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ONE MECHANISM OF PRODUCTION OF ADDITIONAL COMPONENTS IN EMISSION LINES OF THE SPECTRA OF ACTIVE GALAXIES

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A new mechanism is suggested to explain the physical phenomenon of the appearance of additional new emission components of hydrogen lines in the spectra of active galactic nuclei (AGNs). The mechanism is based on the assumption that a dense clump of hydrogen is ejected from an AGN and expands rapidly due to a presumed explosion. Two main features of this phenomenon are explained fairly simply: a) the pronounced shift of the additional components from the main components (up to several thousand kilometers per second); b) the large width of the additional components, reaching 100-200 Å. The large share of emission by the additional components in comparison with the main lines is also explained well. Estimates obtained for the physical parameters of the new formations in AGNs fit well into modern concepts of AGNs and the forms of their activity.

1. Introduction

In the mid-50's, V. A. Ambartsumian [1] advanced the idea of the activity of galactic nuclei (GNs). Ejections from the nuclei of individual clouds of various composition are one form of such activity. Subsequent research has shown that the nuclei of some active galaxies (AGs) exhibit rapid, irregular brightness changes. In the late 60's and early 70's, a number of observational papers on spectrophotometry of active galactic nuclei (AGNs) showed that processes of an explosive nature occur in the central regions of AGs, leading to the ejection of an enormous amount of matter from the nuclei. The small angular sizes of AGNs (10^{-5} arcsec) prevent the detection of new gaseous formations in their vicinity by direct observations, even in the radio range. So detailed spectrophotometric investigation (with a relatively large dispersion) remains the sole possibility for their detection and study. Studies in the optical range are the most effective.

The phenomenon of the appearance of new emission components in AG spectral lines was first detected in 1969 by É. Ye. Khachikian and D. W. Weedman [2, 3]. In the course of one year (between February 1968 and January 1969), broad new emission components in the Hα, Hβ, and Hγ Balmer lines appeared in the spectrum of the galaxy Markanian 6, which is a Seyfert galaxy of type Sy 2. Their Doppler shift in the short-wavelength direction corresponds to a velocity of 3000 km/sec. In January 1970 the intensity of the new component of the Hβ line was over 50% of the intensity of the original emission line within the limits of the linewidth. These observations were confirmed by a number of authors [4-10]. Active objects in whose spectra the Balmer lines exhibit a double structure, such as 3C 390.3 and NGC 1097 and 1566, were noted subsequently (see [11-14]). Several models have been proposed to explain this phenomenon. They include:

ejection of a dense hydrogen cloud in one or two opposite directions from the nucleus [3, 4];

– variability of the AGN itself, resulting in an increase or decrease in the degree of ionization in gas clouds around the nucleus [15];

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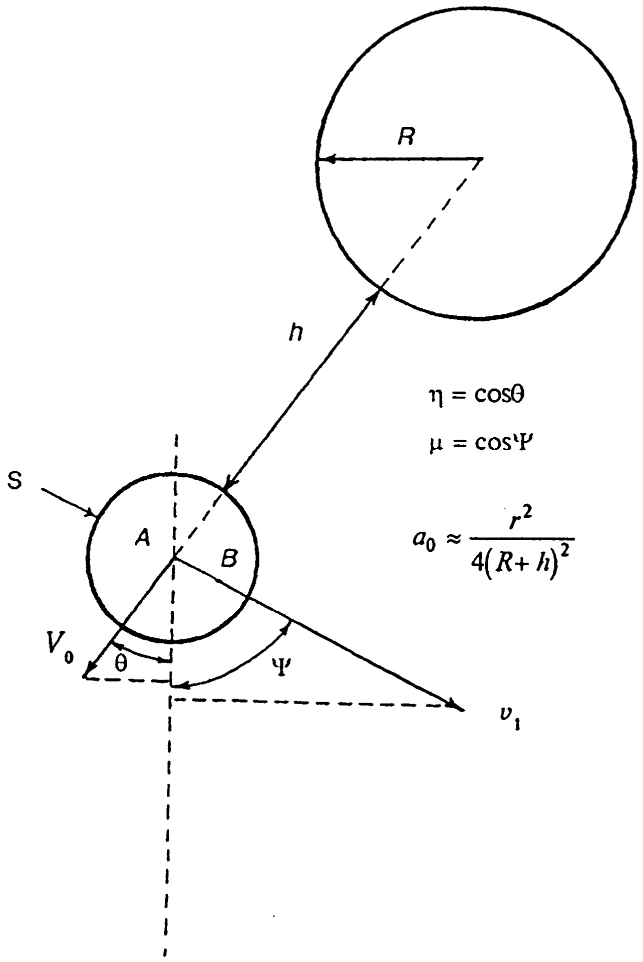

Fig. 1. Schematic depiction of a GN and a cloud S.

– biconical outflow of matter from AGNs, i.e., jets [16, 17];

– the presence of an accretion disk around an AGN. If a hydrogen line has two symmetrical components, this implies the existence of two Balmer-line regions containing two supermassive black holes [18, 19].

All these models encounter considerable difficulties and do not provide any complete explanation for the appearance of broad new components in the main hydrogen lines in AG spectra.

In the present paper we offer a new model to explain the appearance of additional components in Balmer and other subordinate lines of AGs. This model is fairly simple and yields quantitative agreement with observational data.

2. Description of the Model

At the time $t = 0$ let a compact formation S_0 be ejected from an AGN. Having traveled some distance h_0 from the surface of the GN, S_0 explodes at the time $t = t_1$. This explosion produces an expanding gas cloud S, consisting mainly of hydrogen atoms (Fig. 1).

The radiation of L_c photons coming from the GN and falling on the cloud S is transformed in it. Like the situation in gaseous nebulae, the L_c photons ionize hydrogen atoms in S which, as a result of recombination and subsequent cascade transitions, produce photons in subordinate lines of the hydrogen atom. The cloud is assumed to be almost transparent in these subordinate lines, so these photons escape S unhindered and contribute to the emission of the GN itself. As a result, additional components of subordinate emission lines arise in the GN spectrum. The cloud S is assumed to have no internal energy source.

The shift of the additional components with respect to the GN emission lines is explained by the motion of the cloud S as a whole relative to the GN. The width of the additional components is a result of the rapid expansion of S.

Before proceeding to the calculations, we stress that in the present paper we do not have the aim of constructing an exact theory of the suggested model. Simple estimates that will be made below show that relatively small cloud size and mass and realistic expansion velocities can fully explain the fairly high intensity of the additional components.

3. Definitions and Some Equations

We designate the velocity of departure of the center A of S from the GN as V_0 km/sec, and the angle formed by the velocity vector of A with the line of sight as $\theta = \arccos \eta$. For $0 \leq \theta < \pi/2$ the cloud is moving toward the observer. We can also consider values of $\theta \geq \pi/2$ for which the cloud is not hidden by the GN.

We assume S to expand with some "effective" velocity V_1 and at $t > t_1$ it fills a sphere of radius

$$r(t) = V_1 \cdot (t - t_1). \tag{1}$$

The hydrogen density distribution within the sphere can range within fairly wide limits. The velocity distribution of atoms in S also plays no significant role in our further analysis.

Let ν_{L} be the limit of the Lyman continuum, corresponding to $\lambda_{\mathrm{L}} = 912$ Å. We assume the optical depth τ_0 of S at the Lyman limit to be considerably greater than unity. The cloud then absorbs almost completely the UV radiation incident on it in the range

$$\nu > \nu_{\mathrm{L}}' \equiv \nu_L\left(1 + \frac{V_0}{c}\right)^{-1} \approx \nu_L\left(1 - \frac{V_0}{c}\right). \tag{2}$$

The following inequality is required to satisfy this condition:

$$\tau_0 = \frac{3}{4} M_S (1 - x) K_L \left[\pi r^2 m_p\right]^{-1} \geq \tau_1. \tag{3}$$

Here M_S is the cloud's mass, $m_p = 1.67 \cdot 10^{-24}$ g is the mass of a proton, and $K_L = 10^{-17}$ cm^2 is the approximate absorption cross section immediately beyond the Lyman limit, calculated per hydrogen atom; x is the average degree of ionization of hydrogen in the cloud. For τ_1 and x we take the values $\tau_1 = 20$ and $x \geq 0.99$. For such τ_1 the optical path length of L_{c} photons will be fairly long even in the peripheral regions of the cloud S.

The condition of transparency of S in subordinate lines is approximately satisfied due to the relatively small amount of excited hydrogen atoms. The influence of free–free transitions of ionized atoms, scattering of photons from free electrons, and ionization of excited atoms by subordinate and L_{c} photons can also be neglected to first order. Of the nonlinear effects due to the high radiation density inside the cloud, therefore, only the high degree of ionization is taken into account.

As for the role of electron collisions of the first and second kinds, it is relatively small because the medium is rarefied (and these collisions compensate for each other).

4. Production of Subordinate Lines

Let one hydrogen atom be ionized at point B of cloud S. By recombination and subsequent cascade transitions, a photon in the spectral line $k \to m$, where $m > k \geq 1$, is produced with some probability P_{mk}. The frequency of this photon is close to the central frequency ν_{km} of the line under consideration. We shall ignore the line's natural width because of its smallness compared to the Doppler width. The probability P_{km} depends little on the frequency of the ionizing photon. The subordinate photons ($k \geq 2$) are assumed to be emitted isotropically and escape the cloud S unhindered. Some of these photons are detected by the observer. The frequency ν''_{km} of a detected photon in the reference frame of the GN will be

$$\nu''_{km} = \nu_{km}\left(1 + \frac{V_0}{c}\eta + \frac{V_2}{c}\mu\right), \tag{4}$$

where μ is the cosine of the angle between the line of sight and the vector $\vec{AB}$ (Fig. 1) and V_2 is the velocity of atom B away from the center A of the cloud. For most cloud atoms, the velocity V_2 satisfies the condition $V_2 \leq V_1$. Since the number μ ranges from -1 to $+1$, in accordance with (4) we have

$$\nu_{km}' - \Delta\nu_{km} \leq \nu_{km}'' \leq \nu_{km}' + \Delta\nu_{km}, \tag{5}$$

where $\nu_{km}' = \nu_{km}[1 + (V_0/c)\eta]$ is the central frequency of the observed additional emission line (AEL) and $\Delta\nu_{km} = (V_1/c)\nu_{km}$ is its width. Recall that we are calculating the photon's frequency in the reference frame of the GN. It is clear that the line will not be confined to the above limits, since some fraction of the atoms in the cloud have a velocity $V_2 > V_1$.

5. Calculating Equation

In subsequent calculations we assume that the GN has the shape of a sphere with a radius R pc. We designate the fraction of the GN radiation falling on the cloud S at the time t as $a(t)$. Because of the presumed spherical symmetry of the optical properties of the GN, the quantity $a(t)$ does not depend on frequency and is a geometrical characteristic of the GN–S configuration. We can show that we have

$$a(t) \approx \frac{r^2(t)}{4\left[R + h(t)\right]^2}, \tag{6}$$

where $h(t) = h_0 + V_0(t - t_1)$ is the distance of point A from the surface of the GN at the time t.

Let N_L and N_{km} be the numbers of photons emitted by the GN per second in the range $(\nu_L^*;\ \infty)$ and in the $k \to m$ *emission line*, respectively. We introduce the parameter

$$J_{km} = N_L/N_{km}. \tag{7}$$

In the case of Markarian galaxies, this parameter can take fairly large values (200 or more) because of the strong ultraviolet excess of their emission.

We designate the number of photons emitted by S per second in the $k \to m$ line as F_{km}. For it we obtain the approximate equation

$$F_{km} \equiv F_{km}(t) \approx N_L \cdot a(t) \cdot P_{mk},\ k \geq 2. \tag{8}$$

The possibility that, following the recombination of an ionized hydrogen atom, a new L_c photon may appear that is capable of ionizing another hydrogen atom is not taken into account in Eq. (8). Allowance for this possibility increases F_{km} in comparison with (8).

We introduce the new parameter

$$\gamma_{km} \equiv \gamma_{km}(t) = F_{km}(t)/N_{km}. \tag{9}$$

The number γ_{km} represents the observed fraction of the additional component in the $k \to m$ emission line due to the cloud.

6. Calculation of the Probabilities P_{m2}

We confine ourselves to calculating the probabilities P_{mk} for Balmer lines ($k = 2$). Based on well-known theoretical considerations, we assume that each ionized hydrogen atom produces one Balmer photon after recombination. The probabilities P_{m2} therefore coincide with the fractions of photons in the $2 \to m$ line among all Balmer photons.

TABLE 1. Values of D_m, Φ_m, and P_{m2}

m	3 (H_α)	4 (H_β)	5 (H_γ)	6 (H_δ)	7 (H_ϵ)
D_m	2.79	1.00	0.49	0.28	0.18
Φ_m	3.77	1.00	0.44	0.24	0.15
P_{m2}	0.56	0.15	0.04	0.022	0.016

To calculate the quantities P_{m2}, we use the relative intensities of Balmer lines from the theory of gaseous nebulae, i.e., the Balmer decrement. We designate as D_m the ratio of the intensity of the mth ($m = 3, 4, \ldots$) Balmer line to the intensity of the Hβ line ($m = 4$) in case B (see [20]), in which the cloud's optical depth in Lyman lines is assumed to be fairly high. The Balmer decrement depends little on temperature. For the cloud S we take the base value of D_m at $T_c = 20{,}000$ K (see [20], Table 33).

We convert from D_m to the ratio $\Phi_m = F_{2m}/F_{24}$ of the numbers of Balmer photons emitted by the cloud per unit time in the 2 → m line and in the 2 → 4 line. Using the Bohr equation, we obtain

$$\Phi_m = \frac{3m^2}{4\left(m^2 - 4\right)} D_m. \tag{10}$$

The numbers P_{m2} are expressed in terms of Φ_m as follows:

$$P_{m2} = \Phi_m \Big/ \sum_{n=3}^{\infty} \Phi_n. \tag{11}$$

Theoretical values of D_m, $m = 3, \ldots, 7$, calculated by Seaton and borrowed from [20], Table 33, are used in Table 1. The role of the missing values of D_m is taken into account approximately (with an excess), taking $\sum\limits_{m=8}^{\infty} \Phi_m = 1.08$.

The probabilities P_{mk} for $k \geq 1$ can be calculated using the Einstein coefficients A_{mk} for spontaneous transitions. We shall not take up this question in the present paper. We only note that a value for P_{42} close to 0.15 can be obtained in this way.

7. Application of the Model to Hβ Lines of the Galaxy Markarian 6

The above model for the production of additional components in emission lines of AG spectra will be applied below to the additional emission of the broad Hβ line in the spectrum of the galaxy Markarian 6 (see the Introduction).

We assume that the presumed explosion of the compact formation S_0 occurred in the first half of 1968 and the expansion of the cloud S lasted for 600 days, until January 1970, i.e.,

$$T = t - t_1 = 600 \text{ days} = 5.2 \cdot 10^7 \text{ sec.} \tag{12}$$

It is clear that by the date of the event we mean the time of its detection by the observer.

As indicated above, the width of the additional component of the Hβ line was about 150 Å, which corresponds to an effective cloud expansion velocity of

$$V_1 = 4600 \text{ km/sec.} \tag{13}$$

From (1), (12), and (13) we obtain

$$r_1 = V_1 T = 2.9 = 10^{11} \text{ km} = 0.008 \text{ pc.} \tag{14}$$

We take $h_0 << R$ and $h_1 = h(t) = V_0 T$. With allowance for (7), (8), and (9), from (6) we then have

$$R = \frac{r_1}{2}\left(\frac{J_{24} P_{42}}{\gamma_{24}}\right)^{1/2} - h_1. \tag{15}$$

Let us estimate the parameters on the right side of Eq. (15). We have $\gamma_{24} = 0.5$. In accordance with the remark about Eq. (7) in Sec. 5, for J_{24} we take the value

$$J_{24} = 200. \tag{16}$$

According to Table 1, $P_{42} = 0.15$. Using (14) for r_1, from Eq. (15) we obtain

$$R \approx 0.022 \text{ pc}. \tag{17}$$

As noted in the Introduction, the Doppler shift of the additional component of the Hβ line in the spectrum of Markarian 6 corresponds to 3000 km/sec, i.e.,

$$V_0\eta = 3000 \text{ km/sec}. \tag{18}$$

8. Remarks

Within the framework of the model under consideration, the expansion velocity of the cloud S is higher than its velocity away from the GN, and the condition $h_0 << R$ is assumed to be satisfied. After a certain time, therefore, the expanding cloud S, reaching the GN surface, is deformed and loses its spherical shape. It is easy to ascertain that such deformation can increase $a(t)$ in comparison with Eq. (6).

The cloud's mass M_S can be estimated using the inequality (3). For τ_0 we take the value $\tau_0 = 20$, in accordance with Sec. 3. To estimate the degree x of hydrogen ionization inside the cloud, we must use information about the density of L_c radiation in the vicinity of the nucleus of Markarian 6. Since that density may be fairly high, we take

$$x = 0.999,\ 1 - x = 10^{-3}. \tag{19}$$

From the inequality (3) and the above values of the respective parameters, we can obtain the following estimate of the cloud's mass:

$$M_S \approx 10^{-2}\, M_\odot. \tag{20}$$

If x turns out to be even closer to unity, this only increases somewhat the estimate (20) for the cloud's mass and does not qualitatively affect the overall picture of the suggested model.

We have thus found approximate values of the main parameters for which the suggested model explains the phenomenon of the appearance of an additional component of the Hβ line of Markarian 6 in the form of a broad emission line, shifted from the main line by about 3000 km/sec in the short-wavelength direction. The values of some of these parameters, $V_0\eta$, V_1, T, and γ_{24}, are direct consequences of observational data. And the values of the other parameters, R, r_1, M_S, and J_{24}, are consistent with our concepts of AGNs and the physical processes occurring in their vicinity.

To conclude this section, we give the approximate values found for the parameters listed above for Markarian 6.

Cloud's radial velocity away from the GN	$V_0\eta = 3000$ km/sec
Cloud's expansion velocity	$V_1 = 4600$ km/sec
Time of cloud expansion to January 1970	$T = 600$ days
Cloud's radius	$r_1 = 0.008$ pc
Cloud's mass	$M_S = 0.01\, M_\odot$
Radius of GN	$R = 0.022$ pc
Radiation fraction of additional line component	$\gamma = 0.5$.

8. Conclusion

In the present paper we have suggested a new mechanism for producing the additional emission components of subordinate emission lines in the spectra of active galactic nuclei. This phenomenon was discovered in 1969 in the Sy 2 Seyfert galaxy Markarian 6 (see [2, 3]). The explanation of two main physical features of these additional components has an important place in the suggested mechanism:

a) The pronounced shift of the additional lines from the main ones.

b) The large width of the additional lines, reaching 150-200 Å.

These observational facts are explained quite well and simply within the framework of the suggested mechanism. The high intensity of the newly produced component as a fraction of that of the main line is also explained fairly simply.

We made no assumption about the nature of the compact formation, the explosion of which produces the cloud S. We only note that the values obtained for the cloud's mass and expansion velocity are realistic and fit well into modern concepts about the forms of GN activity.

To test, refine, and further develop the suggested model, we propose to carry out comprehensive observational and theoretical investigations in the following main directions:

– accumulation of new observational data on the time variation of additional emission lines (AELs) and their theoretical explanation, including irregular brief and long-term changes in AELs;

– calculation and comparison of additional components of different Balmer emission lines;

– determination of the nature of the compact formation S_0.

The calculations given here are mainly of an estimating nature. A more precise calculation of the radiation field in the cloud S is associated with an examination of linear and nonlinear problems of radiative transfer in an inhomogeneous, spherically symmetric medium, when the radiation field does not have such symmetry. The approach suggested in [21] can be used for this.

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