Simulation of the extended base of emission lines in the spectra of HII regions

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The profile of the additional broadened spectral component of the emission lines of the HII regions in the continuum region is modeled. A simple physical model is proposed to describe the emission profiles of the lines, and the simulation of the observed line profile on real spectrographs is carried out. It is shown that for processing SDSS and DESI data, the integral line profile associated with expanding shells can be described by a single Gaussian function. The test processing of the spectra, taking into account this effect, showed that neglecting the wide component when modeling line profiles can lead to an error in the measured fluxes by up to 10 %, which, in turn, can lead to noticeable systematic shifts in estimates of the physical parameters of the HII regions. The proposed method can be included in the procedures for automatic processing and analysis of a large number of spectra with low and medium spectral resolution.

Keywords: emission lines, HII regions, dwarf galaxies.

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Introduction

The HII regions are zones of ionized hydrogen, which occur around young hot stars of the O and B spectral classes. Their radiation ionizes the surrounding gas and recombination of the hydrogen atoms and other elements originates typical Balmer-series emission lines (H_α, H_β, H_γ, etc.) as well as prohibited lines of metals ([OIII]4959/5007 Å, [NII]6548/6584 Å, etc.).

Simulation of the emission lines in the spectra of the HII regions is an important tool for studying physical properties and a chemical composition of these objects. The low-metal compact blue dwarf galaxies include a large number of the young stars of the O and B classes, thereby making it possible to consider their spectrum as a total spectrum of many HII regions. The dwarf blue galaxies are very interesting objects in terms of observation cosmology: by analyzing their spectra, one can obtain estimates for abundance of primary helium-4 [1–4] and obtain an estimate for a modern value of the Hubble constant [5,6], etc.A key challenge in processing the spectra of these objects is that it is necessary to correct for a large number of systematic effects that lead to a difference between the observed and emitted fluxes of the emission lines in such objects.

One of these effects is presence of a broadened component of the emission lines. This effect was previously described in some studies as applied to analysis of profiles of the lines H_α for obtaining accurate estimation of an intrinsic width of the line, which, in turn, parametrizes dispersion of velocities in the object [7,8]. At the same time, this effect was ignored in papers dedicated to analysis of the dwarf galaxies for cosmological studies [1–6]. Ignoring this effect can result in systematic shifts in the obtained estimates, which is unacceptable in modern precision cosmology when subpercent accuracy of estimation of the cosmological parameters is advocated.

It was shown in the study [9] that a visible additive component is related to radiation in shells of the expanding HII regions. They expand from the zone of ionized hydrogen HII with a typical temperature $T_{HII} = 10^4$ K into a zone of atomic hydrogen HIc$T_{HI} = 10^2$ K due to a pressure difference at both sides of an ionization front. Equations of evolution of the expanding HII region are described in detail in the classical study [10]. There is still search for the fullest model of the expanding HII region, and modern numerical and analytical models are provided in the study [11]. The effect of a broadened base of the emission lines was studied in detail on a small sample of the HII regions in good resolution in the studies [7,8,12]. These studies have investigated a profile of the line H_α and additional spectral components were selected manually in order to achieve the best agreement of a simulated profile of the line with one observed for each individual object. The present study is dedicated to developing a simple and effective model of description of the broadened spectral components of the emission lines of the HII regions, which can be incorporated into codes of automatic processing a large number of spectra with low and middle spectral resolution (for example, spectra from the SDSS and DESI

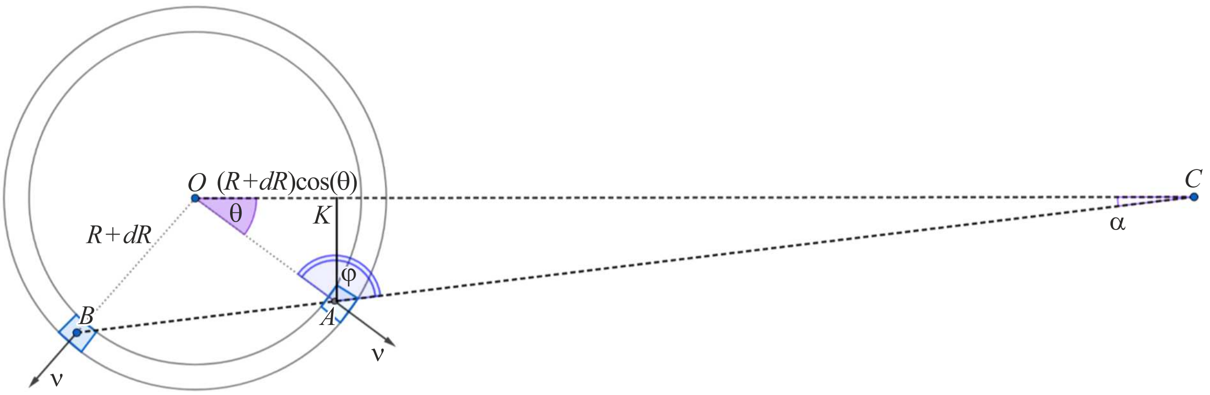

Figure 1. Model of the expanding HII region. C is an observer's position, R is a radius of the main region, α is an angular size, φ: $\left[0, \frac{\pi}{2}\right]$ is an angle between v and CB (motion away from the observer); $\left[\frac{\pi}{2}, \pi\right]$ is an angle between v and CA (a direction towards the observer).

catalogs) as well as to estimating a value of a systematic shift that occurs when ignoring this effect.

1. Model of the expanding HII region

For analytical description of this phenomenon we have considered a Strömgren classical sphere (see [9]) that expands into a cloud of atomic hydrogen HI.

With homogeneous and isotropic expansion at the velocity v one part of the volume of the shell moves towards the observer, so does another one away from the observer, thereby providing two additive contributions into an integral flux of the emission lines. Let us consider an element of the volume $dV = RdRd\theta$, which moves away from the observer (the point B in Fig. 1). Radiation intensity of this portion

$$\int dI_u = \int j_u dV = F_u \int_{\frac{\pi}{2}-\alpha}^{\pi} \psi_u(\theta) d\theta,$$

where F is a value of the flux at the pre-defined u, and it is a fittable model parameter and $\psi_u(\theta) = e^{-\frac{(u-v_0)^2}{2\sigma^2}}$ is the profile of the line with a shift from the line center $v_0 = v \cdot \cos(\varphi)$. According to Fig. 1, $\theta = \pi - \varphi - \alpha$, then in order to transit to a φ integral we obtain $\frac{d\theta}{d\varphi} = -1 - \frac{d\alpha}{d\varphi}$. According to a sine theorem in ΔBOC, we obtain $\sin(\alpha) = \frac{R+dR}{D}\sin(\varphi) \Rightarrow \alpha = \arcsin\left(\frac{R+dR}{D}\sin(\varphi)\right)$, where a distance from the object to the observer $D \gg R$. Let us introduce the parameter $A = \frac{R+dR}{D}$ and after simple transformations and decomp into a series by A, we obtain

$$\frac{d\theta}{d\varphi} = -1 - A\cos(\varphi).$$

Substituting this expression into the intensity equation, we obtain the profile of contribution into the total flux in the line for the shell part the moves away from the observer:

$$I_{from} \sim \int_0^{\frac{\pi}{2}} e^{-\frac{(u-v\cdot\cos(\varphi))^2}{2\sigma^2}} (1 + A\cos(\varphi)) d\varphi.$$

Similarly, we obtain the profile of contribution for the part that moves towards the observer:

$$I_{at} \sim \int_0^{\frac{\pi}{2}} e^{-\frac{(u+v\cdot\cos(\varphi))^2}{2\sigma^2}} (1 - Acos(\varphi)) d\varphi.$$

Let us not that the profile of the wide additive component depends on the velocity of motion of the expanding shell, internal dispersion of the velocities therein and an angular size of the object. Within the framework of the formulated problem we will not take into account the angular size, considering it to be quite small. The obtained profiles of the lines within the framework of this simple model excellently agree with results of full hydrodynamic simulation of the expanding shells, which was performed by means of the ZEUS code [7].

2. Influence of the instrument function of the telescope

After determining a kind of the wide additive component for the emission lines of the HII regions, we can find out how a sum of the two contributions of the expanding shell will look like with taking into account instrument dispersion σ_{inst}, considering that the instrument function is Gaussian, which is often true for the optical telescopes. It is exemplified by velocity dispersion $\sigma = \sqrt{\frac{kT_{HII}}{m_p}} = 10$ km/s and $\sigma_{inst} = 25$ km/s and a result of convolution of the two contributions of the additive component is shown in Fig. 2.

With the typical shell expansion velocity $v = 13$ km/s, a visible difference of the resultant profile from the Gaussian function is not observed up to the values $\sigma_{inst} = 6$ km/s. Therefore, in most cases, the studied effect can be simulated without dividing the additive contribution into the two components I_{from} and I_{at}.

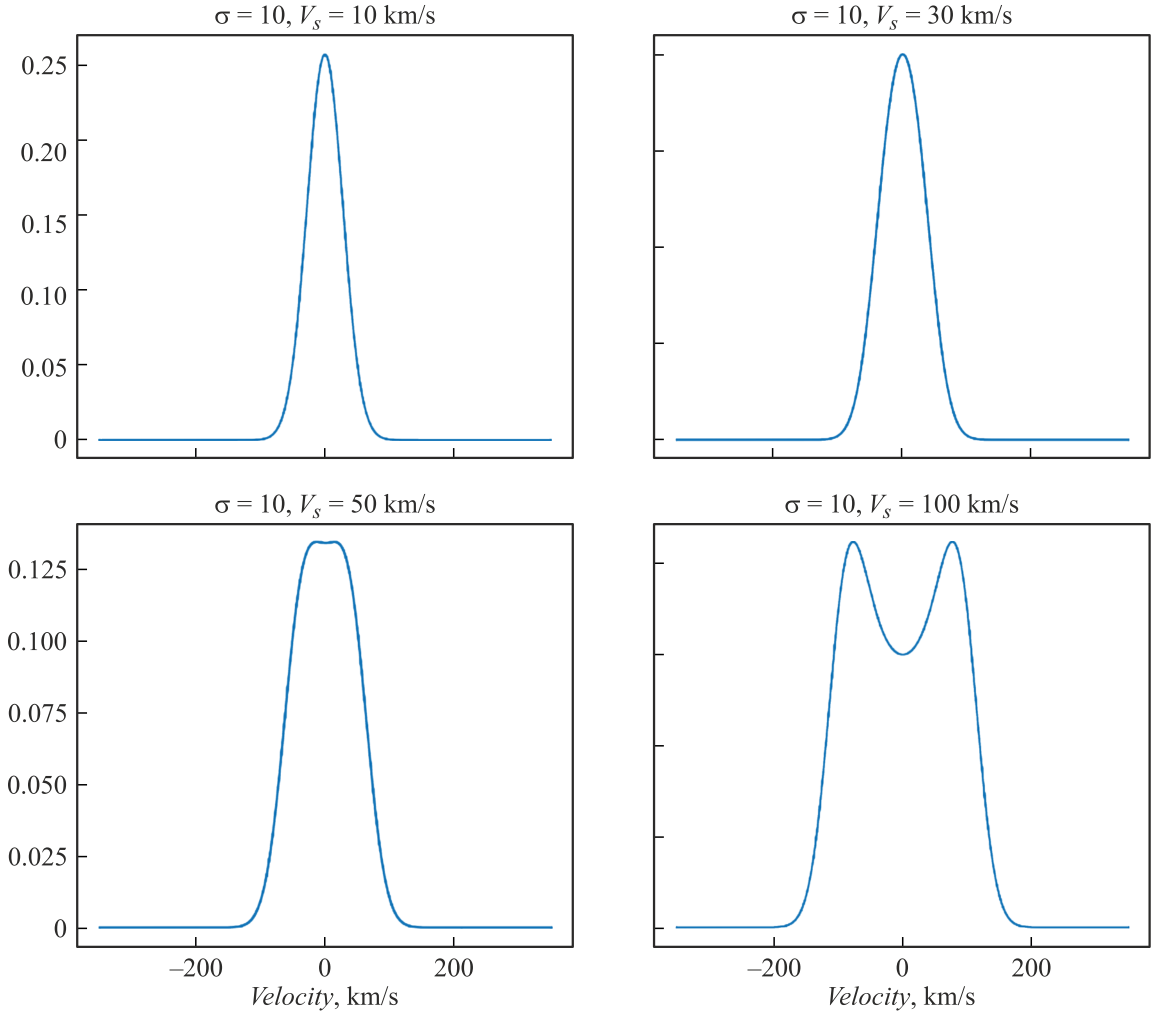

Figure 2. Convolution of the profiles I_{from} and I_{at} of the additive component with velocity dispersion $\sigma = 10$ km/s in the shell that moves at the velocity V_s, with the instrument function with $\sigma_{inst} = 25$ km/s.

3. Simulation of the real spectrum

We have shown that for simulation of the emission line with the wide additive component in the spectra of the blue dwarf galaxies from the SDSSDR17 catalog [13], it is enough to find parameters of a sum of two Gaussians of the pre-defined line, since equipment broadening of this telescope $\sigma_{inst} = 69$ km/s.

It is exemplified by simulation of the profiles of the most powerful lines [OIII] 4959/5007 Å in the galaxy $J1227 + 5137$ with a redshift $z = 0.044$ in Fig. 3. The wide component has low intrinsic intensity, since the volume of the expanding shell is small as compared to the volume of the main area of ionized hydrogen, and a higher width of the line, since velocity dispersion in the main area is less than in the expanding part, due to which it is not always possible to take into account the studied correction in less powerful lines. The optimal parameters of the profiles are determined using the Monte Carlo method and fitting confidence is estimated by the criterion χ^2. Ignoring taking into account the wide component results in the fact that during simulation of the emission lines the integral flux F has an overestimated values, since in fact it is a sum of the intrinsic flux of the line and the flux of the additive component. In the lines shown in Fig. 3 the value of F differs by 10 % without and with taking into account the broadening effect, while the systematic error of simulation decreases in two times. The similar results were obtained for a sample of the galaxies from the study [4].

Conclusion

The study has investigated the influence of radiation of the shell of the expanding HII region on the observed spectrum. Within the framework of the simple model we obtained the kind of the profile of the wide additive components and considered its convolutions with the various instrument functions of the telescope. Simulation of the most powerful emission lines was comparatively analyzed with and without taking into account the new effect. The

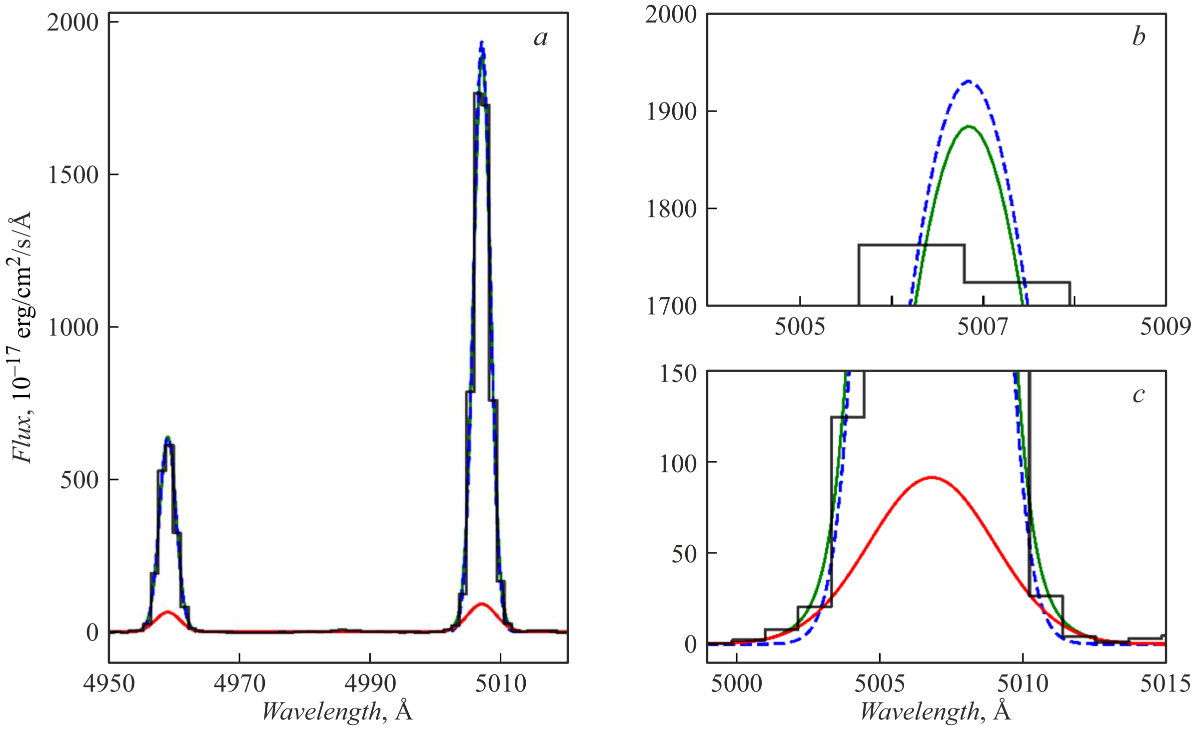

Figure 3. Doublet [OIII] 4959/5007 Å in the galaxy $J1227+5137$ (a); b, c are fragments of the line 5007 Å and its components in an increased scale. The blue line marks simulation without taking into account the additive component; the green line marks the total profile of the line with the additive component; the red line marks the profile of the additive component.

results of the study show that it is necessary to include the studied effect into the future photoionization models of the HII regions. It will allow decreasing the systematic error in the determined parameters of the HII regions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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