First day of type IIP supernova SN 2013fs: Hα from preshock accelerated gas

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Keywords: stars - supernovae - SN 2013fs

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Abstract

I explore the origin of an asymmetry of the Hα emission from a circumstellar (CS) shell around type IIP supernova SN 2013fs in the spectrum taken 10.3 h after the shock breakout. A spherical model of the Hα emission from the CS shell that takes into account a preshock gas acceleration by a supernova radiation permits us to successfully reproduce the Hα profile. Principal factors responsible for the Hα asymmetry are the high velocity of the accelerated CS preshock gas (∼3000 km s⁻¹) and a low Hα Sobolev optical depth in a combination with an occultation of the Hα emission by the photosphere.

1. Introduction

Type IIP supernova (SN IIP) prior to the explosion has a red supergiant (RSG) structure and loses its material via the slow wind (10-30 km s⁻¹). The supernova deceleration in the wind brings about radio and X-ray emission (Chevalier 1982) thus permitting us to infer the wind density parameter \( w = \dot{M}/u \sim 10^{14} - 10^{15} \text{ g cm}^{-1} \) (Chevalier et al. 2006). Optical emission lines from the wind of that density are too weak for their detection. Particularly, the expected recombination Hα luminosity of the RSG wind is \( \approx 4.8\cdot10^{37}w_{15}^2/(v_9t_d) \text{ erg s}^{-1} \), where \( v_9 \) is the maximal velocity of the undisturbed supernova envelope in units of \( 10^9 \text{ cm s}^{-1} \), \( t_d \) is the supernova age in days, \( w_{15} \) is in units of \( 10^{15} \text{ g cm}^{-1} \). Such a wind suggests the Hα luminosity \( \sim 5\cdot10^{35-37} \text{ erg s}^{-1} \) and the Thomson optical depth \( \tau_T \sim (0.03 - 0.3)/t_d \).

Meanwhile, spectra of some SNe IIP taken during first couple days after the explosion show rather strong emission lines with narrow core and broad wings (Groh 2014, Khazov et al. 2016, Yaron et al. 2017). These lines indicate that the radiation of the circumstellar shell experiences multiple Thomson scattering implying shell optical depth in the range of 2-3 (Groh 2014, Chugai 2001). Of special interest is well studied SN 2013fs (Yaron et al. 2017) with a set of spectra taken starting with 6 h after the shock breakout. The luminosity
of Hα on 1.4 day from the CS shell is of $1.9 \cdot 10^{39}$ erg s$^{-1}$, far above the expected luminosity from RSG wind. Observational data suggest that preSN in that case has a dense CS shell with the radius of $<10^{15}$ cm and mass of (several)$\times 10^{-3} M_\odot$ (Yaron et al. 2013).

The origin of a confined dense shell around SNe IIP is not fully understood. The shell might originate due to the enhanced mass loss during several years prior to the explosion. Alternatively, this shell could be a buffer zone between the RSG atmosphere and the wind likewise the shell around Betelgeuse (Dessart et al. 2017). The latter extends up to $\sim 2 \cdot 10^{15}$ cm and has aspherical clumpy structure (Kervella et al. 2011). Its dynamical equilibrium is maintained presumably by the RSG pulsations or/and vigorous convection (Kervella et al. 2011). This picture is supported by CO observations that see upward and downward motions with velocities in the range 10–30 km s$^{-1}$ (Ohnaka et al. 2011).

The study of confined dense shell of SNe IIP is crucial for the understanding its origin, and particularly for the issue, to what extent the dense shell in SN IIP is of the same nature as the shell of Betelgeuse. In this regard it has not escaped my attention the fact that the SN 2013fs spectrum taken on Keck/LRIS at 10.3 hours after the shock breakout shows a pronounced asymmetry in Hα (Yaron et al. 2017) that is not explained by the spectral model. A hint at similar asymmetry is seen in previous four Keck spectra but in the last spectrum of the set the asymmetry is most apparent, which is emphasised by the Gaussian decomposition (Yaron et al. 2017, Supplement Fig. 2). It is noteworthy that in the descried model (Yaron et al. 2017) Hα forms in the CS shell with the constant expansion velocity of 100 km s$^{-1}$ that is some approximation since a significant preshock acceleration probably takes place at this early phase.

The present paper addresses the issue of the Hα asymmetry in the early SN 2013fs spectrum hopefully to understand, whether this asymmetry could originate in a spherically symmetric CS shell or may be it is related to the asphericity of the CS shell. As will be shown, the Hα asymmetry is not caused by the shell asymmetry, instead it arises naturally in the spherical case.
The study is based on the SN 2013fs spectrum taken by Keck-I/LRIS 10.3 hours after the shock breakout (Yaron et al. 2017). The spectrum is retrieved from the database WISeREP (Yaron & Gal-Yam 2012) (https://wiserep.weizmann.ac.il).

2. Modelling Hα

2.1. Model overview

Radiative cooling of the shock wave following the shock breakout favours the formation of a thin dense shell which serves as the photosphere for several days in the case of SN 2013fs (Chugai 2020). It should be emphasised that the photosphere is defined as the level at which the effective optical depth is unity. The CS shell even in the case of the Thomson optical depth of $\tau_T \approx 2$ is effectively thin, i.e., $\tau_T[k_a/(k_a + k_T)]^{1/2} \ll 1$, where $k_a$ and $k_T$ are coefficients of the absorption and Thomson scattering respectively. The kinetic temperature in the CS shell is assumed to be equal to the photosphere temperature 25000 K with the photospheric radius of $R_1 = 10^{14}$ cm at $t = 10.3$ h (Yaron et al. 2017). The outer radius of the CS shell is adopted to be $R_2 = 5 \cdot 10^{14}$ cm (Yaron et al. 2017). Following the model of early SN 1998S (Chugai 2001) we adopt that the spherical photosphere of the radius $R_1$ with sharp boundary is imbedded into an ionized CS gas distributed in the range of $R_1 < r < R_2$. The density distribution is assumed to be homogeneous in the range of in accord with the previous model (Chugai 2020).

A powerful initial luminosity accelerates the CS gas, which results in the formation before the outer shock of the velocity distribution with the negative velocity gradient. Basically, the kinematics of the accelerated CS gas should be computed by the supernova explosion model (e.g., Dessart et al. 2017). However we use here a convenient description

$$v = (v_1 - v_2)[(R_2 - r)/(R_2 - R_1)]^q + v_2,$$

where $v_1$ is the gas velocity before the shock wave at $r = R_1$ and $v_2$ is the velocity of the undisturbed wind at $R_2$ taken to be 50 km s$^{-1}$, close to the spectral resolution (60 km s$^{-1}$).
The free parameters are $\tau_T$, $v_1$, $q$, and the parameter of the Sobolev optical depth $\tau_0 = (\pi e^2/\text{mc}) f_{23} \lambda_{23} n_2 (R_1/v_1)$, where $f_{23}$ and $\lambda_{23}$ are the H$\alpha$ oscillator strength and wavelength, $n_2$ is the population of the second level; the rest of values have usual sense. The Sobolev optical depth at the radius $r$ for a photon with the wave vector $k$, and a direction $\mu = (kv)/(kv)$ is $\tau_S = \tau_0 (v_1/R_1)(r/v)/[1 - \mu(\gamma - 1)]$, where $\gamma = (r/v)(dv/dr)$.

The radiation transfer in the CS shell with Thomson and resonant scatterings is calculated employing the Monte Carlo technique. The model includes also a diffuse reflection from the photosphere. But this effect is small even for high albedo $\omega = 0.5$ since reflected photons scatter in the far blue wing due to the high photosphere velocity of $\sim 26000 \text{ km s}^{-1}$ at this stage (Chugai 2020) and do not affect the profile in the considered range of radial velocities, so we adopt $\omega = 0$.

2.2. Results

The preliminary modelling suggests that the formerly adopted SN 2013fs redshift $v_{rs} = 3554 \text{ km s}^{-1}$ according to the redshift of the host galaxy NGC 7610 ($z = 0.011855$, NED) in fact should be corrected by the additional redshift +140 km s$^{-1}$. The conclusion is supported by the spectrum taken on day 51 (P200/BBSP, Yaron et al. 2017). The latter contains weak narrow emissions of H$\alpha$ and [O III] 5006.843 Å, both showing additional redshift +140 km s$^{-1}$. Below we use the corrected redshift $v_{rs} = 3694 \text{ km s}^{-1}$.

The modelling reveals that for any choice of parameters the agreement with the observed spectrum requires optically thin H$\alpha$. For $\tau_0 > 0.1$ the observed line asymmetry cannot be reproduced. The optimal model (Fig. 1) with parameters $\tau_0 = 0$, $v_1 = 3000 \text{ km s}^{-1}$, $\tau_T = 2$, and $q = 1.7$ successfully describes the H$\alpha$ profile including the asymmetry that is most apparent in Fig. 1b. Parameter uncertainties are $\pm 0.3$ for $\tau_T$, $\pm 0.1$ for $q$, and $\pm 500 \text{ km s}^{-1}$ for $v_1$.

The effect of the low H$\alpha$ optical depth of $\tau_0 = 0.2$ for the unchanged other parameters is shown in Fig. 2a. In this case the model shows the pronounced absorption and the
asymmetry of the opposite sense with the red wing stronger than the blue one. This is a convincing demonstration that the Hα indeed should be optically thin. The model with the preshock velocity $v_1 = 1000 \text{ km s}^{-1}$ (Fig. 2b) demonstrates the significance of the preshock velocity. In this case the asymmetry almost fully disappears, which suggests that the model with the higher preshock velocity is preferred.

The conclusion on the small Hα optical depth can be compared to the computation of the hydrogen ionization and excitation of the second level. The two-level ($n = 1$ and $n = 2$) plus continuum approximation is used with all the relevant radiation and collisional processes taken into account. The stationary kinetic equations are solved for parameters $R_1, R_2, \text{ and } T$ adopted above for the optimal model and electron number density suggested by the Thomson optical depth $\tau_T = 2$. The found solution shows high ionization $x = 0.999$ and low population of the second level that implies the low Sobolev optical depth $\tau_S = 7 \cdot 10^{-4}$ at the level $r = R_1$ in accord with the Hα modelling. A problem is however that the Sobolev optical depth increases outward and at the radius $r = 3.5R_1$ becomes large $\tau_S = 0.1$ in obvious disagreement with the conclusion about transparent Hα. The controversy can be resolved, if one admits that the shell is clumpy with the volume filling factor $f < 0.01$. It should be emphasised that the clumpiness does not affect the Thomson optical depth provided the number of clouds along the shell radius exceeds unity.

It is critical to check whether the radiation is able to accelerate CS gas up to 3000 km s$^{-1}$. A sensible estimate can be provided by the acceleration due to the Thomson scattering and neglecting gas displacement during the acceleration time. The equation of motion results in the velocity at the radius $r$ at the given age $t$

$$v = \frac{k_T E_r}{4\pi r^2 c} = 8.5 \cdot 10^7 E_{r,48} r_{14}^{-2} \text{ cm s}^{-1},$$

(2)

where $k_T = 0.34 \text{ cm}^2 \text{ g}^{-1}$ is the Thomson opacity, $E_{r,48}$ is the integrated luminosity during 10.3h in units of $10^{48} \text{ erg}$, $r_{14}$ is the radius in units of $10^{14} \text{ cm}$, and other values have the usual sense. The SN 2013fs luminosity at $t = 3.6$ after the shock breakout is $L \approx 3 \cdot 10^{44} \text{ erg s}^{-1}$ (Yaron et al. 2017) that implies the radiation energy $E_r \approx 4 \cdot 10^{48} \text{ erg}$.
With this value the equation \(^2\) gives the velocity estimate of \(\sim 3400 \text{ km s}^{-1}\) at the radius of \(10^{14} \text{ cm}\) and the moment of 10.3 h. The preshock velocity in our model 3000 km s\(^{-1}\) thus turns out to be consistent within uncertainties with the expected velocity of the gas accelerated by the radiation.

3. Discussion and Conclusions

The aim of this paper has been to provide an explanation for the H\(\alpha\) asymmetry in the early spectrum of SN 2013fs. We find that the spherical model for the H\(\alpha\) emission in the dense CS shell is able to account for the asymmetry provided special conditions are met. Specifically, apart from the Thomson scattering the model should include the presence of the CS gas accelerated by the radiation. Remarkably, that the recovered preshock velocity of 3000 km s\(^{-1}\) turns out to be in good agreement with the value expected from the radiative acceleration. The additional requirement for the asymmetry is the very low Sobolev optical depth in H\(\alpha\), which takes place in the preshock layers of the CS gas. However the clumpy structure with the low filling factor seems to be needed in outer layers of the CS shell to avoid significant H\(\alpha\) absorption. In this regard it would be of great interest to check whether other SNe IIP with dense confined shells would reveal the H\(\alpha\) absorption component in day-age spectra?

Dessart et al. (2017) computed spectra for the arbitrary SN IIP model at the early stages for different cases of a dense CS envelope with the preshock kinematics produced by the radiation hydrodynamics. The reported model spectra show two cases with the required H\(\alpha\) asymmetry: the model r1w5r at 20 h and the model r1w5h at 11.6 h. However it is not clear whether the employed computational procedure would show the required H\(\alpha\) asymmetry in the model appropriate for SN 2013fs at 10.3 h.

In the case of SN 1998S the model for the early H\(\alpha\) with the narrow core and broad wings takes into account the radiative acceleration of the CS gas with the preshock velocity of 1000 km s\(^{-1}\) (Chugai 2001). However neither the observed line, nor the model profile show the line asymmetry. The reason is that due to the large Thomson optical depth (\(\tau_T = 3.6\))
and the low preshock velocity the Thomson scattering washes out the asymmetry effect in this case.

An interesting coincidence draws our attention. For the density of the CS shell of \( \rho \approx 1.5 \cdot 10^{-14} \text{ g cm}^{-3} \) implied by the optimal model and the velocity of the photosphere of \( v_s = 2.6 \cdot 10^4 \text{ km s}^{-1} \) at 10.3 h (Chugai 2020) the kinetic luminosity of the shock wave is \( L = 2\pi R_1^2 \rho v_s^3 = 1.6 \cdot 10^{43} \text{ erg s}^{-1} \) that coincides with the estimated observational bolometric luminosity at this moment (Yaron et al. 2017). At first glance the outer shock determines the luminosity at this stage. However, for the CS density in the optimal model the cooling time of the postshock gas is several days, so a significant contribution of the forward shock to the supernova luminosity at 10 h is doubtful.

The spherical symmetry of the confined dense shell of SN 2013fs raises a question whether a close analogy between CS shell in SN 2013fs and the shell of Betelgeuse is actually takes place. The point is that the shell around Betelgeuse shows strong asphericity and clumpiness (Kervella et al. 2011). If the latter asymmetry is caused by the asymmetry of the mass loss due to a large scale convection (Kervella et al. 2011) then one should admit that the sphericity of shell around preSN IIP indicates rather the spherical regime of the mass loss by preSN probably due to radial pulsations.
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Рис. 1: Hα в SN 2013fs спектре на 10.3 ч после взрыва шока. Оптимальная модель наложена на наблюдаемый спектр (серый) в большом диапазоне радиальных скоростей (a) и близко к линии центра (b). В последнем случае линейная асимметрия выглядит более очевидной.
Рис. 2: The same as Fig. 1, but Fig. 2a showing the optimal model in which the optical depth parameter of Hα is \( \tau_0 = 0.2 \), and Fig. 2b showing the model with the preshock velocity of \( 1000 \text{ km s}^{-1} \). Both models apparently are inconsistent with the observed spectrum.