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^{56}Ni production in aspherical explosion of massive WO star

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Recent supernova surveys have found peculiar type Ic supernovae, i.e., super-luminous type Ic supernovae. SN 2007bi is reported as one of the most luminous SNe Ic. It is considered to produce very large amount of radioactive ^{56}Ni more than 3.5M$_\odot$. Since most normal SNe Ic produce only ~ 0.1M$_\odot$ or so, this is a very exceptional case. The previous study shows that a 40M$_\odot$ of C+O core spherically explodes by core collapse with 3×10^{52} erg of energy, which can produce such a large amount of ^{56}Ni. Although the progenitor of SN 2007bi is still unclear, we extend this possibility for the case of aspherical (jet-like) explosion.

We performed a sequence of hydro-dynamical simulations of aspherical explosion with more than 10^{52} erg of energy using two massive WO-star progenitors ($M_{\rm MS} = 110$M$_\odot$ and 250M$_\odot$ and $Z = 0.004$). We investigate the dependence of ^{56}Ni production on a sphericity of explosion. In the case of jet-like explosion both the ejecta mass and produced ^{56}Ni mass are reduced compared with spherical case, because large fraction of material is accreted onto the centeral remnant due to fall-back. We discuss restrictions on aspherical explosion models from ^{56}Ni mass and other observed quantities of SN 2007bi. But in final, considering such restrictions, we can safely conclude that aspherical model of core-collapse explosion of massive WO star still hold to present the progenitor of SN 2007bi.

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1. Introduction

SN 2007bi is reported as one of very luminous type Ic supernovae(SNe). The ejected ^{56}Ni amount is estimated to be 3.5$M_\odot$ from the peak magnitude and 3.7$M_\odot$ < M(^{56}Ni) < 7.4$M_\odot$ from the nebular spectra [1]. This is pretty large compared with other luminous SNe Ib/c; 0.6$M_\odot$ of SN1998bw [2] and 0.02$M_\odot$ of SN 2008D [3]. From such extreme production, Gal-Yam et al. [1] suggested that SN 2007bi is originated from Pair instability (PI) SN of He core progenitor with 100$M_\odot$ of mass. This scenario succeeded mainly in reproducing the yield of ^{56}Ni and elemental composition.

SN 2007bi is also discussed according to core collapse (CC) scenario. Umeda & Nomoto [4] discussed that a SN with a kinetic energy of $\sim 3\times10^{52}$ erg can produce more than 3$M_\odot$ of ^{56}Ni if the C+O core of the progenitor is larger than $\sim$ 35$M_\odot$. Moriya et al. [5] constructed CC explosion model of a massive C+O core and synthesized light curves. Spherical explosion of $(M_{\rm C+O}, E_{\rm ex})$ = (43$M_\odot$, 30×10^{51}erg) can reproduce the mass of ^{56}Ni and light curve evolution of SN 2007bi. They concluded CC SN as well as PI SN can be the progenitor of SN 2007bi. Yoshida & Umeda [6] investigated the evolution of very massive stars with the main-sequence mass of 100$M_\odot$ < $M_{\rm MS}$ < 500$M_\odot$ and the metallicity of $Z = 0.004$. They discussed whether the origin of 2007bi is CC or PI SN in terms of their population. They concluded that the possibility of CC SN is 40 times larger than that of PI SN.

But in general, SN 2007bi cannot be fully explained by CC SN model of spherical explosion, because such highly energetic explosion more than $E_{\rm ex} = 10^{52}$ erg (called *hypernova*) seems to occur aspherically. If the progenitor explodes aligned with an axis, spatial distribution of produced ^{56}Ni will be restricted around the axis and fall-back from equatorial region will be considerable. We can easily presume that total ejecta and ^{56}Ni amount will severely depends on the sphericity of explosion. This *aspherical effect* may possibly change the total view of core-collapse scenario for SN 2007bi from spherical explosion.

Thus, our aim is to construct an aspherical explosion model based on CC SN with ejecting as possible as large amount of ^{56}Ni. From the aspherical model, we will discuss whether CC SN model for SN 2007bi still holds.

2. Model & Method

We considered two WO stars as the progenitors suitable for type Ic SN 2007bi. One is 110$M_\odot$ in main sequence and the other is 250$M_\odot$. Since SN 2007bi shows no He signature in the spectrum, this is preferable property for this study. More details for the progenitors are described in Yoshida et al. [7].

We performed 2D hydro-dynamical simulations in order to model the aspherical explosion. We determined explosion energy $E_{\rm ex}$ from the observational quantities using the relations

$$v_{\rm ph} \propto E_{\rm ex}^{1/2} M_{\rm ej}^{-1/2}$$
$$t_{\rm rise} \propto E_{\rm ex}^{-1/4} M_{\rm ej}^{3/4}, \qquad (2.1)$$

where $v_{\rm ph}$ is photometric velocity and $t_{\rm rise}$ is light curve rising time [8]. Proportional constants are taken from well known type Ib SN 2008D [8]. We assumed the special case where $M_{\rm ej}$ will be

Table 1: Main sequence mass ($M_{\rm MS}$), and WO star mass ($M_{\rm WO}$) and approximately maximum explosion energy ($E_{\rm ex,max}$) estimated from eq.2.1. of the progenitors

$M_{\rm MS}/{\rm M}_\odot$	$M_{\rm WO}/{\rm M}_\odot$	$E_{\rm ex,max}/10^{51}$ erg
110	43.1	∼50
250	60.0	∼70

almost maximum ($M_{\rm ej} \lesssim M_{\rm WO}$) because $M_{\rm ej,max}$ always gives $E_{\rm ex,max}$. We assume that SN 2007bi should be as powerful explosion as possible in order to reproduce extremely large ^{56}Ni production. The progenitor mass and explosion energy are summarized in table 1.

We modeled aspherical explosion by putting energy into a cone around polar axis with some opening angle $\theta_{\rm op}$. If collapsar engine serving GRB like explosion can be assumed for this hypernova model, $\theta_{\rm op}$ may become 10° or so. But as we do not have a clear idea about asphericity of hypernova, we calculated many models with various $\theta_{\rm op}$ and investigate in which range of $\theta_{\rm op}$ SN 2007bi can be reproduced. Our selection of $\theta_{\rm op}$ is 7.03, 11.25, 22.5, 45.0, 67.5, 78.75 and 90.0°. $\theta_{\rm op} = 90.0°$ is equivalent to spherical model.

We also calculated nucleosynthesis by post-process. We discretized all the mass element of the progenitor into 5200 Lagrangean particles at the beginning of explosion. All of them follow the thermo-dynamical histories during the full evolution of hydro-dynamical simulation.

3. Results

Figure 1 shows the initial distribution of all Lagrangean pariticles for a jet-like explosion model ($\theta_{\rm op} = 22.5°$) and the color shows the final destiny of each particle. ^{56}Ni is produced in the narrow region around an axis, and fall-back is distinguished in the equatorial region.

Figure 2 shows the mass of ejecta and ejected ^{56}Ni as a function of $\theta_{\rm op}$. We see the total trend that jet-like (small $\theta_{\rm op}$) explosion is likely to lose a large fraction of stellar mass. This is because fall-back onto the central remnant occurs heavily. Since highly aspherical model gives kinetic energy around the axis, material nearby equatorial plane falls onto the central remnant almost freely. $M_{\rm ej}$ ranges $46-58{\rm M}_\odot$ for $250{\rm M}_\odot$ progenitor and $28-41{\rm M}_\odot$ for the $110{\rm M}_\odot$ progenitor.

^{56}Ni is produced by Si burning in high temperature region ($T > 5 \times 10^9$ K). For jet-like explosion, the high temperature region emerges only around the polar axis where contains less density than central region. Therefore produced ^{56}Ni is reduced in jet-like explosion. Since the estimated ^{56}Ni amount for SN 2007bi from some observations seems good to be $3.5{\rm M}_\odot < {\rm M}(^{56}{\rm Ni}) < 7.0{\rm M}_\odot$, the $250{\rm M}_\odot$ progenitor is consistent over all the range of $\theta_{\rm op}$, and the $110{\rm M}_\odot$ progenitor is consistent in $\theta_{\rm op} > 30°$.

We evaluated the photometric velocity $v_{\rm ph}$ and the light curve rising time $t_{\rm rise}$ from the explosion energy and the ejecta mass for each aspherical explosion model. Eq.2.1 shows the relation of $v_{\rm ph}$, $t_{\rm rise}$, $E_{\rm ex}$ and $M_{\rm ej}$. We took the range of the rising time estimated from the observation as $40 < t_{\rm rise} < 97.5$ days [1]. The rising time has large uncertainty because the initial observation is sparse. We used the photometric velocity of $v_{\rm ph} = 12000$ km s^{-1} derived from the observation [1] and supposed an uncertainty of ± 500 km s^{-1} (summarized in table 2). Figure 3 shows the photometric velocity and the light curve rising time as a function of the opening angle of aspherical

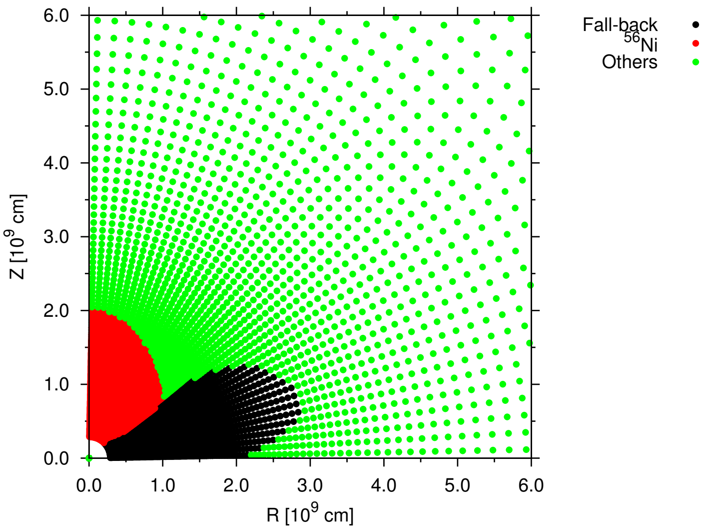

Figure 1: Initial distribution of Lagrangean particles focused on the central region ($R = Z = 6.0 \times 10^9$cm) for the $\theta_{\rm op} = 22.5°$ model of 110M$_\odot$ progenitor. Aspherical explosion is driven by energy injection around Z axis. Colors show the final destiny of each particle; Black particles fall into the central remnant, red particles are enriched in ^{56}Ni and green particles are other of the two.

Table 2: Observed quantities, ejecta mass ($M_{\rm ej}$), explosion energy ($E_{\rm ex}$), photometric velocity ($v_{\rm ph}$) and light curve rising time ($t_{\rm rise}$) of SN 2007bi and well known type Ic SNe SN 2008D.

SN	$M_{\rm ej}/{\rm M}_\odot$	$E_{\rm ex}/10^{51}$ erg	$v_{\rm ph}$ [km s^{-1}]	$t_{\rm rise}$ [day]	ref.
2007bi	-	-	12000	> 40	Gal-Yam et al. (2009) [1]
2008D	7	6	10000	19	Mazzali et al. (2008) [3]

model. The ranges of the photometric velocity and the rising time from the observations are also drawn in Figure 3.

We set explosion energy under the assumption that ejecta mass becomes as large as possible ($M_{\rm ej} \sim M_{\rm WO}$), because very luminous SN 2007bi requires as large explosion energy as possible and large $M_{\rm ej}$ always gives large $E_{\rm ex}$. However, as we can see in some of the jet-like models in Figure 3, $v_{\rm ph}$ and $t_{\rm rise}$ are no longer consistent with observation, because $M_{\rm ej}$ is non-negligibly reduced from $M_{\rm WO}$.

We can estimate the range of $\theta_{\rm op}$ in which SN 2007bi is reproduced from these simulations. Aspherical explosion models of the 250M$_\odot$ progenitor reproduce all the observational quantities in $\theta_{\rm op} \gtrsim 30°$. The models of the 110M$_\odot$ progenitor reproduce in $\theta_{\rm op} \gtrsim 45°$. In either case, the restriction on $\theta_{\rm op}$ is mainly caused by $v_{\rm ph}$ and $t_{\rm rise}$, and ^{56}Ni mass does not become a severe restriction in this study.

4. Conclusion

Concerning CC explosion model, this study suggests that aspherical explosions as well as spherical one can explain luminous type Ic SN 2007bi. We clarified that jet-like explosion have

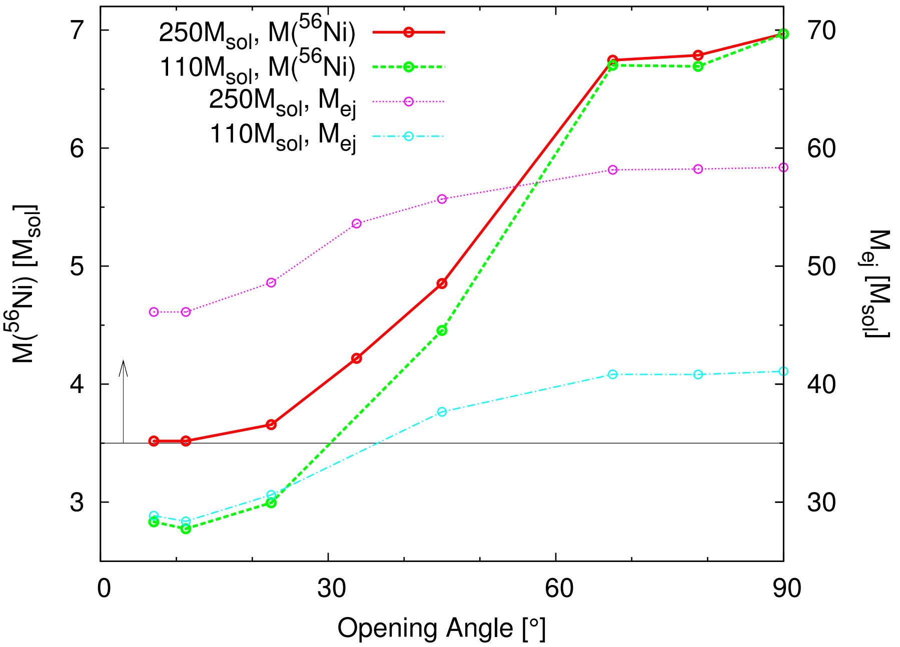

Figure 2: Ejecta mass and ^{56}Ni mass ejected from aspherical SN explosion with different θ_{op} models. The lower limit for $M(^{56}\mathrm{Ni})$ of SN 2007bi estimated from observation is drawn by black dashed line.

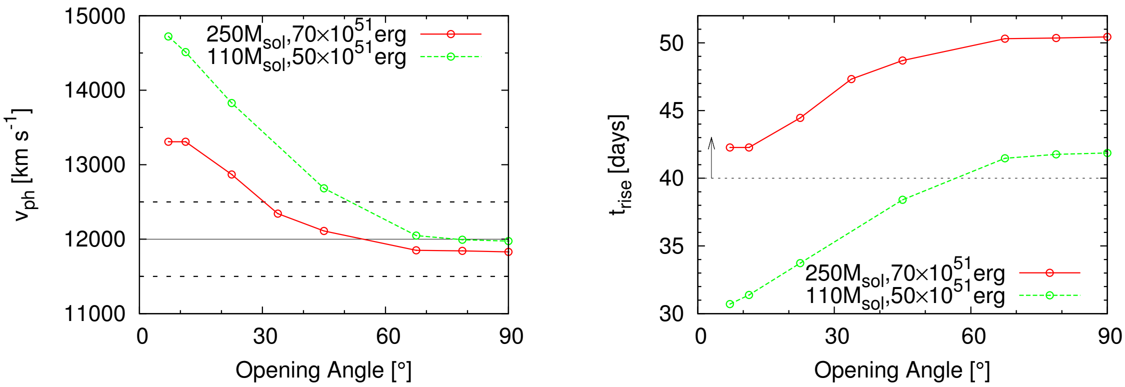

Figure 3: The photospheric velocity (left panel) and the light curve rising time (right panel) as a function of the opening angle. In the left panel, solid line is the observed velocity and the two dashed lines indicate the uncertainty. In the right panel, dotted line is the lower limit of the observed light curve rising time.

more severe restriction to reproduce SN 2007bi than simple spherical explosion model. The main reason is that ^{56}Ni and ejecta mass is reduced by fall-back.

The most severe restriction is emerged from whether limited amount of E_{ex} ejects sufficiently large M_{ej}. Eq.2.1 connects E_{ex} with M_{ej} by observed quantities. This means that energetic explosion requires sufficiently large ejecta mass. Some of extremely jet-like (the most small θ_{op}) models cannot eject sufficiently much material, because they cannot prevent the material nearby the equatorial plane falling onto the central remnant. Reduced M_{ej} is no longer consistent with explosion energy and observed quantities. Therefore, our aspherical models clarify the range in which model calculation is consistent with observation. For the $110M_{\odot}$ models the range is $\theta_{\rm op} \gtrsim 45^{\circ}$, and for the $250M_{\odot}$ models it is $\theta_{\rm op} \gtrsim 30^{\circ}$.

Although it has not been well known how jet-like explosion occurs in hypernova progenitor, the scenario that the SN 2007bi is originated from CC SN still holds. Supposing that $250M_{\odot}$ star at the end of its life explodes like GRB but fails to collimate the jet, opening angle of explosion may become broader than 30°. We consider such a progenitor is appropriate to become hypernova and serve the explosion like SN 2007bi.

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