (the product $t_i\varphi(t_i)$ increases slowly with increasing t_i). It is clear that, for sufficiently large dimensions of the galaxy or for sufficiently high concentrations of hydrogen in the second energy level, the intensity of the absorption line may predominate over the intensity of the emission line, as a result of which, in the integrated spectrum of the galaxy, the Balmer series will be present in absorption lines.

Table 1

H_i	t_α^0	n_2^0
10^{-12}	2.7	10^{-10}
10^{-13}	26	10^{-9}
10^{-14}	110	10^{-8}

At the equality sign in (1), we shall evidently find that value of the optical thickness t_i^0, and thereby the concentration of hydrogen atoms n_2^0 in the second energy state, at which the intensity of the absorption line is equal to the intensity of the emission line; in this case we should observe no line in the integrated spectrum of the given galaxy. Then the condition for the appearance of an absorption line will be $t_i > t_i^0$, and the condition for the appearance of an emission line $t_i < t_i^0$.

Equating (5) to (7), we shall have, for determining t_i^0 (for $t_i \gg 1$):

$$2(t_i^0)^2 H_i \varphi(t_i^0) = \varepsilon_{iD}. \tag{8}$$

Table 1 gives the values of t_α^0, found from this relation for the first line of the Balmer series of hydrogen H_α, for various values of the flux (in a unit frequency interval) near this line in the continuous spectrum of the galaxy' s radiation and at its outer boundaries, H_i. In calculat-

it was assumed: $n^+ = n_e = 1$ cm^{-3}, $A_{32} = 4.39 \cdot 10^7$ sec^{-1}, $z_3(T_e) = 0.23 \cdot 10^{-20}$ for $T_e = 10\,000^\circ$ ([4]), $D \approx 10000$ parsecs $\approx 3 \cdot 10^{22}$ cm. In this same table are given the values of n_2^0 in cm^{-3}, determined from the relation $n_2^0 = t_\alpha / s_\alpha D$, where $s_\alpha = 4.8 \cdot 10^{-13}$ cm^2.

As follows from the data of Table 1, Balmer absorption lines can arise in the integrated spectrum of those galaxies in which $t_\alpha > 1$, $H_i \sim 10^{-12}$–10^{-13} erg/cm^2 · sec · Hz (near the H_α line), and $n_2 \sim 10^{-9}$–10^{-10} cm^{-3} for $D \sim 3 \cdot 10^{22}$ cm. The last requirement is the most essential. The concentration $n_2 \sim 10^{-9}$–10^{-10} cm^{-3}, although 2-3 orders of magnitude smaller than the value of n_2 for planetary nebulae ([6]), is nevertheless still sufficiently high. Such a high concentration n_2 under galactic conditions ($n_0 \sim 1$ cm^{-3}) can be produced at a sufficiently high density of L_α-radiation. In order to have a high density of L_α-radiation, it is sufficient that there be L_c-radiation and the required number of neutral atoms capable of absorbing it and converting it into L_α-quanta.

For the appearance of the effect under consideration it is advantageous that the ionization of hydrogen be low. This will occur when it is produced by L_c-radiation of synchrotron origin. We assume that in some galaxies there exist extensive magnetic fields, and that their volume is filled with relativistic electrons. The braking of these electrons in magnetic fields is accompanied by the emission of synchrotron radiation of all wavelengths, including at the frequencies of L_c-radiation, the intensity of which is represented by the expression ([7])

$$I_\nu = \frac{1 - e^{-\tau_c}}{n_1 \chi_c} C(\gamma) \, K H^{\frac{\gamma+1}{2}} \nu^{\frac{1-\gamma}{2}} \quad (\nu > \nu_0), \tag{9}$$

where n_1 is the concentration of normal hydrogen atoms; χ_c is the coefficient of continuous absorption per one neutral hydrogen atom; τ_c is the optical thickness of the medium at the frequencies of L_c-radiation; ν_0 is the ionization frequency of hydrogen; H is the magnetic-field strength, while K and γ characterize the energy spectrum of the relativistic electrons: $N_e(E) = KE^{-\gamma}$. The function $C(\gamma)$ is tabulated in ([7]).

Taking the relation between the density of L_α-radiation ρ_α and the density of L_c-radiation ρ_c in the form $\rho_\alpha \approx \omega \tau_c \rho_c$, where $\omega = k_\alpha / \chi_c$, k_α is the absorption coefficient per hydrogen atom in the L_α-line, we find from (9), for $\tau_c = n_1 \chi_{cD} \gg 1$,

$$\rho_\alpha = 4\pi\omega\tau_c \frac{h\nu_0}{c} \int_{\nu_0}^{\infty} \frac{I_\nu}{h\nu} \, d\nu = \frac{8\pi\omega}{c(\gamma - 1)} DC(\gamma) \, KH^{\frac{\gamma+1}{2}} \nu_0^{\frac{3-\gamma}{2}}. \tag{10}$$

From the condition of equality of transitions between the first and second levels,

$$\frac{n_2}{n_1} = \frac{8\pi\omega k_\alpha}{h\nu_\alpha A_{21}} \frac{C(\gamma)}{\gamma - 1} DKH^{\frac{\gamma+1}{2}} \nu_0^{\frac{3-\gamma}{2}}. \tag{11}$$

From this relation one can determine the quantity K for given values of H and n_2/n_1, after which the concentration of relativistic electrons N_e can be found from the relation $N_e(> E_0) = \frac{K}{\gamma - 1} E_0^{1-\gamma}$, where E_0 is the energy of the electrons at which the greatest number of quanta of frequency ν_m is emitted ($\nu_m = 1.4 \cdot 10^6 H(E/mc)^2$ sec^{-1}).

Further, in determining the parameters of the energy spectrum of the relativistic electrons it is assumed that ν_m corresponds to a frequency close to the ionization frequency of hydrogen, i.e. $\nu_m \sim 3 \cdot 10^{15}$ sec^{-1} ($\lambda_m \sim 1000$ Å). Then for $H \sim 10^{-5}$ gauss we shall have $E_0 \sim 7.5 \cdot 10^{12}$ eV. Calculations carried out for the case $n_2/n_1 = 5 \cdot 10^{-9}$ and $\gamma = 3$ give $K = 2.2 \cdot 10^{-11}$ erg/cm^3

and $N_e(> 7.5 \cdot 10^{12}) = 0.75 \cdot 10^{-13}$ cm^{-3}. For the concentration of relativistic electrons with energy $E_0 > 3.4 \cdot 10^{12}$ eV, when visible quanta ($\lambda \sim 5000$ Å) are emitted, under the same assumptions one obtains $N_e(> 3.4 \cdot 10^{12}) = 4 \cdot 10^{-13}$ cm^{-3}. (In the calculations it was assumed that $D = 3 \cdot 10^{22}$ cm, $\omega = 10^4$, $k_\alpha = 6.2 \cdot 10^{-14}$ cm^2.) The obtained value of N_e, although several orders of magnitude smaller than, for example, in the case of the Crab Nebula ([8]), is nevertheless large in comparison with our Galaxy.

The degree of ionization of interstellar hydrogen, calculated by means of the formula given in (7), is found to be $n^+/n_1 \sim 0.1$, i.e. $n_1 \approx n_0 \sim 1$ cm^{-3}, and, since in the calculations $n_2/n_1 = 5 \cdot 10^{-9}$ was adopted, $n_2 \sim 5 \cdot 10^{-9}$ cm^{-3}, i.e. the order of magnitude needed for the formation of interstellar hydrogen absorption lines in the integral spectrum of a galaxy.

Thus, the synchrotron radiation of relativistic electrons, in all probability, is capable of maintaining, throughout the volume of a galaxy, an ionization high enough to facilitate the transformation of L_c-quanta into L_α-quanta, and at the same time low enough to leave on the second level of hydrogen the required number of atoms.

If synchrotron radiation is emitted in a galaxy, then, obviously, it will be superposed on the general continuous radiation of the galaxy, which is of stellar origin. Let us estimate the order of magnitude of the intensity of synchrotron radiation, for example, in the case of M82 in comparison with the Crab Nebula, whose emission in the continuous spectrum is entirely synchrotron in nature, making use of the fact that the energy spectra of the relativistic electrons are known for both objects. We may write for the ratio of the surface brightness in photographic rays of M82 (I_1) to the surface brightness of the Crab Nebula (I_2), on the assumption that the emission of both objects is of purely synchrotron nature (for $\gamma = 3$):

$$\frac{I_1}{I_2} = \frac{D_1}{D_2} \frac{K_1}{K_2} \left(\frac{H_1}{H_2} \right)^2 . \tag{12}$$

Taking $D_1 \sim 10000$ parsecs, $K_1 = 2.2 \cdot 10^{-11}$ erg/cm^3, $H_1 = 10^{-5}$ gauss for M82 and $D_2 \sim 1.5$ parsecs, $K_2 = 1.2 \cdot 10^{-9}$ erg/cm^3 and $H_2 = 3 \cdot 10^{-4}$ gauss for the Crab Nebula ([8]), we find $I_1/I_2 \sim 0.15$. On the other hand, the mean surface brightnesses of M82 and of the Crab Nebula in photographic rays are, in order of magnitude, identical ([3,9,10]). Hence it follows that the intensity of synchrotron radiation may amount to a quantity of the order of 15% of the intensity of the total continuous radiation of M82 in photographic rays.

In view of the considerations set forth, the fact of the radio emission of M82, which is undoubtedly of nonthermal origin ([11]), as well as the comparatively high degree of polarization of the radiation of M82 in photographic rays ([9]), becomes understandable, at least qualitatively.

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Byurakan Astrophysical Observatory
Academy of Sciences of the ArmSSR

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