DISPARITY BETWEEN H\textalpha AND H\beta IN SN 2008in:
INHOMOGENEOUS EXTERNAL LAYERS OF TYPE IIP
SUPERNOVAE?

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ABSTRACT

We study disparity between H\textalpha and H\beta in early spectra of the type IIP supernova SN 2008in. The point is that these lines cannot be described simultaneously in a spherically-symmetric model with the smooth density distribution. It is shown that an assumption of a clumpy structure of external layers of the envelope resolves the problem. We obtain estimates of the velocity at the inner border of the inhomogeneous zone ($\approx 6100$ km s$^{-1}$), the filing factor of inhomogeneities ($\leq 0.5$), and the mass of the inhomogeneous layers ($\sim 0.03$ M$_\odot$). The amplitude of flux fluctuations in the early spectrum of H\textalpha ($\Delta F/F \sim 10^{-2}$) imposes a constraint on the size of inhomogeneities ($\leq 200$ km s$^{-1}$). A detection of fluctuations in the early H\textalpha of type IIP supernovae might become an observational test of the inhomogeneous structure of their envelopes. We propose also the indirect test of the clumpy structure of external layers: the study of properties of the initial radiation outburst due to the shock breakout. The inhomogeneous structure of external layers of type IIP supernovae could be an outcome of density perturbations and density inversion in outer convective layers of presupernova red supergiant.

Keywods: supernovae and supernova remnants; stars — structure and evolution

1. Introduction

Type IIP supernovae (SN IIP) represent majority of core-collapse events in the mass range of $9 - 25$ M$_\odot$ (Heger et al. 2003). Despite the explosion mechanism is not well understood, the major observational characteristics of SN IIP indicate that we deal with

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the red supergiant (RSG) explosion (Grassberg et al. 1971; Falk & Arnett 1977; Eastman et al. 1994; Baklanov et al. 2005; Utrobin 2007). Yet detailed modelling of eight well observed SN IIP uncovers a serious problem that progenitor masses of all of them turn out to be significantly larger $M_{\text{psn}} \geq 15 \, M_\odot$ compared to the lower limit ($\approx 9 \, M_\odot$) of massive stars (Utrobin & Chugai 2013, henceforth UC13). Although this sample is small and selection effects might skew the distribution, this fact poses a difficult question, whether we understand adequately the SN IIP light curve and spectrum formation.

Recently, modelling the type IIP supernova SN 2008in revealed an unexpected problem, namely, that Hα and Hβ line profiles cannot be described simultaneously in the spherically-symmetric model (UC13). Specifically, Hβ absorption turns out to be substantially deeper compared to the prediction based on the model adjusted to Hα. The problem seems to be rather serious keeping in mind simplicity of the hydrogen spectrum and the fact that the Balmer lines have the common lower level. In that paper we suggested that the inconsistency between Hα and Hβ could be an outcome of an inhomogeneous structure of supernova envelope in outer layers.

Here we explore a possibility for the solution of the Hα/Hβ problem in SN 2008in by assuming the inhomogeneous (clumpy) matter distribution in outer layers of supernova. We confine ourselves to the question, whether one could find an acceptable description of Hα and Hβ profiles assuming a clumpy atmosphere, and, if so, what should be the optimal parameters of the inhomogeneous structure. We start with a description of Hα/Hβ problem using the model with a smooth density distribution (section 2). We then present the inhomogeneous model and results of the modelling for Hα and Hβ line profiles (section 3). In section 4 we consider the issue of flux fluctuations in the Hα line related to the inhomogeneous structure.

Our study is based on spectra of SN 2008in published by Roy et al. (2011).

2. Hα/Hβ problem

We consider a freely expanding spherical envelope with the Lagrangian velocity and radius obeyed the relation $v = r/t$, where $t$ is the time since the explosion. A photosphere is presumably sharp and resides at the level $v_p$; above that level the atmosphere is transparent in the continuum. For the moderate Hα optical depth ($\tau_{23} < 10^5$) the size of the scattering region of a photon is of the order of the sound scale length $l_s \sim ut$, ($u$ is the hydrogen thermal velocity). Given $l_s \ll r \sim v_p t$, the Sobolev approximation for the local photon scattering is valid with the high precision. The line profile formed in the supernova envelope is determined by the behavior of the local optical depth $\tau(v)$ and source function $S(v)$. Since
we are interested in the relative flux, in case of the uniform brightness $I^e$ of the photosphere the source function can be written in the dimensionless form $S = W + S_0$, where $W$ is the dilution factor. The first term is for the scattering of photospheric radiation and the second term is for the intrinsic emission. The power law is adopted for the optical depth $\tau(v) = \tau_p(v/v_p)^{\delta}$ and for the source function $S_0(v) = S_{0,p}(v/v_p)^{\varphi}$, where $\tau_p$ and $S_{0,p}$ are values at the photosphere.

In Fig. 1 we show two versions of models for SN 2008in on day 11. The first one is aimed at reproducing H$\alpha$, whereas the second at reproducing H$\beta$. The photospheric velocity is 6100 km s$^{-1}$ in both cases. The plots show that the model being good for the H$\alpha$ is bad for H$\beta$. Two possibilities for H$\beta$ are shown: without and with the net emission. In both cases the fit is bad. On the other hand, the model aimed at the description of H$\beta$ does not reproduce H$\alpha$. This modelling demonstrates the core of the H$\alpha$/H$\beta$ problem in the early spectrum of SN 2008in: the lines cannot be reproduced simultaneously in the model of the smooth spherically-symmetric envelope. To put it straightforwardly, the H$\beta$ absorption is stronger than that in the model based on H$\alpha$. The opposite is true as well: the H$\alpha$ absorption is weaker than that in the model based on the H$\beta$. It should be emphasized that this controversy cannot be resolved by taking metal lines into account because at this stage metal lines are very weak and cannot markedly affect hydrogen line profiles.

We explored the effects of a multiple Thomson scattering off thermal electrons taking into account the H$\alpha$ and H$\beta$ photons created at large optical depth $\tau_T \leq 3$. This mechanism is known to produce broad wings in Balmer lines of some SN IIn (Chugai 2001). Our modelling shows however that for reasonable temperature ($\sim 10^4$ K) the effects of wings are negligible and cannot resolve the H$\alpha$/H$\beta$ problem anyway.

3. Inhomogeneous envelope

Arguments for the consideration of the inhomogeneous model stem from the fact that in the clumpy medium with the large cloud to intercloud contrast the line absorption depth is determined by both atomic constants and the cloud filling factor. The situation is conceivable when the H$\alpha$ and H$\beta$ absorptions in clouds are saturated. In this case, if the intercloud gas is absent, the H$\alpha$/H$\beta$ absorption ratio could become close to unity, i.e., significantly lower than the homogeneous model predicts.
3.1. Overview of inhomogeneous model

We suggest that the supernova atmosphere consists of an ensemble of dense clouds embedded in a rarefied intercloud medium. The inhomogeneous structure is characterized by the volume filling factor $f = NV_c/L^3$, where $N$ is the average cloud number in a volume $L^3$, $V_c$ is the average volume of a cloud. Generally, $f$ is a function of the Lagrangian radius. If a cloud size $l_c$ much larger than the size of a resonance region (or sound radius) $l_c \gg l_s$, the average total area of sections of clouds by a random plane (resonance plane in our case) with the area $\Delta A$ is equal $f \Delta A$ according to the well-known theorem of geometrical probability (Kendal & Moran 1963). With this result, the intensity of the escaping photospheric radiation (neglecting emission component) at the radial velocity $v_z$, i.e., at the frequency $\nu = \nu_0(1 - v_z/c)$ is

$$I_\nu = I_\nu^c[f \exp(-\tau_c) + (1 - f) \exp(-\tau_{ic})],$$

(1)

where $\tau_c$ is the line optical depth of the cloud and $\tau_{ic}$ is the optical depth in the intercloud medium. The expression in square brackets has a meaning of the attenuation factor; it depends on the frequency and the radius. In the limit $l_c \gg l_s$ this factor does not depend on the cloud size. In case of an emission component the effect of clumpiness can be calculated similar to the absorption component.

As we will see below, to reproduce Balmer lines, the inhomogeneity should be invoked only in the outermost layers. We therefore consider the smooth matter distribution ($f = 1$) in the inner envelope zone $v < v_f$ and the clumpy distribution in the outer zone ($v \geq v_f$) assuming a power law for the radial variation

$$f = f_0(v/v_f)^k.$$

(2)

In case of small clouds ($l_c \sim l_s$) the relation (1) is not generally applicable. Using this expression would result in the error which can be estimated by the Monte Carlo (MC) technique. To this end we adopt a random distribution of spherical clouds with a radius $a$ in the envelope with the kinematics $v = r/t$. For $a = 5l_s$ we find that the attenuation factor calculated by MC coincides with the value found from the equation (1). In case of $a = 3l_s$ the analytic formula gives the attenuation factor 8% larger than MC simulation; for $a = l_s$ the difference is 23%. The analytic formula therefore is applicable in a broad range of cloud sizes $l_c > 3l_s$. 
3.2. Modelling results

We start with the constant filling factor \( f = f_0 \) (i.e., \( k = 0 \)) for \( v > v_f \). In this case to sensibly describe Balmer lines in SN 2008in on day 11, the whole atmosphere should be inhomogeneous, \( v_f \approx v_p = 6100 \text{ km s}^{-1} \). The optimal value of the filling factor should be \( f = 0.4 \) to fit the H\( \beta \) (Fig. 2b). Yet the model \( f = \text{const} \) fails to adequately describe simultaneously both the H\( \alpha \) and H\( \beta \) lines (Fig 2). The shown model is transparent in the intercloud medium. Introducing a finite absorption in the intercloud gas worsen the agreement. We conclude therefore that the model with constant filling factor should be abandoned.

Assuming a variable filling factor permits us to easily come to the optimal model describing both Balmer lines (Figs. 2c,d, model D11 in Table). Table contains the velocity at the photosphere derived from H\( \alpha \) and H\( \beta \) [\( v_p(\text{H}\alpha) \) and \( v_p(\text{H}\beta) \)], the velocity at the inner boundary of the inhomogeneous zone (\( v_f \)), the optical depth of clouds (\( \tau_c \)) and intercloud gas (\( \tau_{ic} \)) in the H\( \alpha \) at \( v = v_f \), power law index \( p \) in the \( \tau \propto v^p \) relation, power law index \( q \) in the \( S \propto v^q \) relation, and power law index \( k \) in the equation (2). An interesting point of our results is the relatively weak radial dependence of the population of the hydrogen second level \( n_2 \propto \tau_{23} \propto v^{-5.5} \) compared to total density \( \rho \propto v^{-7.6} \) in the hydrodynamic model of SN 2008in (UC13). A similar remark refers to the flat behavior of the source function \( S_e = \text{const} \). Both facts indicate the enhanced excitation of hydrogen compared to the case when the excitation by the photospheric radiation dominates.

The inhomogeneous zone in our model extends as deep as the photosphere \( v_f \approx v_p = 6100 \text{ km s}^{-1} \). This poses a question, whether the inhomogeneous structure extends to deeper layers. As to the situation on day 11, the density distribution of the SN 2008in hydrodynamic model (UC13) suggests that the mass of the inhomogeneous atmosphere (\( v > 6100 \text{ km s}^{-1} \)) turns out to be \( \approx 0.03 \text{ M}_\odot \). This is only \( \sim 2 \times 10^{-3} \) of the total mass of ejecta (13.6 \text{ M}_\odot). The mass of the inhomogeneous zone is a crucial observational constraint on the mechanism of the inhomogeneities formation in the outer layers of SN IIP.

3.3. Evolution effects

The possible clumpy structure in the inner layers (\( v < 6100 \text{ km s}^{-1} \)) can be studied using the spectrum of SN 2008in on day 18 (Roy et al. 2011) when the photosphere is deeper than on day 11. We thus can check whether the inhomogeneous structure at \( v < 6100 \text{ km s}^{-1} \) is needed in order to describe H\( \alpha \) and H\( \beta \) at this stage. First, however, we answer the question whether the H\( \alpha \)/H\( \beta \) problem retains on day 18 in the homogeneous model.
Unlike previous epoch, the spectrum on day 18 shows rather strong metal lines which could affect hydrogen line profiles. We therefore should calculate the spectrum taking into account metal lines. The list of $\approx 1.9 \times 10^4$ lines in the spectral range 3500-10000 Å for the condition of supergiant with the temperature of 7000 K has been retrieved from the VALD database (Kupka et al. 1999). From this list we select lines in the range of Hα and Hβ with the optical depth $\tau > 0.3$ at the photosphere for the excitation temperature of 7000 K. We assume that in metal lines the radiation is scattered with a finite absorption probability ($\sim 10^{-2}$) taken to be the same for all metal lines. In the Hα and Hβ lines we take into account both scattering and emission. Level populations are not in equilibrium which poses some problem. Fortunately, in the Hα band Si II 6347, 6371 Å doublet dominates, while in the Hβ band Fe II multiplet 42 prevails which facilitates a search for the optimal model. Ion abundances for adopted excitation temperature (7000 K) are adjusted using different correction factors for iron peak elements, Si, and hydrogen.

The modelling shows (Fig. 3) that to reproduce the Hβ line, the hydrogen second level population should be larger by a factor of three than that recovered from the Hα. Remarkably, the similar factor value is needed to reproduce the Hα and Hβ lines on day 11 using the smooth model (UC13). The modelling demonstrates that the problem of the Hα/Hβ disparity retains on day 18 in the model of smooth density distribution. The question left to answer is whether the clumpy model for day 11 is applicable to day 18.

First, however, we comment an interesting fact which was missing formerly in available analysis of SN IIP spectra. The point is that on day 18, unlike the earlier phase, the velocity at the photosphere measured from the Hα and Hβ turns out to be different: 4200 km s$^{-1}$ and 4700 km s$^{-1}$ respectively. At first glance the value derived from the Hβ with a low net emission is more confident than that derived from the Hα. Moreover, Fe II 4924, 5018, 5169 Å lines (multiplet 42) confirm the value found from Hβ (Fig. 3a). On the other hand, the velocity of 4200 km s$^{-1}$ obtained from Hα is consistent with the Si II 6347, 6371 Å doublet (Fig. 3b) which also rules out larger velocity (> 4300 km s$^{-1}$). This fact indicates that the photosphere indeed lies at different levels in the Hα and Hβ bands: it is deeper for the Hα than for the Hβ. We believe that this difference is related to the fact that the contribution of metal lines in the quasi-continuum is larger in the Hβ band compared to the Hα band. The velocity at the photosphere around day 20 in these bands could become a valuable constraint on the model of SN IIP based on the multi-group radiation transfer.

We turn now to the modelling of the Hα and Hβ on day 18 taking into account inhomogeneities in the envelope. The same model of the inhomogeneous structure is used as on day 11. Parameters of the optimal model D18 are given in Table. The calculated profiles for this model fit the observations well enough. In this model the photospheric velocities in the Hα
and Hβ lines are 4100 km s$^{-1}$ and 5300 km s$^{-1}$ respectively which qualitatively agree with the velocities found in the smooth model. Remarkably, parameters of the inhomogeneous structure seem to be the same on days 11 and 18 with the exception that the intercloud optical depth on day 18 is a bit lower, 1.5 instead of 2, which is in line with the excitation decrease demonstrated by the spectra. The fact that parameters of the inhomogeneous structure did not change noticeably means that inhomogeneity scales evolve homologously $l \propto r$ which in turn indicates the early formation of the inhomogeneous structure perhaps at the shock breakout stage.

4. Inhomogeneous structure and flux fluctuations in Hα

The Hα emission in the inhomogeneous model originates from dense clumps. One should expect therefore the presence of flux fluctuations in the emission component. The detection of these fluctuations could become a test for the inhomogeneous structure. A rough estimate of the fluctuation amplitude can be obtained assuming the Poisson distribution of clouds. In this case the amplitude of the flux fluctuations in the range of radial velocities $\Delta v$ is equal $\Delta F/F \sim N^{-1/2}$, where $N$ is the number of clouds that contribute to the line radiation flux $F$ in this velocity range

$$N \approx (3/4)f(v_p t/a)^2(\Delta vt/a). \quad (3)$$

Here $f$ is the volume filling factor of clouds, $a$ is the average cloud radius, $v_p$ is the velocity at the photosphere. In the observed spectrum on day 11 the amplitude of flux fluctuations in the Hα profile is approximately $\Delta F/F \sim 1\%$. The number of clouds in the layer with the width corresponding to the spectral resolution $\Delta v \approx 300$ km s$^{-1}$ should be thus $N \approx 10^4$. With this value the equation (3) results in the cloud radius $a \sim 60$ km s$^{-1}$ assuming $f \sim 0.3$ and $v_p = 6100$ km s$^{-1}$. The characteristic size of inhomogeneities is thus $\sim 2a \sim 10^2$ km s$^{-1}$, if the fluctuations are actually related to the inhomogeneous structure.

The Poisson distribution however overestimates the fluctuation amplitude because it admits the cloud overlapping. This hardly occurs in reality since the inhomogeneities usually form in the process of fragmentation which basically suggests divergent flows. In order to avoid overlapping, we use the hard sphere model for the clouds; a similar model was assumed for the analysis of fluctuations in the [O I] 6300 Å doublet in SN 1987A (Chugai 1994). The cloud distribution is realised in several steps. First we place a sphere of a radius $a$ randomly in a cubic cell of the size $b = a(4\pi/3f)^{1/3}$ with the filling factor $f$ being the function of velocity $f(v) \propto v^{-2}$. Cubic cells are placed in a spherical layer of a radius $r$ and the thickness of $b$ in the following way. The cells are placed one by one in a ring element $2\pi r^2 b \sin \theta d\theta$ (where $\theta$ is the polar angle measured from $z$-axis which directed along the line of sight).
In each other ring the initial random shift was introduced. Each filled spherical layer is rotated on the random angle around \(y\)-axis which lies in the sky plane. The overall result is a random angular distribution of non-overlapping spherical clouds in the envelope. In the radial distribution the randomness presents only in the radial position of a sphere in each cell. The lack of a full chaos along the radius does not affect the result because we are interested only in a one-dimensional projection of the three-dimensional velocity space on the \(z\)-axis in a narrow interval around zero radial velocity (\(|v_z| < v_p\)). In this case the flux fluctuations in the H\(\alpha\) are not sensitive to the radial distribution of clouds.

With the obtained random distribution of spherical clouds in the supernova envelope we performed a set of computations for the velocity of 6100 km s\(^{-1}\) at the photosphere adopting the behavior of the source function and optical depth in clouds according to those found on day 11. The derived line profile is convolved with the Gaussian adopting the full width at half maximum of 300 km s\(^{-1}\) to allow for the spectral resolution. We show in Fig. 5a the calculated residual spectrum \(\Delta F/F = F/F_{sm} - 1\) (where \(F_{sm}\) is heavily smoothed version of \(F\)) for two cases \(a = 100\) km s\(^{-1}\) and \(a = 250\) km s\(^{-1}\). The comparison of these residuals with that for the observed spectrum of SN 2008in on day 11 (Fig. 5b) permits us to constrain the scale of inhomogeneities. It is obvious that the inhomogeneities substantially larger than \(2a \sim 200\) km s\(^{-1}\) (e.g., 500 km s\(^{-1}\)) are ruled out because they predict too large fluctuations. The data do not rule out the cloud scales of \(\sim 200\) km s\(^{-1}\). Note that the observed fluctuations include not only fluctuations related to inhomogeneities but also other noise sources (e.g., photon noise, background noise, and device noise). The expected fluctuations related to the envelope inhomogeneous structure therefore are lower than 1%. This suggests that an inhomogeneity scale should not exceed 200 km s\(^{-1}\).

The model of spherical clouds is an oversimplification of the reality. It may well be that a significant fraction of inhomogeneities forms due to the corrugation of the shock front and subsequent shock focusing on density perturbations. In that case one expects the creation of inhomogeneities with a filamentary geometry. Such inhomogeneities should be characterized by two essentially different scales. The inhomogeneities with the filamentary structure could be generated also by Richtmyer-Meshkov, Rayleigh-Taylor, and Kelvin-Helmholtz instabilities which can develop during the shock propagation in the medium with the density inversion and density perturbations in the RSG atmosphere. The issue of the flux fluctuations in the H\(\alpha\) profile thus may turn out to be a more complicated than in our simple model. Particularly, the filamentary structure could result in a second scale related to the filament length in the fluctuation spectrum.
5. Discussion

The paper has been aimed at the study of the disparity between the H\(\alpha\) and H\(\beta\) in early spectra of SN 2008in. The point is that in a standard model with a smooth density distribution the density required to reproduce the H\(\beta\) line is by a factor of three larger than that required for H\(\alpha\). We find that this problem arises not only on day 11 but on day 18 as well. Assuming inhomogeneous (clumpy) density distribution in the outer layer of the supernova envelope, we are able to describe H\(\alpha\) and H\(\beta\) profiles using the same model on days 11 and 18. This suggests homologous evolution of clumpy structure, which is expected, if inhomogeneities form at the early expansion phase.

The hydrodynamic model of SN 2008in permits us to estimate the mass of the external clumpy zone \((v \geq 6100 \text{ km s}^{-1})\) which turns out to be \(\approx 0.03 \, M_\odot\), i.e., only 0.2% of the ejecta mass. Confronting the flux fluctuations in the model H\(\alpha\) profile against the observed fluctuations on day 11 \((\leq 1\%)\) suggests the upper limit of the inhomogeneities size to be \(\sim 200 \text{ km s}^{-1}\). This value should be closely related to a process responsible for the formation of the inhomogeneous structure. In order to detect the fluctuations related to the inhomogeneities, the spectra in the H\(\alpha\) band should be obtained with the signal-to-noise ratio of \(\approx 200\) and the spectral resolution of \(\approx 100 \text{ km s}^{-1}\).

We suggest that the formation of the inhomogeneous structure is related to specific conditions of the shock propagation in the RSG external layers with a mass of \((\text{several}) \times 10^{-2} \, M_\odot\). It is remarkable, in this respect, that RSGs are known to have a density inversion at the outer boundary of convective zone (Maeder 1992; Chiavassa et al. 2011). The depth of the density inversion in RSGs with masses of 10...20 \(M_\odot\) corresponds to 0.003...0.1 \(M_\odot\) of external mass (Fadeev 2013, private communication). It is noteworthy that the mass of heterogeneous layers of SN 2008in \((\sim 0.03 \, M_\odot)\) falls into that range. The propagation of the radiation-dominated shock across the density inversion should be accompanied by the formation of a thin swept-up shell and its subsequent fragmentation.

Another mechanism for the inhomogeneous structure could be related to density perturbations produced by a vigorous convection. In the RSG outer layers the velocity of convective flow is comparable with the sound speed \(v \sim c_s\) (Maeder 1992). Since the density perturbations are of the order of \(\Delta \rho/\rho \sim (v/c_s)^2\) (Landau & Lifshitz 1987), the expected perturbations can be as large as \(\Delta \rho/\rho \sim 1\). The shock propagation in the medium with that strong density perturbations should result in the formation of inhomogeneities with the large density contrast. Laboratory experiments on the shock propagation in a turbulent medium demonstrate a significant increase of amount of inhomogeneities with the increase of the Mach number (Hesselink & Sturtevant 1988). Disregarding the H\(\alpha\)/H\(\beta\) problem, it is little doubt that the inhomogeneous structure of the outer layers of SN IIP should emerge...
anyway due to the shock wave propagation in the convective zone of the RSG. Moreover, inhomogeneities can be generated additionally by the shock interaction with the RSG density inversion layer.

An interesting outcome of the inhomogeneous structure of the external layers could be a modification (compared to the homogeneous case) of the initial radiation outburst of SN IIP related to the shock breakout. Indeed, the radiation diffusion time depends on the characteristics of inhomogeneities in addition to absorption and scattering coefficients. This issue is of significant importance in view of the search for the initial ultraviolet radiation outburst from core-collapse SNe at the high redshift.

Another interesting consequence of the inhomogeneous structure of outer layers of SN IIP concerns the circumstellar interaction. The ejecta inhomogeneities could modify a standard picture of the direct and reverse shock. Instead of a spherical reverse shock a complicated system of the intercloud reverse shock and slow cloud shock should emerge. Moreover, the structure of the direct shock may be modified by protrusions created by dense ejecta clumps. All these features could affect the properties of radio, X-ray, and optical radiation of SN IIP (and possibly SN IIL) related to the circumstellar interaction.

To what extent the H\textalpha/H\beta problem is ubiquitous for SN IIP? In case of SN 2006bp (type IIP), for which a good set of spectra has been obtained at the early epoch (Quimby at al. 2007), the synthetic spectra that describe the H\beta at 8-16 days predict too deep H\alpha absorption compared to observations (cf. Dessart et al. 2008). The early spectra of SN 2006bp and SN 2008in look similar: the H\beta absorption is strong whereas the H\alpha absorption is absent. A similar picture is seen in early spectra of other normal SN IIP, particularly, SN 1999em (Leonard et al. 2002) and SN 2012A (Tomasella et al. 2013). Remarkably, the modelling of the spectrum of SN 1993J (type IIb) on day 10 with the PHOENIX code (Baron et al. 1995) shows the same problem: the strong model H\alpha absorption for the sensibly fitted H\beta absorption (Fig. 5 in the referred paper). It should be noted that the SN 1993J pre-SN was a yellow supergiant (Aldering & Humphreys 1994). On the other hand, for SN 1987A, in which case the pre-SN was a blue supergiant, the disparity between H\alpha and H\beta is absent (UC13). This fact supports our conjecture that the H\alpha/H\beta problem arises only in the case of explosions of red (yellow) supergiants and not blue supergiants.

6. Conclusions

We demonstrate that the problem of the H\alpha/H\beta disparity takes place in early spectra of SN 2008in both on day 11 and day 18. It is shown that the problem can be solved in
terms of the clumpy density structure in the outer SN layers with a mass of $\sim 0.03 \, M_\odot$. The clumpy structure of the outer layers of supernova is suggested to be an outcome of the density perturbation in the RSG external convective zone combined with the density inversion. The shock propagation in this medium presumably generates inhomogeneities in SN ejecta with a high density contrast.

Tests are proposed for the verification of the clumpy density distribution of outer layers of SN IIP. The first is based on the detection of the flux fluctuations in the early H$\alpha$ line profile at the level of $\leq 1\%$. The second, indirect, test suggests the analysis of the properties of the initial radiation outburst related to the shock breakout.

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Table 1: Clumpy models on days 11 and 18

| Model | $v_p(\text{H}\alpha)$ | $v_p(\text{H}\beta)$ | $v_f$ | $\tau_c$ | $\tau_{ic}$ | $p$ | $q$ | $f_0$ | $k$ |
|-------|------------------|------------------|------|--------|--------|----|----|------|----|
| D11   | 6100             | 6100             | 6100 | 100    | 2      | -5.5| 0  | 0.55 | -2 |
| D18   | 4100             | 5300             | 6100 | 100    | 1.5    | -5.5| 0  | 0.55 | -2 |
Fig. 1.— H$\alpha$ and H$\beta$ lines in SN 2008in spectrum on day 11 (thin line) compared to models of the spherical smooth supernova atmosphere. Panel a is the case with parameters adjusted to fit H$\alpha$; panel b is the model H$\beta$ for the same population of the hydrogen second level as for H$\alpha$ without net emission (lower line) and with the net emission (upper line); panel c is the model H$\alpha$ for the second level population adjusted for the H$\beta$ (panel d). The plots demonstrate the obvious disparity between H$\alpha$ and H$\beta$ in the model of the spherical smooth ejecta.
Fig. 2.— The same as in Fig. 1 but with the models of clumpy envelope. Panels a and b show the model with a constant filling factor in the atmosphere. This model fails to describe simultaneously the Hα and Hβ lines. Panels c and d present the model with the filing factor decreasing outward. The model successfully reproduces both lines.
Fig. 3.— H\(\beta\) (panel a) and H\(\alpha\) (panel b) bands in the SN 2008in spectrum (thin line) on day 18 compared to the model of smooth atmosphere in which the metal lines are taken into account. Shown also are the positions of strongest Fe II lines (multiplet 42) and Si II doublet which contribute to the H\(\beta\) and H\(\alpha\) bands respectively. Note, in the H\(\beta\) model population of the second level is three times larger than that for the H\(\alpha\) model. This demonstrates that the disparity between the H\(\alpha\) and H\(\beta\) exists on day 18 as well.
Fig. 4.— Hα and Hβ in the SN 2008in spectrum on day 18 (thin line) compared to the clumpy model that was applied on day 11. The successful description of both lines indicates that between day 11 and 18 the clumpy structure evolves homologously.
Fig. 5.— Residual spectrum of Hα in the model of cloudy envelope (panel a) for cloud radius of 100 km s$^{-1}$ (thick line) and 250 km s$^{-1}$ (thin line) on day 11. Panel b is the residual spectrum in the same band for the observed Hα line on day 11. The residual spectrum is the spectrum divided on the heavily smoothed spectrum with the subsequent subtraction of unity.