Circumstellar Na I and Ca II Lines in Type IIP Supernovae and SN 1998S

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Received April 1, 2008

Abstract—We investigate the possibility of detecting the circumstellar Na I D₁,₂ and Ca II H, K absorption lines in the spectra of type IIP supernovae at the photospheric phase. Our modeling shows that the Na I doublet lines will not be seen in the spectra of type IIP supernovae at moderate stellar wind densities, for example, characteristic of SN 1999em, while the rather intense Ca II lines with P Cyg profiles should be detectable. The same model is used to describe the circumstellar Na I and Ca II lines in the spectrum of SN 1998S, a type IIL supernova with a dense wind. We show that the circumstellar line intensities in this supernova are reproduced only if there is an ultraviolet excess that is mainly attributable to the Comptonization of supernova radiation in the shock wave.

PACS numbers: 97.60.Bw
DOI: 10.1134/S1063773708090028

Key words: supernovae and supernova remnants.

INTRODUCTION

Type IIP supernovae (SN IIP) originate from stars with initial masses in the range 9–25 M⊙ (Heger et al. 2003). Immediately before the explosion, a pre-SN IIP has the structure of a red supergiant (RSG) (Grasberg et al. 1971) that presumably loses its matter in the form of a slow dense wind. It would be natural to assume that the mass loss rate by pre-SN IIP should correspond to RSGs with initial masses characteristic of SN IIP, i.e., ∼(1–10) × 10⁻⁶ M⊙ yr⁻¹ (Chevalier et al. 2006). However, it is by no means clear whether this is actually the case. It is believed that massive (10–20 M⊙) RSGs lose their matter in the form of a superwind with a rate of ∼10⁻⁴ M⊙ yr⁻¹ due to pulsational instability within 10⁴ yr before their collapse (Heger et al. 1997). On the other hand, for (type IIP) SN 1999em with a known pre-SN mass, ∼20 M⊙, the mass loss rate estimated from X-ray and optical data is only M ∼ 10⁻⁶ M⊙ yr⁻¹ (Chugai et al. 2007), i.e., it is lower than not only the pulsational mass loss, but also the value of ∼8 × 10⁻⁶ M⊙ yr⁻¹ predicted by the phenomenological relation of Nieuwenhuijzen and de Jager (1990) for a RSG with the same initial main-sequence mass. This discrepancy confirms the significant uncertainty in the question of mass loss by pre-SN IIP. A fairly large sample of SN IIP with estimated circumstellar (CS) gas densities will be required to construct a clearer picture.

At present, the mass loss rate by pre-SN IIP is judged from the radio and X-ray emission produced by a shock interaction between the supernova and the wind (Chevalier 1982; Pooley et al. 2002), with the estimates based on X-ray data being probably more reliable. For SN 1999em, SN 1999gi, SN 2004dj, and SN 2004et, the mass loss rates derived from X-ray data lie within the range (1–2.5) × 10⁻⁶ M⊙ yr⁻¹ (Chevalier et al. 2006; Rho et al. 2007), while an estimate of ∼10⁻⁵ M⊙ yr⁻¹ was obtained for SN 2006bp (Immler et al. 2007). Recently, another method based on an analysis of the high-velocity absorption components in the Hα and He I 10830 Å lines has been suggested, which yields an estimate of ∼10⁻⁶ M⊙ yr⁻¹ for SN 1999em (Chugai et al. 2007).

Here, we investigate the possibility of using a more direct method of diagnosing the wind density for SN IIP based on the observation of the CS Na I D₁,₂ and Ca II H, K absorption lines against the bright SN photosphere. At present, these CS absorption lines have been confidently detected by this method only in type IIL SN 1998S (Bowen et al. 2000). No search for the CS lines has been conducted for SN IIP, although such a search is being carried out for SN Ia (Patat et al. 2007a, 2007b). In the case of SN 1998S, the wind density, judging by its high X-ray and radio...
luminosity, is fairly high and corresponds to a mass loss rate of $\sim 2 \times 10^{-4} M_\odot$ yr$^{-1}$ (Pooley et al. 2002). For this reason, it is not clear in advance whether the Na I and Ca II lines can be observed at all in SN IIP, for which the mass loss rate is much lower than that for SN 1998S.

In this paper, we study the formation of Na I and Ca II lines in the RSG wind after a SN IIP explosion and the use of these lines for diagnosing the wind density. We begin with a description of the model, calculate the ionization of Na I and Ca II in the wind before and after the explosion, and then present model profiles of the CS Na I 5890 Å and Ca II 3934 Å lines for typical wind densities. Subsequently, we apply our model to explain the CS Na I 5890 Å and Ca II 3934 Å lines in the spectrum of type IIL SN 1998S and discuss the conditions under which the Na I and Ca II lines have the observed intensities in the spectrum of this SN. In conclusion, we consider the possibilities for detecting the CS lines and the factors that can lead to deviations of the line intensities from the model results.

**THE MODEL**

Below, we consider a spherically symmetric stationary wind with density $\rho = u/(4\pi r^2)$ and velocity $u$ in which a SN IIP explodes. In what follows, it is convenient to deal with a dimensionless wind density parameter $\omega$ defined by the relation $u = 6.3 \times 10^{13} \omega$ g cm$^{-1}$; $\omega = 1$ corresponds to a mass loss rate of $10^{-6}(u/10$ km s$^{-1})M_\odot$ yr$^{-1}$. Before the SN explosion, the wind hydrogen is neutral, while Na and Ca can be singly ionized in the RSG radiation field. The main agent that ionizes the pre-SN wind is the chromospheric radiation from the RSG.

The Galactic RSG $\alpha$ Ori (Betelgeuse) gives an idea of the intensity and spectrum of the chromospheric radiation from a pre-SN. According to the IUE data (Rinehart et al. 2000), the fluxes in the 1250–1750 Å and 1900–3200 Å bands are $(4-6) \times 10^{-11}$ and $(2-3) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, respectively. For a power-law spectrum, $f_\lambda \sim \lambda^q$, these fluxes are reproduced with $q = 5$. The absolute monochromatic luminosity of the chromosphere of $\alpha$ Ori can be determined using a standard distance of 131 pc. To calculate the ionization of metals in the wind, we numerically solve time-dependent ionization equations by taking into account the gas motion with the velocity $u = 15$ km s$^{-1}$ and by assuming that the ultraviolet luminosity is the same as that of Betelgeuse. The metals that make a major contribution to the electron number density (Mg, Si, Fe) are treated as a single element with an abundance of $10^{-4}$ relative to hydrogen and with a mean ionization potential of 7.9 eV. The time–dependent ionization equations for metals, Na and Ca, are solved on a time scale of $10^5$ yr. The wind temperature is assumed to be equal to the local radiation temperature $T = T_e W^{0.25}$, where $W$ is the dilution factor and $T_e = 3900$ K is the effective temperature of the RSG, which corresponds to a luminosity of $10^5 L_\odot$ and a radius of $700 R_\odot$.

The calculated ionization fractions of Na I and Ca II in the pre-SN wind are then used as the initial conditions to calculate the time–dependent ionization of these ions after the SN explosion (Chugai 2008). The high initial luminosity of the SN with a temperature $\geq 10^5$ K leads to a strong ionization of hydrogen in the wind, which has no time to recombine during the subsequent period of 50 days under consideration. For this reason, we assume the wind hydrogen to be completely ionized. The ionization of metals is calculated for a fixed wind temperature of $3 \times 10^4$ K, which is intermediate between the characteristic extreme values of $10^4$ and $10^5$ K (Lundqvist and Fransson 1988).

The SN bolometric luminosity and the velocity at the photospheric level as functions of time are taken to be the same as those for SN 1999em (Utrobin 2007). To describe the ultraviolet spectrum, we introduce a time– and wavelength-dependent suppression factor for blackbody radiation. The suppression factor and its evolution are reconciled with the evolution of the ultraviolet spectrum for SN 1987A (Pun et al. 1995).

When calculating the line profiles, we consider the wind region outside the shock wave that coincides with the radius of the contact surface at the SN–wind boundary in the thin-shell model (Chevalier 1982). The evolution of this radius is calculated in a numerical model of the deceleration in the wind of a SN shell with a mass of $18 M_\odot$ and a kinetic energy of $1.3 \times 10^{51}$ erg, close to the parameters of SN 1999em (Utrobin 2007). The density distribution in the SN envelope is specified in the form of a plateau in the inner zone, $v < v_b$, a power-law drop $\rho \propto v^{-9}$ in the outer zone, $v > v_b$, and a sharp decrease at the $v = v_b$ boundary. The existence of such a sharp boundary is related to the shock breakout and the transition from adiabatic to radiative regime (Grasberg et al. 1971). The boundary velocity is taken to be $v_b = 15 000$ km s$^{-1}$, in agreement with the radial velocities in the blue Hα wing in the early spectra of normal SN IIP: SN 1999em (Leonard et al. 2002a) and SN 1999gi (Leonard et al. 2002b). The adopted velocity also agrees qualitatively with the hydrodynamic modeling of SN 1999em, which yields $v_b = 13 400$ km s$^{-1}$ (Utrobin 2007).

**RESULTS**

According to our model calculations, the metals in the pre-SN wind are completely ionized within