Early Bolometric Luminosity of SN 2013fs without Photometry

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Abstract—A novel method is proposed for the reconstruction of the early bolometric light curve for supernovae IIP with the available set of Hα emission spectra on the first day after the shock breakout. The method uses the effect of radiative acceleration of the preshock circumstellar gas that is manifested in broad Hα wings. The efficiency of the method is demonstrated in the case of SN 2013fs for which the spectra were taken between 6 and 10 h after the shock breakout. An important feature of this method is that it does not require any photometry, distance, and extinction.

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1. INTRODUCTION

A type IIP supernova (SN IIP) results from the explosion of a red supergiant (RSG) caused by core collapse. After the explosion, the SN ejecta expand in the environment created by the presupernova mass loss. The RSG wind has a moderate density parameter \( \dot{M}/u \sim 10^{14} - 10^{15} \text{ g cm}^{-1} \) that follows from the radio and X-ray emission of SNe IIP (Chevalier et al. 2006). The expected optical emission lines, in particular, Hα, from a wind with such a density are too weak to be detected. Yet the spectra for several SNe IIP show strong narrow emission lines from a confined ionized dense circumstellar (CS) shell during the first two days (Quimby et al. 2007; Groh et al. 2014; Khazov et al. 2016; Yaron et al. 2017).

The most interesting case is SN 2013fs with spectra starting from 6 h after the shock breakout (Yaron et al. 2017). An analysis of these spectra led the authors to conclude that the early CS emission lines originate from the confined shell \( (r < 10^{15} \text{ cm}) \) with a mass of \( (\text{several}) \times 10^{-3} M_\odot \), an expansion velocity of 50–100 km s\(^{-1}\), and a Thomson optical depth \( \tau_T \sim 1-2 \) (Yaron et al. 2017).

The line profiles in the early spectra of SN 2013fs show a narrow core and broad wings like the emission lines of early SN 1998S, in which case they were attributed to the emission from a dense CS shell with a Thomson optical depth \( \tau_T \sim 3-4 \) (Chugai 2001, Shivvers et al. 2015). However, this interpretation fails for SN 2013fs, because the broad wings observed in Hα are much more intense than those in the Thomson scattering model; furthermore, the blue wing is stronger than the red one, in contrast to the model (Yaron et al. 2017). The contradiction is resolved when the radiative acceleration of the preshock CS gas is taken into account (Chugai 2020a); for Hα at 10.3 h the recovered preshock CS velocity is 3000 km s\(^{-1}\). The broad Hα wings in the early spectra of SN 2013fs are essentially dominated by the emission from the accelerated CS gas and not by the Thomson scattering. Remarkably, in SN 1998S the effect of the radiative acceleration of the circumstellar gas up to 1000 km s\(^{-1}\) is overwhelmed by the Thomson scattering (Chugai 2001). Dessart et al. (2017) investigated numerically the effects of a dense CS shell around SN IIP using radiation hydrodynamics and non-LTE radiation transfer. The models predict a significant acceleration of the CS gas up to >5000 km s\(^{-1}\) during the first two days. However, it is unclear from the presented synthetic spectra in which cases the line wings are dominated by either Thomson scattering or the bulk velocity of the accelerated CS gas.

The proposed explanation of the the early Hα spectrum of SN 2013fs suggests that the preshock velocity inferred from the early Hα can be used to probe the early bolometric luminosity of SN 2013fs that otherwise is poorly determined. Here I propose a new method for reconstructing the early bolometric light curve of SN 2013fs based on an analysis of the preshock velocity extracted from the Hα emission line. To this end, we first determine the velocities of the preshock CS gas from Hα in the Keck-I
spectra between 6 and 10 h after the shock breakout. The velocities found are used then to recover the bolometric luminosity of SN 2013fs within the first 10 h after the shock breakout. This study is based on the spectra of SN 2013fs retrieved from the WISEREP database (Yaron and Gal-Yam 2012) (https://wiserep.weizmann.ac.il).

2. MODEL

The shock breakout of an exploding star with an extended envelope is accompanied with the sweeping of the outmost atmosphere into the dense shell (Grasberg et al. 1971). For the exploding RSG the mass of the thin dense shell is $10^{-4} - 10^{-3} M_\odot$ (Chevalier 1981). The thin shell decelerates in the CS gas that results in the formation of the forward and reverse shock with the thin dense shell in between (Chevalier 1982a; Nadyozhin 1985). The reverse shock is generally radiative, so the shocked cold ejecta are accumulated in the thin dense shell that we dub the cold dense shell (CDS) since its kinetic temperature is lower than the temperature of both shocks.

The size and density of the dense CS shell of SN 2013fs can be recovered from spectral data in the following way. On day 2.42 the spectrum shows the broad He II 4686 Å emission (Bullivant et al. 2018) that is attributed to the fragmented CDS with the expansion velocity of $v_{c_{\text{ds}}} = 16600$ km s$^{-1}$ (Chugai 2020b). Narrow H$\alpha$ associated with the CS shell disappears between the epochs of Keck-II spectra on day 2.1 and 5.1 (Yaron et al. 2017). This means that at about $t \sim 3$ d the CS shell is overtaken by the CDS, which gives us the extension of the CS shell $R_{c_{\text{ds}}} \sim v_{c_{\text{ds}}} t \sim 5 \times 10^{14}$ cm. The H$\alpha$ modeling in the spectrum on 10.3 h implies the Thomson optical depth of the CS shell $\tau_T \sim 2$ (Chugai 2020a). The average electron number density in the CS shell is thus $n_e = \tau_T/(R_{c_{\text{ds}}} \sigma_T) \sim 6 \times 10^9$ cm$^{-3}$ and the density $\rho_0 = 1.2 \times 10^{-14}$ g cm$^{-3}$ assuming hydrogen abundance $X = 0.7$. Below we adopt homogeneous CS shell with the density $\rho_0 = 1.35 \times 10^{-14}$ g cm$^{-3}$ that is by a factor of three higher compared to the model that is aimed at the minimization of the explosion energy of SN 2013fs (Chugai 2020b).

One can apply the hydrodynamics in the thin shell approximation (see Chugai 2020b) to find the CDS dynamics that matches the expansion velocity on day 2.42. The rate of the CDS deceleration is determined by the CS density and the SN ejecta density distribution in outer layers; the latter generally follows the power law $\rho(v) = \rho_1 (v_1/v)^3 (v_1/v)^q$. We adopt $q = 7.6$ in line with the hydrodynamic model of the normal type IIP SN 2008in (Utrobin and Chugai 2013). For the reference values $t_1 = 1$ d, $v_1 = 10^4$ km s$^{-1}$ the CDS expansion satisfies the velocity constrain on day 2.42 (Fig. 1) for $\rho_1 (t_1, v_1) = 3.44 \times 10^{-10}$ g cm$^{-3}$.
At the initial phase of $\sim 1$ day the photosphere of SN 2013fs coincides with the CDS. Indeed, the momentum flux conservation suggests that the CDS density is $\rho_0(v_{cds}/c_s)^2 \sim 6 \times 10^{-9} \text{ g cm}^{-3}$ (Grasberg et al. 1971), where $c_s \approx 37 \text{ km s}^{-1}$ is the isothermal sound speed for the CDS temperature of $T \sim (L/4\pi r^2 \sigma)^{0.25} \sim 3.5 \times 10^4 L_{43}^{0.25}/r_{14}^{0.5} \text{ K}$. For these conditions the Rosseland opacity $k_R \sim 2$ (Badnell et al. 2005). With the CDS mass of $\sim 3 \times 10^{-4} M_\odot$ and the CDS radius at $t = 10 \text{ h}$ of $R_{cds} \sim 10^{14} \text{ cm}$ (Fig. 1) the CDS optical depth turns out to be $\tau = k_R M_{cds}/(4\pi R_{cds}^2) \sim 10$, so the CDS at the considered phase is opaque and the photosphere resides at the CDS.

The overall picture of the H$\alpha$ formation at the stage considered can thus be described as a photosphere (CDS) of radius $R_{cds}$ enclosed by a hot forward shock of radius $R_s \approx \xi R_{cds}$ that is embedded into the ionized confined CS shell $R_s < r < R_{cs}$. Note that the H$\alpha$ model is not sensitive to the parameter $\xi$. We adopt $\xi = 1.2$ that corresponds to the self-similar solution for $q = 7$ and the uniform CS medium (Chevalier 1982). The forward shock

**Fig. 2.** H$\alpha$ emission in the spectra of SN 2013fs. Model H$\alpha$ (thick line) is plotted on the observed spectra (grey) taken at the moments 0.26 (a), 0.3 (b), 0.37 (c), and 0.42 d (d) after the shock breakout. Thin black line shows the models with a constant CS gas velocity of 100 km s$^{-1}$. The overall picture of the H$\alpha$ formation at the stage considered can thus be described as a photosphere (CDS) of radius $R_{cds}$ enclosed by a hot forward shock of radius $R_s \approx \xi R_{cds}$ that is embedded into the ionized confined CS shell $R_s < r < R_{cs}$. Note that the H$\alpha$ model is not sensitive to the parameter $\xi$. We adopt $\xi = 1.2$ that corresponds to the self-similar solution for $q = 7$ and the uniform CS medium (Chevalier 1982). The forward shock
The high number density in the forward shock ($n \sim 3 \times 10^{10} \text{ cm}^{-3}$) implies a fast electron–proton thermal equilibration compared to the expansion time, so the electron temperature is $T_e = 1.6 \times 10^9 \nu_{s,4}^2$, where $\nu_{s,4} = v_s/10^4 \text{ km s}^{-1}$. The radiative cooling time is significantly longer than the expansion time, however the Compton cooling time $t_c = 1.2 \times 10^4 r_{14} L_{43}^{-1}$ s can be comparable to the expansion time; the post-shock electrons can therefore cool by a factor of $\sim 2$. We therefore adopt $T_e = 10^9 \text{ K}$ through the postshock layer. Noteworthy that the $H\alpha$ profile is not sensitive to the variation of the electron temperature even by a factor of ten.

The powerful early SN radiation results in a significant acceleration of the CS gas, with the velocity being maximal just before the shock and decreasing outwards. We describe the velocity distribution of the CS gas at a fixed moment by the expression

$$v(r) = (v_{ps} - v_{cs}) \left( \frac{R_{cs} - r}{R_{cs} - R_s} \right)^s + v_{cs},$$

where $v_{ps}$ is the preshock CS velocity at $r = R_s$ and $v_{cs}$ is the velocity of the undisturbed CS gas at $r = R_{cs}$. The exponent is $s \approx 1.6$ for optimal $H\alpha$ models.

### 3. RESULTS

#### 3.1. CS Gas Velocity

The radiation transfer of $H\alpha$ photons in the CS shell is treated using the Monte Carlo technique. The $H\alpha$ emission is dominated by the recombination mechanism, so the emissivity in the uniform CS envelope is assumed to be constant along the radius. The model radiation transfer takes into account the resonant scattering in $H\alpha$ in the Sobolev approximation. However the previous modeling of the $H\alpha$ at 10.3 h (Chugai 2020a) indicates that the Sobolev optical depth in $H\alpha$ should be negligibly small. This situation reflects strong depopulation of the hydrogen second level due to the high photoionization rate by the SN radiation.

The angle-averaged frequency redistribution function (Mihalas 1978) is applied for the photon scattering on thermal electrons. The $H\alpha$ profile is not sensitive to the exact value of the CS electron temperature since the broadening is dominated by the high velocities of the radiatively accelerated CS gas. Nevertheless the modeling takes into account the evolution of the electron temperature. At the first iteration we use the value $T_e = 4 \times 10^4 \text{ K}$ for all the considered epochs. With this temperature we recover CS velocity from $H\alpha$, the bolometric luminosity and the effective temperature. This temperature is adopted as the electron temperature and these values of $T_e$ are used for the final $H\alpha$ models. The radiation transfer includes a diffuse reflection of photons from the photosphere. However this effect for $H\alpha$ photons is equivalent to zero albedo because reflected photons scatter in the far blue wing due to the high photosphere velocity of $\gtrsim 26000 \text{ km s}^{-1}$ at the considered epoch (Fig. 1).

The optimal $H\alpha$ models are shown for the observed low-resolution (160 km s$^{-1}$) spectra between 6 and 10 h (Fig. 2) with the parameters given in the Table 1. The table columns contain the time after the shock breakout, the CDS radius, the electron temperature of the CS gas, the preshock Thomson optical depth, and the preshock velocity inferred from the $H\alpha$ fit. The bottom line includes the result obtained earlier for the high resolution spectrum at 10.3 h (Chugai 2020a). The uncertainty of the inferred velocity is within 20%. The similar uncertainty refers to the Thomson optical depth recovered from $H\alpha$. The primary indicator of the Thomson optical depth is the profile skewing towards blue that is apparent in all the profiles of Fig. 2. However, $\tau_T$ in Table 1 are taken from the interaction model for consistency; these values are used in the $H\alpha$ model.

The significant role of the radiative acceleration of the CS gas for the $H\alpha$ profile is emphasized by the $H\alpha$ computed without the radiative acceleration effect.
and using the constant velocity of 100 km s\(^{-1}\) for the CS shell (Fig. 2). It is clear that the Thomson scattering exclusively cannot account for the observed H\(\alpha\). This differs SN 2013fs from SN 1998S where the Thomson scattering dominates over the effect of the moderate radiative acceleration of 1000 km s\(^{-1}\) (Chugai 2001).

**3.2. Early Bolometric Luminosity**

Preshock CS velocity \(v_{ps}\) is a direct indicator of the radiation energy \(E_r\) emitted by the supernova between the shock breakout and the observation epoch. The radiative force is dominated by the Thomson scattering for conditions in the CS shell (see Chugai et al. 2002). Neglecting the CS gas displacement the solution of the equation of motion of the CS gas in the SN radiation field results in the preshock velocity

\[
v_{ps} = \frac{k_T E_r}{4\pi R_s^2 c},
\]

where \(k_T = 0.34 \text{ cm}^2 \text{ g}^{-1}\) is the Thomson scattering coefficient, \(c\) is the speed of light.

The inferred \(v_{ps}\) values (Table 1) with Eq. (2) permit us to recover \(E_r\) for the explored moments. We apply two different descriptions of the initial stage of the luminosity decline: the exponential law \(L = L_0 \exp(-t/t_0)\) and the power law \(L = L_0/[1 + (t/t_0)^p]\). In each case parameters are determined by the \(\chi^2\) minimization. For the exponential law \(t_0 = 0.12\) d and \(L_0 = 7.23 \times 10^{44} \text{ erg s}^{-1}\), whereas for the power law \(t_0 = 0.12\) d, \(L_0 = 5.8 \times 10^{44} \text{ erg s}^{-1}\), and \(p = 2.6\) (Fig. 3). Both descriptions for the luminosity coincide within 10%, while the energy radiated during initial 0.5 d in both cases is \(7.4 \times 10^{48} \text{ erg}\). The relative error of \(E_r\) is the same as that of the velocity, i.e., 20%.

The recovered bolometric luminosity is compared (Fig. 3b) to the reported bolometric light curves obtained from the multiband photometry in two ways (Yaron et al. 2017). The first approach suggests the reconstruction of the spectral energy distribution (SED), while the second method is based on the recovered blackbody temperature, photospheric radius, and the blackbody luminosity \(L = 4\pi R^2 \sigma T^4\). These two reported versions differ by a factor of 100 (Fig. 3b) at the first observational epoch that emphasizes the difficulties of the early light curve reconstruction from the photometric data. Amazingly, our light curve is consistent with the blackbody version of the reported light curve despite of radically different methods.

It should be emphasized that the early bolometric light curve of SN 2013fs recovered from the radiative acceleration effect in H\(\alpha\) is not needed in the photometry, the distance, and the extinction. The point is that this method exploits only measurements of the velocities based on spectra expressed in relative fluxes.

**4. CONCLUSIONS**

This study was aimed at reconstructing the early bolometric light curve of SN 2013fs based on the
effect of the radiative acceleration of the CS gas manifested in the width of the Hα emission wings. The proposed method turns out to be successful in the case of SN 2013fs owing to the unique set of Keck-I spectra between 6–10.3 h after the shock breakout. An attractive feature of the novel method is that the early bolometric light curve of SN 2013fs is reconstructed without using any photometry, distance, and extinction.

Some uncertainty might stem from the choice of the function that approximates the luminosity decline after the shock breakout. In fact, this arbitrariness does not affect the result. Two different choices, exponential and a power law, result in bolometric light curves that agree with each other within 10%; moreover, the total radiation emitted within 0.5 day after the shock breakout in both cases is the same. Surprisingly, the recovered bolometric luminosity is close to the luminosity estimated using the blackbody approximation for the moments 0.16, 0.36, and 0.55 d (Yaron et al. 2017). The agreement between the results obtained by two completely different approaches suggests that both methods catch the behavior of the real luminosity of SN 2013fs at the initial stage.

Yet, in contrast to SN 2013fs with a known distance of 47–51 Mpc (NED) and low extinction (Yaron et al. 2017), for more nearby SNe IIP with a less certain distance and significant extinction the systematic errors in the bolometric luminosity recovered from photometry can be large. All three factors of the uncertainty (distance, extinction, and photometric incompleteness) are absent in the new method. The potential significance of the new method for reconstructing the early bolometric luminosity of a future SN IIP in our Galaxy should be emphasized, since, in this case, significant uncertainties in the distance and extinction are possible. Obviously, a successful application of the proposed method requires the observation of a set of spectra within the first day after the explosion.

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