TYPE IIP SUPERNOVA 2009kf: EXPLOSION DRIVEN BY BLACK HOLE ACCRETION?

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Abstract

The unusually bright type IIP supernova (SN) 2009kf is studied employing hydrodynamic modeling. We derived optimal values of the ejecta mass of 28.1 $M_\odot$, explosion energy of $2.2 \times 10^{52}$ erg, and presupernova radius of $2 \times 10^3 R_\odot$ assuming that $^{56}$Ni mass is equal to the upper limit of 0.4 $M_\odot$. We analyzed effects of the uncertainties in the extinction and $^{56}$Ni mass and concluded that both the ejecta mass and explosion energy cannot be significantly reduced compared with the optimal values. The huge explosion energy of SN 2009kf indicates that the explosion is caused by the same mechanism which operates in energetic SNe Ibc (hypernovae), i.e., via a rapid disk accretion onto black hole. The ejecta mass combined with the black hole mass and the mass lost by stellar wind yields the progenitor mass of about 36 $M_\odot$. We propose a scenario in which massive binary evolution might result in the SN 2009kf event.

Key words: gamma-ray burst; general – stars: evolution – stars: massive – supernovae: general – supernovae: individual (SN 2009kf)

1. INTRODUCTION

Type IIP supernovae (SNe IIP) are believed to originate from 9 to 25 $M_\odot$ stars which end their life with the core collapse into neutron star and the subsequent envelope ejection via the neutrino-driven mechanism (Heger et al. 2003) or, alternatively, via the magneto-rotational mechanism (Moiseenko et al. 2006). In fact, limits for the mass range of SNe IIP progenitors (main-sequence stars) are fuzzy, because the theory of both stellar evolution and SN IIP explosion is still in progress and cannot reliably predict the outcome. On the other hand, the observational constraints for the progenitor masses are rather ambiguous. Indeed, the progenitors of SNe IIP recovered from pre-explosion images turn out to be predominantly low-mass (8–17 $M_\odot$) stars (Smartt 2009), while the hydrodynamic modeling of the handful of well-observed SNe IIP indicates that SNe IIP primarily originate from high-mass (15–25 $M_\odot$) progenitors (Utrobin & Chugai 2009, and references therein).

More massive (25–100 $M_\odot$) stars end up with the black hole formation which may be accompanied with a very weak explosion (Heger et al. 2003); they are associated with underluminous SNe IIP (Turatto et al. 1998). Alternatively, the underluminous SNe IIP might originate from the low-mass end of massive star range (Chugai & Utrobin 2000; Kitaura et al. 2006; Utrobin et al. 2007; Utrobin & Chugai 2008). A tiny fraction (order of 1%) of stars producing black holes is responsible for energetic SNe (hypernovae) powered by the disk accretion onto black hole (Galama et al. 1998; Iwamoto et al. 1998; MacFadyen & Woosley 1999; MacFadyen et al. 2001; Heger et al. 2003). It should be stressed that all the hypernovae so far observed are exploding Wolf–Rayet (WR) stars lacking any hydrogen in the outer layers.

Recently, a distant ($z = 0.182$) type IIP SN 2009kf has been discovered by the Pan-STARRS 1 survey (Young et al. 2009), which turns out to be unusually luminous for this class of SNe. With the mid-plateau magnitude $M_V \approx -18.4$ mag, it is 1.5–2 mag brighter compared with normal SNe IIP. Despite a large distance this SN became a subject of the detailed photometric and spectroscopic study (Botticella et al. 2010). Apart from the high optical luminosity the SN is unusually bright in the ultraviolet (UV) band of Galaxy Evolution Explorer (GALEX), with the near UV absolute magnitude $M_{NUV} = -21.5$ mag, and has unusually large photospheric velocity $\sim 9000$ km s$^{-1}$ on day 61 (Botticella et al. 2010). Authors suggest that the standard model of SN IIP is not applicable to SN 2009kf. They mention several possibilities to account for this unusual SN IIP: a huge explosion energy ($> 10^{52}$ erg), a large pre-SN radius ($> 1000 R_\odot$), a large $^{56}$Ni mass, and a strong interaction of ejecta with a dense circumstellar (CS) shell.

Given unusual characteristics of SN 2009kf, we present results of the hydrodynamic simulations of this object in a framework of the explosion of a red supergiant (RSG). We recover basic parameters of the event and find that the required explosion energy is indeed tremendous, comparable to the explosion energy of hypernovae. We evaluate the role of alternative power sources, viz., radioactive $^{56}$Ni decay and CS interaction, and find them irrelevant. Implications of our results for the pre-SN and the progenitor are discussed.

2. HYDRODYNAMIC MODEL AND PRESUPERNOVA

The spherically symmetric hydrodynamic code with one-group radiation transfer is employed to model SN 2009kf. The code was described in detail earlier (Utrobin 2004) and was used to study several other well-observed SNe IIP (Utrobin & Chugai 2009, and references therein). The explosion energy is modeled by the supersonic piston applied at the mass cut, which presumably is a border between the collapsing core and ejected mass. A non-evolutionary massive RSG in hydrostatic equilibrium is used as a pre-SN model. The helium core of pre-SN is presumably mixed with the hydrogen envelope, and the density jump between the helium core and hydrogen envelope is essentially smoothed. Arguments in favor of a non-evolutionary pre-SN for the hydrodynamic models of SNe IIP were presented by Utrobin & Chugai (2008).

Principal fitting parameters, which determine the light curve and the expansion velocity at the photosphere, are the explosion energy, ejecta mass, pre-SN radius, and amount of $^{56}$Ni. A “second order”, but also important, ingredient of the model...
is mixing between helium core and hydrogen envelope. The mixing determines the shape of the plateau at the final stage, and generally a high degree of mixing is needed to account for the light curve shape (Utrobin 2007). Mixing of $^{56}$Ni also affects the light curve at the transition from the plateau to the radioactive tail. The issue of the dependence of the hydrodynamic model parameters was explored in detail earlier (Utrobin 2007).

Preliminary computations of SN 2009kf light curves and expansion velocities showed that the explosion energy in the optimal model should exceed $10^{52}$ erg. That enormous energy is beyond the capabilities of the explosion mechanisms usually associated with the core collapse into the neutron star and seems to indicate the same explosion mechanism as for hypernovae (MacFadyen & Woosley 1999; MacFadyen et al. 2001; Heger et al. 2003). We therefore consider below models with the large mass of collapsing core that forms presumably a black hole with the rest mass of $4.5 M_\odot$. The latter is close to the minimal value which provides the required explosion energy by the accretion of $\sim 2 M_\odot$ for $\sim 1\%$ efficiency.

3. RESULTS

The extensive study of a parameter space led us to the optimal model of SN 2009kf that can describe simultaneously the $V$ light curve (Figure 1), the early strong bolometric luminosity peak along with the end phase of the plateau (Figure 2), and the expansion velocity at the photosphere (Figure 3). The observational $V$ light curve is taken from Botticella et al. (2010), and the bolometric light curve is constructed with a blackbody fit to the $g$, $r$, $i$, $z$ photometry and the NUV flux, only for the first three epochs, assuming a total extinction $A_V = 1$ mag. The velocity at the photosphere of $7350 \pm 350$ km s$^{-1}$ is recovered from the spectrum on day 61 (Botticella et al. 2010) using the modeling of the H$\alpha$ and He i 5876 Å line profiles. In fitting the light curves, we rely primarily on the $V$-band data rather than on the bolometric light curve in which the initial peak is mainly determined by the NUV flux which in turn is severely hampered by errors in the total extinction.

The parameter set of the optimal model consists of the ejected mass $M_{\text{env}} = 28.1 M_\odot$, explosion energy $E = 2.2 \times 10^{52}$ erg, pre-SN radius $R_0 = 2 \times 10^3 R_\odot$, and the $^{56}$Ni mass of $0.4 M_\odot$. The latter is the upper limit reported by Botticella et al. (2010). On the basis of the $V$ light curve and the velocity at the photosphere, we determine the SN parameters with an accuracy of $\sim 10\%$. The ejecta mass combined with the adopted mass of the black hole of $4.5 M_\odot$ gives a pre-SN mass of $32.6 \pm 3 M_\odot$, maximal among other pre-SNe for previously modeled SNe IIP (cf. Utrobin & Chugai 2009).

It should be emphasized that for the adopted value of the $^{56}$Ni mass, the ejecta mass and the explosion energy of the model are minimal; a decrease of the $^{56}$Ni mass would require larger ejecta mass and explosion energy. The $V$ light curve for the model with the $^{56}$Ni mass of $0.0765 M_\odot$ and the model without $^{56}$Ni illustrates this point (Figure 1): with the lower $^{56}$Ni mass the plateau is shorter, so larger ejecta mass and explosion energy are needed to account for the plateau duration for the same photospheric velocity. Computations show that in order to produce sensible fit of the bolometric light curve with $0.0765 M_\odot$ of $^{56}$Ni, one needs to increase the ejected mass and explosion energy by a factor of $\sim 1.5$. The light curve at the end of the plateau depends also on the extent of the $^{56}$Ni mixing. Remarkably, in the model with the $^{56}$Ni mass of $0.4 M_\odot$ the $^{56}$Ni should be mixed homogeneously in the inner ejecta up to $7700$ km s$^{-1}$.

The luminous broad initial peak of the bolometric light curve of SN 2009kf is related, as usually for SNe IIP, with the large pre-SN radius. The recovered radius $R_0 \sim 2 \times 10^3 R_\odot$ is larger than the radii of pre-SNe of well-studied SNe IIP, which lie in the range of $35\sim1500 R_\odot$ (Table 1). Keeping in mind that the radius of massive RSG increases with the progenitor mass (Heger et al. 1997), the large pre-SN radius can be considered as independent evidence in favor of the relatively large pre-SN mass compared with normal SNe IIP.
The primary uncertainty of the derived SN parameters is related to the poorly determined extinction in the host galaxy. We explore this uncertainty assuming a total extinction to be $A_V = 0$ and $A_V = 1.5$ mag. In the case of $A_V = 0$ mag the upper limit of $^{56}\text{Ni}$ mass is 0.16 $M_{\odot}$. With this amount of $^{56}\text{Ni}$ the pre-SN radius should be smaller, $R_0 = 200 R_{\odot}$, while the ejecta mass and the explosion energy of the model increase up to $\sim 40 M_{\odot}$ and $\sim 3 \times 10^{52}$ erg, respectively. Note that the $E/M$ ratio is to be invariant because the velocity at the photosphere on day 61 is fixed. For $A_V = 1.5$ mag the upper limit of the $^{56}\text{Ni}$ mass is 0.63 $M_{\odot}$. This amount of $^{56}\text{Ni}$ permits us to obtain a satisfactory fit of the light curves to the observations with the same ejecta mass and the explosion energy as for the optimal model, but with the pre-SN radius increased by a factor of $\sim 2$. However, if the adopted $^{56}\text{Ni}$ mass is lower than the upper limit, then one needs to increase the ejecta mass and the explosion energy to reproduce the light curves together with the velocity at the photosphere on day 61. We thus conclude that the ejecta mass and explosion energy cannot be lower than the values for the optimal hydrodynamic model.

4. DISCUSSION

The major result of the hydrodynamic modeling of SN 2009kf is the conclusion that the SN has been caused by the energetic explosion of a massive and extended RSG. Parameters of hydrodynamic model for SN 2009kf are listed in Table 1 together with parameters of other SNe IIP studied earlier (see Utrobin & Chugai 2009). The columns in the order contain SN name, pre-SN radius, ejecta mass, explosion energy, $^{56}\text{Ni}$ mass, maximal velocity of the $^{56}\text{Ni}$ mixing zone, minimal velocity of the hydrogen matter, mass of the collapsed core, pre-SN mass, mass lost by the wind, and progenitor mass. In the case of SN 2009kf progenitor, we suggest a single star scenario, while the total mass lost through the wind outflow is adopted to be equal to that lost by the progenitor of SN 2004et. SN 2009kf stands out from the list of other SNe IIP by its extremely large explosion energy which is 10 times greater than the explosion energy of SN 2004et, the most energetic event among previously studied SNe IIP. An exceptional nature of SN 2009kf is emphasized by its position on diagrams of the explosion energy and the $^{56}\text{Ni}$ mass versus progenitor mass (Figure 4). Despite the fact that SN 2009kf does not deviate from the general trends on both plots, the explosion physics of SN 2009kf is likely essentially different from that of other SNe IIP.

Before the further discussion of implications of the results we should consider alternative explanations for the unusually high luminosity of SN 2009kf. Given the rather confident upper limit for the $^{56}\text{Ni}$ amount, the only remaining possibility for the power source is the CS interaction. This mechanism suggests that the kinetic luminosity, released in the radiative shock wave, is emitted by the cool dense shell (CDS) at the ejecta/CS interface likewise it is the case for SNe IIn. Quick look at the spectra of SN 2009kf at the plateau stage shows that the strong CS interaction is unlikely in this case, because the spectra have little to do with the SN IIn spectra. Indeed, the latter never show pronounced broad absorption lines (cf. Filippenko 1997); by contrast, the H$\alpha$ line of SN 2009kf has the deep absorption component (see Botticella et al. 2010), quite similar to other SNe IIP. To strengthen further arguments against the CS interaction, we note that the maximal velocity detected at the contact surface, expands with the velocity $> 10^4$ km s$^{-1}$. This means that the double-shock structure, formed by the forward and reverse shocks with the CDS at the contact surface, expands with the velocity $> 10^4$ km s$^{-1}$. Meanwhile, the H$\alpha$ absorption component indicates that the continuum source resides at velocities $v < 6000$ km s$^{-1}$, which is at odds with the assumption that the bulk radiation originates from the high-velocity ejecta/CS interface. This evidence thus rules out the CS interaction as a major source of the SN 2009kf luminosity.

| SN     | $R_0$ ($R_{\odot}$) | $M_{\text{inv}}$ ($M_{\odot}$) | $E$ ($10^{51}$ erg) | $M_{\text{Ni}}$ ($10^{-2}M_{\odot}$) | $v_{\text{max}}$ ($\text{km s}^{-1}$) | $v_{\text{min}}$ ($\text{km s}^{-1}$) | $M_{\text{NS}}$ ($M_{\odot}$) | $M_{\text{pre-SN}}$ ($M_{\odot}$) | $M_{\text{lost}}$ ($M_{\odot}$) | $M_{\text{ZAMS}}$ ($M_{\odot}$) | Ref. |
|--------|---------------------|-------------------------------|---------------------|--------------------------------------|----------------------------------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|------|
| 1987A  | 35                  | 18                            | 1.5                 | 7.65                                 | 3000                             | 600                              | 1.6                             | 19.6                            | 1.7                             | 19.8–22.8                       | 1    |
| 1999em | 500                 | 19                            | 1.3                 | 3.60                                 | 660                              | 700                              | 1.6                             | 20.6                            | 1.6                             | 21.0–23.4                       | 2    |
| 2003Z  | 14                  | 229                           | 0.245               | 0.63                                 | 535                              | 360                              | 1.4                             | 15.4                            | 0.2–0.8                         | 14.4–17.4                       | 3    |
| 2004et | 1500                | 22.9                          | 2.3                 | 6.8                                  | 1000                             | 300                              | 1.6                             | 24.5                            | 1.4–3.4                         | 25.0–29.0                       | 4    |
| 2005cs | 600                 | 15.9                          | 0.41                | 0.82                                 | 610                              | 300                              | 1.4                             | 17.3                            | 1.0                             | 17.6–20.4                       | 5    |
| 2009kf | 2000                | 28.1                          | 21.5                | 40.0                                 | 7700                             | 410                              | 4.5                             | 32.6                            | 3.4                             | $\geq 36^b$                      | 6    |

Notes. Table 1 gives mass estimates of type IIP progenitors according to the following relation: $M_{\text{ZAMS}} = M_{\text{NS}}$ or $M_{\text{BH}} + M_{\text{inv}} + M_{\text{lost}}$.

References. (1) Utrobin 2004; (2) Utrobin 2007; (3) Utrobin et al. 2007; (4) Utrobin & Chugai 2009; (5) Utrobin & Chugai 2008; (6) The present work.
Regardless of the role of the CS interaction, the upper limit of the wind density could be valuable. The wind density can be estimated using the upper limit of the luminosity at the nebular stage \( M_R > -16.3 \) mag on day 236 (Botticella et al. 2010), which can be converted into the upper limit of the optical luminosity, \( L < 5 \times 10^{41} \) erg s\(^{-1}\), assuming that the spectral energy distribution is similar to that at the end of the plateau stage. To recover the upper limit of the wind density, we employ the interaction model based on the thin shell approximation (Chugai et al. 2007) for the ejecta mass and the explosion energy found for SN 2009kf. For the adopted \(^{56}\)Ni mass of \( 0.4 \ M_\odot \), the upper limit of the wind density parameter turns out to be \( w = M/\mu = 6 \times 10^{15} \) g cm\(^{-1}\). This estimate refers to the epoch of 236 days and the radius of \( 6 \times 10^{16} \) cm. Assuming the wind velocity \( \mu = 10 \) km s\(^{-1}\), we conclude that the upper limit of the wind density corresponds to the mass-loss rate \( M < 9 \times 10^{-5} \ M_\odot \) yr\(^{-1}\) at the stage \( \sim 2 \times 10^3 \) yr before the SN explosion. The question arises on the nature of the central “infernal machine” responsible for the huge explosion energy \( E \sim 2 \times 10^{52} \) erg, one order magnitude exceeding the energy of normal SNe IIP. In fact, the explosion energy of SN 2009kf is comparable with the explosion energy of energetic SNe Ic (hypernovae), associated with gamma-ray bursts (e.g., SN 1998bw). According to the recent compilation of Tanaka et al. (2009), the explosion energies of hypernovae lie in the range of \((0.6–5) \times 10^{52} \) erg; SN 2009kf falls into this interval. The absence of alternative possibilities compels us to suggest that SN 2009kf is caused by the “engine” associated with the hypernova phenomenon. The possibility that the collapsar mechanism could operate in massive stars with retaining the hydrogen envelope and produce a very powerful SN was proposed by MacFadyen et al. (2001) and Woosley et al. (2002).

The widely shared view is that the hypernova explosion is powered by a rapid disk accretion into the black hole (MacFadyen & Woosley 1999; MacFadyen et al. 2001; Heger et al. 2003). Two conceivable scenarios are proposed for how the black hole and accretion disk system with the high accretion rate might arise: (1) a core collapse in a single rapidly rotating star (collapsar model; Woosley 1993; MacFadyen & Woosley 1999), or (2) a black hole (neutron star) merger with the He core of massive companion (merger model; Fryer & Woosley 1998). The merger scenario suggests that the neutron star, merged with He core as a result of a super-Eddington accretion, rapidly grows a black hole surrounded by the accretion disk.

The presence of a massive hydrogen envelope in SN 2009kf imposes constraint on the single star scenario: the progenitor should be less massive than the critical mass \( M_{WR} \) above which WR stars form due to the complete removal of the hydrogen envelope. This boundary is not well known because of uncertainties in the mass-loss rate; for the solar metallicity the currently preferred value is in the range of \( 30–40 \ M_\odot \) (Heger et al. 2003). Thus, in the single star scenario the progenitor mass should be \( < 40 \ M_\odot \).

The merger scenario includes two major stages: (1) conservative evolution of a close massive binary that ends up with the formation of the neutron star (black hole) in a pair with the massive normal star and (2) spiral-in of the neutron star (black hole) in the massive star companion with subsequent merging with the helium core. The neutron star in the process of merging grows a black hole (Chevalier 1993), so that the final stage of pre-SN is the central black hole surrounded with the dense helium accretion disk embedded in the massive hydrogen envelope.

As an example, the original close binary might consist of \( M_1 = 25 \ M_\odot \) and \( M_2 = 20 \ M_\odot \) stars. After the conservative mass transfer, the primary ends up as a \( 5–8 \ M_\odot \) He star in a pair with the secondary \( 37–40 \ M_\odot \) star. The subsequent evolution of the helium star leads to SN Ib/c or SN I Ib explosion with the neutron star (black hole) left behind in pair with the massive star. This is the stage of massive X-ray binary. After the secondary forms a He core, the stellar radius grows, the Roche lobe overflows, and the common envelope forms. The common envelope stage ends up as a black hole surrounded with the helium accretion disk within the massive hydrogen envelope. The rapid disk accretion onto black hole eventually gives rise to the SN 2009kf event.

The energetic SNe IIP produced by the hypernova mechanism are extremely rare events. This is indicated by the large distance of the unique SN 2009kf. To a first approximation, the rate ratio of SN 2009kf-like to SN 1998bw-like events can be estimated interpreting their distances (\( D_1 = 740 \) Mpc and \( D_2 = 40 \) Mpc, respectively) as the closest neighbor distances. The closest neighbor distance \( R \) is defined by the obvious equation \((1/3)^2 \Omega \eta G t = 1\), where \( \Omega \) is the solid angle of the survey, \( \eta \) is the detection efficiency, \( G \) is the SN rate per unit volume, and \( t \) is the total observation time. Assuming that \( \Omega, \eta, \) and \( t \) are comparable for the detection of both hypernovae and SN 2009kf-like events, we obtain the rough estimate of the rate ratio \( G_1/G_2 \sim (D_2/D_1)^3 \sim 10^3\). Note that Malmquist bias cannot change this ratio significantly because the absolute magnitudes of these phenomena are comparable. We conclude therefore that roughly 0.01% of all hypernovae can retain a massive hydrogen envelope and produce SN 2009kf-like events.

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