CHIN.PHYS.LETT. Vol. 21, No. 7 (2004) 1398

Optical Evidence for Circumstellar Interaction Around SN 1993J *

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(Received 16 March 2004)

We study the circumstellar interaction around SN 1993J by its intermediate-band light curves obtained by the 60/90 cm Schmidt telescope at Xinglong Station. The optical emission showed a slow decay of 0.05±0.02 mag/100 d in the period from 1995 to 2003, invoking a main energy contribution from SN-circumstellar interaction at late times. The relatively flat power law SN density model fits better with the observations. In particular, the line ratio of [O Ⅲ]$\lambda\lambda$4959, 5007 and Na I D relative to H_α are well reproduced by the model. Moreover, the H_α light curve displayed obvious bump structures at some epochs, which is probably attributed to the density fluctuations in the ambient material that surrounds the reverse shockwave.

PACS: 97. 60. Bw, 98. 38. Mz, 97. 10. Fy, 97. 10. Me

Massive stars undergo mass loss during various evolutionary phases during their lifetimes. When they finally end their lives as supernovae (SNe), the interaction of SN ejecta with surrounding winds from presupernova mass loss creates a fast shock wave in the circumstellar wind and a reverse shock front in the outer supernova gas. The hot gas heated by the shock wave is broadly observed in x-ray wavelength for young supernova remnants. Nevertheless the primary observational evidence for the interaction comes from radio emission. There is also supporting evidence at ultraviolet and infrared wavelengths. However, the reports on the optical evidence for circumstellar interaction seems to be relatively sparse. That situation has changed significantly in the past decade with the improvement of the ability to follow the optical emission from supernovae to late times. Late-time observations of Type II supernovae (SNe Ⅱ) reveal that some SNe Ⅱ halts their luminosity decline, remaining optically detectable for years and even decades after explosion.[1] SNe 1980K and 1987A are two of the best observed old SNe that had optical observations lasting for more than 10 yr.[2] SN 1993J provided us another good opportunity in the study of circumstellar interaction. It occurred in the nearby galaxy M81 and reached a maximum brightness of $M_V = 10.8\,\mathrm{mag}$,[3] which allowed extremely detailed observations over a long time interval. In this Letter, we intend to analyse SN 1993J's late-time emission through intermediate-band photometry and present optical evidence for the circumstellar interaction around SN 1993J.

We kept monitoring SN 1993J roughly once a year since 1995 using the 60/90 cm Schmidt telescope located at Xinglong station of National Astronomical Observatory of China (NAOC). This telescope is equipped with a 2048 × 2048 CCD camera and a photometric system with 15 intermediate-band filters covering 3000 Å to 10000 Å.[4] These filters are designed to avoid contamination from the night sky emission lines. Compared to the broad band photometry, the intermediate-band observations are more sensitive to the variations in optical emission. In particular, because of M81's small heliocentric velocity ($-34\,\mathrm{km}\ s^{-1}$), we found that the intermediate-band filters could map some broad flat-topped emission lines of SN 1993J at late times.[5] Parameters of the filters we are concerned with and the corresponding emission lines they trace are listed in Table 1. The light curves of SN 1993J available in eight intermediate bands are presented in Fig. 1 (for the details of the observations and data reduction see Ref. [5]).

Table 1. Details of the intermediate-band filters and corresponding emission lines they map.

Filter	λ_{eff} (Å)	FWHM (Å)	Emission lines
d	4540	332	[O Ⅲ]λ4363 (red edge)
e	4925	374	[O Ⅲ]λ4959, 5007 + H_β
f	5267	344	···
g	5790	289	Na I$\lambda\lambda$5890, 5896+He Iλ5876
h	6074	308	···
i	6656	491	H_α
j	7057	238	···
k	7546	192	···

It is evident that SN 1993J fades very slowly during the period 1995 to 2003 when the decline rate is only $0.05 \pm 0.02\,\mathrm{mag}/100\,\mathrm{d}$. The slow luminosity decay suggests that there is a persistent energy source powering SN 1993J up to the most recent observations. The possible mechanisms accounting for the late-time emission include the radioactive decay of long-lived isotopes, light echoes and interaction with the CSM. However, the mass of long-lived isotopes ^{44}Ti (half-life ≃60 yr) needed to produce current optical emissions (i.e. i-band emission)

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* Supported by the National Natural Science Foundation of China under Grant Nos 10303002 and 10173003.

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is $3.1 \times 10^{-3}(D_{\rm M81}/3.63\,{\rm Mpc})^2 M_{\odot}$, far greater than that predicted from $13-25M_{\odot}$ models[6] or produced in SN 1987A.[7] The light echo as an important energy source is also disfavored by the fact that the observed flux from the light echoes around SN 1993J is $\sim 4.3\times10^{-18}$ erg cm^{-2} s^{-1} Å^{-1} in year 2001,[8] versus a corresponding flux 7.9×10^{-17} erg cm^{-2} s^{-1} Å^{-1} measured in i-band, or about 5.4% at nearly the same epoch. It therefore points to SN/CSM interaction which lightened SN 1993J at late times. The stronger fluxes shown in the i-, e-, g-bands can be identified with H_α, [O Ⅲ]$\lambda\lambda$4959, 5007 + H_β and Na I$\lambda\lambda$5890, 5896+He Iλ5876 line emissions in the spectra, respectively. Moreover, the emission in the d-band can be partially attributed to [O Ⅲ]λ4363 line. These emission lines at optical wavelengths provide direct evidence for the circumstellar interaction. Moreover, the fact that all late-time optically detectable SNe exhibits that strong radio emission is also consistent with the idea that the main late-time energy source is the interaction of the expanding SN ejecta with slowly moving circumstellar wind.[9]

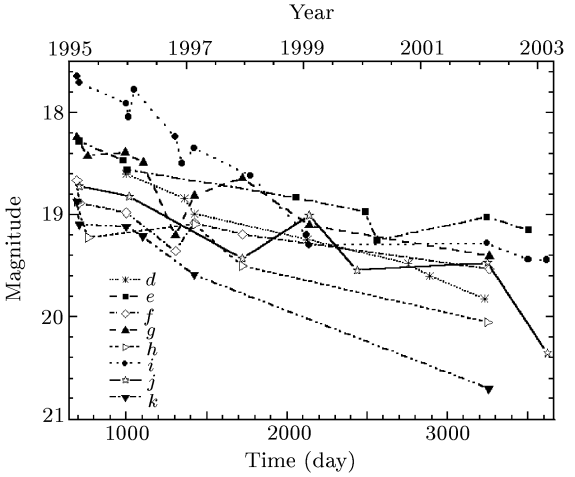

Fig. 1. Light curves of SN1993J in eight intermediate bands versus days since the explosion.

Circumstellar interaction depends primarily on the density profile of the freely expanding supernova ejecta, which, in turn, depends on the structure of the progenitor star and the shock acceleration of the gas during the explosion according to Chavelier and Fransson (1994)[10] (hereafter CF94). Two different models have been considered for the structure of the ejecta. One is a power law, most applicable to the explosion of compact progenitor, while the other uses the density structure of a red supergiant (RSG) which displays a sharp drop at outer layers (e.g. at $\sim$7000 km s^{-1}). The difference in the density profile usually leads to different temperature of reverse shock and therefore different emitted spectrum. Both the evolution of the emission lines and their intensity ratios are important diagnostics of the ejecta structure. Thus we could make some constraints on the progenitor star by comparing the observations with the models.

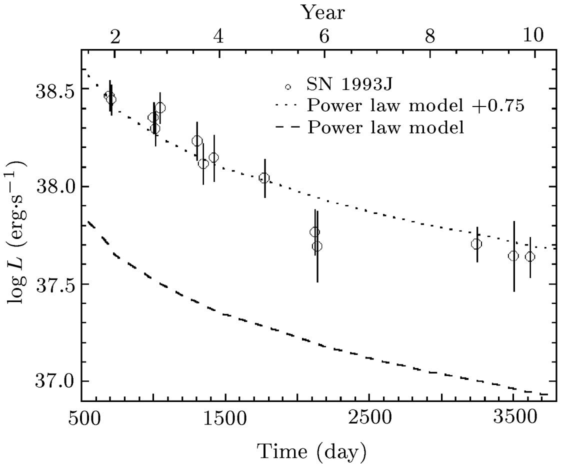

Fig. 2. The i-band light curve showing the evolution of the H_α luminosity (filled circles). The dashed curve represents the predicted H_α luminosity from the power law SN density model of CF94, while the dotted curve is added by a constant of 0.75.

Figure 2 shows the evolution of SN 1993J's H_α luminosity implied from the i-band light curve in the period 1995–2003. The H_α luminosity decreased by less than 7 times over eight years since 1995. Such a slow late-time decline of the H_α emission is consistent well with the trend of a decreasing luminosity predicted by the power-law model as a result of the decline of the ionizing luminosity as well as decrease of density. The current H_α luminosity ($\sim$10 yr after explosion) is estimated to be about 4.0×10^{37} erg s^{-1} by assuming a distance of 3.63 ± 0.31 Mpc and a reddening of $E(B-V) = 0.18$ mag toward SN 1993J.[11] This absolute value is higher than the power-law model prediction but seems to be in agreement with the value predicted by the red supergiant (RSG) model. Nevertheless, it must be noted that the calculated line luminosities depend sensitively on the adopted mass-loss rate of the progenitor star.[10]

Relative line strength may provide more reliable diagnostic of the ejecta structure, which is almost independent of the distances and reddening. It is apparently difficult to estimate the strengths of [O Ⅲ]λ4959, 5007 and Na I D independently because of the line blend. Nonetheless the detailed analysis of the latter spectra reveals that the contribution of H_β to the [O Ⅲ]+H_β blend is about 10–30% while the He I λ5876 and Na I $\lambda\lambda$5890, 5896 contribute approximately equally to the broad emission feature around 5800 Å.[12] Figure 3 shows the evolution of the line ratios [O Ⅲ]/H_α and Na I/H_α. Although the larger uncertainties involved with the photometry, the measured strength of both [O Ⅲ]$\lambda\lambda$ 4959, 5007 and Na I D relative to the H_α does increase, such as the general trend in the models. The [O III]/H_α ratio shows an interesting evolution with time. Initially, the [O III] optical emissions are weaker. Because the [O III] emission arises principally from heated SN ejecta, strong ejecta clumping could significantly weaken this emission through collisional deexcitation ($n_{\rm crit}$[O III] $= 10^6\,{\rm cm}^{-3}$). As the density decreases, they become important coolants of the ionized ejecta, and after an age of 10 yr, they dominate the optical spectrum (see the light-curve tails of Fig. 1). To facilitate a direct comparison, we give the observed line luminosities at 9–10 yr and corresponding predicted values from both power-law and RSG models at 10 yr in Table 2. Both the strengths of [O III]$\lambda\lambda$4959, 5007 and Na I D relative to H_α are weaker than those predicted, but closer to the calculated values by the power law model. A smaller ratio is probably due to a flatter density profile of the ejecta or smaller value of the reverse shock velocity. Notably, the RSG density model has a much larger [O III]/H_α ratio (16.66 vs 1.65) and a much lower Na I/H_α ratio (0.17 vs 0.73) than observations. Therefore, the power-law photoionization model gives better agreement with the observed late-time optical emission of SN 1993J. The optical spectroscopic observations of SN 1993J during its first 2500 d tend to give the same conclusion.[12]

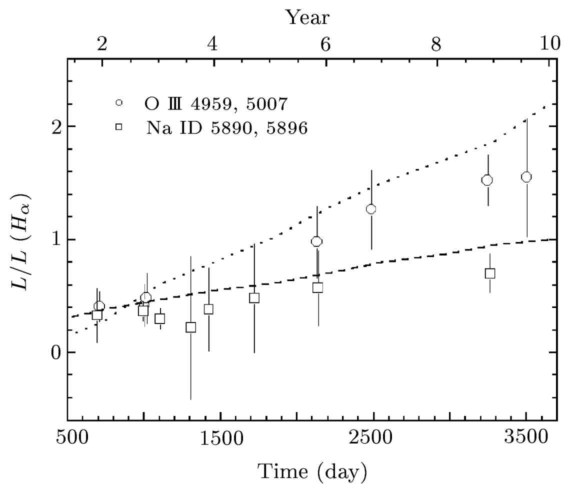

Fig. 3. Evolution of the observed line strength of [O III]$\lambda\lambda$4959–5007 (filled circles) and Na I D (filled squares) relative to H_α. The lines represent the predicted [O III]/H_α (dotted lines) and Na I/H_α (dashed lines) for $n = 8$ power-law model.

The [O III] lines may be able to constrain further the density. The $\lambda\lambda$4959, 5007 lines are contaminated by H_β, i.e. ∼20–30% from years 2–6, but probably less than 10% thereafter. Moreover, the fluxes shown in the d-band probably indicate of less than half of the total line emission by [O III]λ4363 according to the transmission of the Filter.[13] Considering the above effects, the [O III]($\lambda\lambda$4959, 5007/λ4363) ratio is ~ 1 at days 1000. To obtain [O III]($\lambda\lambda$4959, 5007/λ4363) as low as 1, the temperature must be at least 10000 K. The electron density under these conditions would be $n_e \gtrsim 10^8\,{\rm cm}^{-3}$. By day 3245, the ratio is ~ 2.1, implying a density of $n_e \approx 10^7\,{\rm cm}^{-3}$. At higher temperature, the required density drops. No matter what the temperature is, the increase of the [O III]$\lambda\lambda$4959, 5007 to λ4363 ratio with time implies a decreasing density, as one would expect in the expanding ejecta.

Table 2. Comparison of SN 1993J line strengths with circumstellar model predictions.

Line	I (2002/2003)	Power Law	RSG
$H_\alpha^{\rm a}$	4.0	0.91	4.86
[O III]λ4959–5007$^{\rm b}$	1.65	2.05	16.60
Na I D$^{\rm b}$	0.73	1.00	0.17

$^{\rm a}$ Luminosities in 10^{37} erg s^{-1}.
$^{\rm b}$ Line strengths relative to H_α.

Closer inspection of Fig. 1 reveals bump structures in the light curves. Photometric errors may be one of the culprits for the jounce, but it cannot explain the repetitive bumps seen in the i-band (H_α) light curve which has a typical uncertainty $\lesssim 0.1$ mag. The H_α light curve shows a rapid decline between day 1000 and 1016, followed by a rapid increase at day 1049. A similar behaviour could have occurred between day 1049 and day 1422, which is also obviously seen in the f- and g-bands. The rapid decline after day 1773 is evident (see Figs. 1 and 2), but the recovery time is uncertain for the lack of data between day 2126 and day 3245. The existence of the latter two dips are evidenced by the x-ray observations in which the light curve shows rapid decline and recovery at about the same epochs.[14]

The variations in the optical and x-ray light curves probably indicate deviations from a power law in the local density profiles of the CSM. For instance, a local increase in the density will cause an increase of the flux density, and vice versa. We suggest that each of the dips seen in the H_α light curve may be attributed to a density depression which is followed by a rise in density. If the shock wave runs into a lower density regime, few matter will be shocked and heated, the matter heated so far will simply expand. Thus the x-ray luminosity from the shock and the strength of x-ray photoionized emission lines (e.g. H_α) will decline rapidly ($\propto t^{-2}$) for isothermal expansion. After some time the shock wave encounters a jump in the density to significantly higher values. The density increase raises the x-ray luminosity and the optical emissions.

The notion that the density fluctuations account for the change in the light curve also obtains the support from the radio observations. The expansion rate of the radio images revealed that the shock wave underwent several discontinuous decelerations.[15] The epoch when the deceleration occurred agrees well with the density jump time given by the x-ray model.[14] Whether the density fluctuations in the ambient matter characterizes a change in the wind parameters of the progenitors or an asymmetry caused by a possible binary scenario needs to be further pursued.

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