Is SN 2006X from a WD + MS system with optically thick wind?

X. Meng\textsuperscript{a}, M. Yang\textsuperscript{a}, X. Geng\textsuperscript{b}

\textsuperscript{a}Department of Physics and Chemistry, Henan Polytechnic University, Jiaozuo, 454000, China, conson859@msn.com
\textsuperscript{b}Academic publishing Center, Henan Polytechnic University, Jiaozuo, 454000, China

Abstract

The single-degenerate channel is widely accepted as the progenitors of type Ia supernovae (SNe Ia). Following the work of Meng, Chen & Han (2009), we reproduced the birth rate and age of supernovae like SN 2006X by the single-degenerate model (WD + MS) with an optically thick wind, which may imply that the progenitor of SN 2006X is a WD + MS system.

Key words: binaries:close-stars:evolution-supernovae:general-individual (SN 2006X)

1.

Although type Ia supernovae (SNe Ia) showed their importance in determining cosmological parameters, e.g. $\Omega_M$ and $\Omega_\Lambda$ (Riess et al. 1998; Perlmutter et al. 1999), the progenitor systems of SNe Ia have not been confidently identified yet (Hillebrandt & Niemeyer 2000; Leibundgut 2000). Two basic scenarios for the progenitor of SN Ia have been discussed over the last three decades. One is a single degenerate (SD) model (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984), in which a CO WD increases its mass by accreting hydrogen- or helium-rich matter from its companion, and explodes when its mass approaches the Chandrasekhar mass limit. The companion may be a main-sequence star (WD + MS) or a red-giant star (WD + RG) (Yungelson et al. 1995; Li & van den Heuvel 1997; Hachisu et al. 1999a,b; Nomoto et al. 1999, 2003; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2007, 2009; Han 2008; Meng, Chen & Han 2009; Lü et al. 2009, Wang et al. 2009a, b). An alternative is the double degenerate (DD)
model (Iben & Tutukov 1984; Webbink 1984), in which a system consisting of two CO WDs loses orbital angular momentum by gravitational wave radiation and merges finally. The merger may explode if the total mass of the system exceeds the Chandrasekhar mass limit (see the reviews by Hillebrandt & Niemeyer 2000 and Leibundgut 2000). In theory, a large amount of circumstellar materials (CSM) may form around SNe Ia via an optically thick wind for the SD model (Hachisu et al. 1996), while there is no CSM around DD systems. Then, a basic method to distinguish the two progenitor models is to find the CSM around progenitor systems. The CSM may play a key role to solve the problem of the low value of reddening ratio (Wang 2005), which is very important for precision cosmology (Wang et al. 2008). In addition, it is possible for the CSM to be the origin of color excess of SNe Ia (Meng et al. 2009).

Evidence for CSM was first found in SN2002ic (Hamuy et al. 2003), which has shown extremely pronounced hydrogen emission lines which have been interpreted as a sign of strong interaction between supernova ejecta and CSM. The discovery of SN2002ic may uphold the SD model (Han & Podsiadlowski 2006). The evidence for CSM was also found in a normal SN Ia (SN 2006X) defined by Branch, Fisher & Nugent (1993) and the CSM is proposed to be from a wind from a red-giant companion (Patat et al. 2007), while Hachisu et al. (2008) argued a WD + MS nature for this SN Ia. Blondin et al. (2009) found a similar signal to that of SN 2006X in another SNe Ia (SN 1999cl) and their results indicated that the supernovae like SN 2006X are rare objects (2/31 ∼ 6%). Recently, the third example like SN 2006X (SN 2007le) was reported (Simon et al. 2009), and then the ratio of 2006X-like supernova is increased to 3/32 ∼ 9%.

In theory, SNe Ia can explode during the optically thick wind phase or after the optically thick wind while in stable or unstable hydrogen-burning phase (Han & Podsiadlowski 2004). The materials lost as the optically thick wind form CSM (Hachisu et al. 2008; Meng et al. 2009). If a SN Ia explodes after the optically thick wind, the CSM have been dispersed too thin to be detected immediately after the SN Ia explosion (Hachisu et al. 2008; Meng, Yang & Geng 2009). If a SNe Ia explodes during the optically thick wind phase, the materials lost from system form CSM very near the SN Ia, which may show the signal similar to SN 2006X (Hachisu et al. 2008; Meng, Yang & Geng 2009). Recently, Meng, Chen & Han (2009) performed binary stellar evolution calculations for more than 25,000 close WD + MS binary systems with various metallicities. In their works, the prescription of Hachisu et al.
(1999a) for the accretion efficiency of hydrogen-rich material was adopted by assuming an optically thick wind (Hachisu et al. 1996), and then their works provide a possibility to check whether the SD model with optically thick wind can explain the birth rate of supernovae like SN 2006X. The purpose of this paper is to check the possibility by a binary population synthesis (BPS) approach.

In section 2 we simply describe our method. We show the results in section 3 and give discussions and conclusions in section 4.

2. Method

2.1. optically thick wind

Meng, Chen & Han (2009) studied the WD+MS system with optically thick wind. In their studies, they adopted the prescription of Hachisu et al. (1999a) on WDs accreting hydrogen-rich material from their companions instead of solving stellar structure equations of a WD. In a WD + MS channel, the companion fills its Roche lobe at MS or during HG, and transfers material onto the WD. If the mass-transfer rate, $|\dot{M}_2|$, exceeds a critical value, $\dot{M}_{\text{cr}}$, they assumed that the accreted hydrogen steadily burns on the surface of WD and that the hydrogen-rich material is converted into helium at the rate of $\dot{M}_{\text{cr}}$. The unprocessed matter is assumed to be lost from the system as an optically thick wind at a rate of $\dot{M}_{\text{wind}} = |\dot{M}_2| - \dot{M}_{\text{cr}}$ (Hachisu et al. 1996). The hydrogen-rich material lost as the optically thick wind may exist as CSM. If the WD explodes at the wind phase, the CSM locates near the SN Ia, which may show the signal similar to SN 2006X (Hachisu et al. 2008; Meng, Yang & Geng 2009). In this paper, we assume that if SN Ia explodes during the optically thick wind phase, it is a supernova like SN 2006X.

2.2. method

We use the rapid binary evolution code developed by Hurley et al. (2000, 2002) to study the birth rate of supernovae like SN 2006X. To investigate the birth rate, we followed the evolution of $10^7$ binaries. The primordial binary samples are generated in a Monte Carlo way and a circular orbit is assumed for all binaries. The basic parameters for the simulations are the same as that in Meng, Chen & Han (2009). In theory, when the initial WD mass in a binary system is smaller than 0.9$M_\odot$, the WD never explodes at the optically thick wind phase (Hachisu et al. 2008; Meng, Yang & Geng 2009; Meng, Chen & Han 2009). Meng, Chen & Han (2009) have shown the
parameter spaces for the supernovae exploding at the wind phase (see Fig. 2 in Meng, Chen & Han 2009), and we assume that these supernovae are those like SN 2006X. For our binary population synthesis study, we assume that if the initial orbital-period, $P_{\text{orb}}^i$, and the initial secondary mass, $M_2^i$, of a WD + MS system is located in the appropriate regions in the $(\log P_{\text{orb}}^i, M_2^i)$ plane for supernovae like SN 2006X at the onset of RLOF, a 2006X-like supernova is produced.

For our BPS study, common-envelope (CE) ejection efficiency ($\alpha_{\text{CE}}$, the fraction of the released orbital energy used to eject the CE) is a very important parameter, and in this paper, we set $\alpha_{\text{CE}}$ to be 1.0 or 3.0. Two cases for star formation history are checked, i.e. a single starburst and a constant star formation rate ($\text{SFR}$) over the last 15 Gyr. For the constant star formation rate, we assume that one binary with primary larger than 0.8 $M_\odot$ is born in the Galaxy each year (see Iben & Tutukov 1984; Han, Podsiadlowski & Eggleton 1995; Hurley et al. 2002). From this calibration, we can get $\text{SFR} = 5 M_\odot$ yr$^{-1}$ (see also Willems & Kolb 2004).

3. The Results of Binary Population Synthesis

In Figs. 1 and 2, we show the evolution of the birth rates for all SNe Ia and supernovae like SN 2006X with a single starburst and a constant star formation rate, respectively. From the two figures, we can see that SNe similar to SN 2006X are a relatively rare subclass of SNe Ia: 1 - 14 in 100 SNe Ia can be of this type, which depends on the $\alpha_{\text{CE}}$. The observational results in Blondin et al. (2009) indicated that out of 100 SNe Ia, about 6 supernovae should belong to the subclass of 2006X-like objects. The probability is located in the range given in this paper, even that SN 2007le is included.

In the figures, we can see that $\alpha_{\text{CE}}$ affects the birth rate significantly. High $\alpha_{\text{CE}}$ results in a lower birth rate. This result results from the influence of $\alpha_{\text{CE}}$ on the channels forming WD + MS systems. There are three channels to form WD + MS systems: He star channel, EAGB channel and TPAGB channel. The classification is based on the evolutionary phase of the primordial primary at the onset of the first Roche Lobe overflow (RLOF), which means that the primordial primary is in HG or on RGB (i.e. case B evolution defined by Kippenhahn & Weigert (1967), in early asymptotic giant branch stage (EAGB) (i.e. helium is exhausted in the core, while thermal pulses have not yet started) or at the thermal pulsing AGB (TPAGB) stage for He star, EAGB and TPAGB channels, respectively (see Meng, Chen & Han...
Figure 1: The evolution of the birth rates of SNe Ia for a single starburst of $10^{11}M_\odot$ with different $\alpha_{CE}$. The thick lines are for all the SNe Ia, while the thin lines are for those like SN 2006X.

2009 for the channels in details). Because of the low binding energy of the common envelope and a long primordial orbital period, $\alpha_{CE}$ has a remarkable influence on CO + WD systems from the TPAGB channel. Generally, if a CE can be ejected, a low $\alpha_{CE}$ produces a shorter orbital-period WD + MS system, which is more likely to fulfill the conditions for SNe Ia. Therefore, we see obvious contributions from the TPAGB channel when $\alpha_{CE} = 1.0$, but no contribution from this channel when $\alpha_{CE} = 3.0$. This is reason why a high $\alpha_{CE}$ leads to low birth rate.

From Fig. 1 we can see that if SN 2006X is originated from a WD + MS system as suggested in this paper, the delayed time of 2006X-like object is constrained in a very narrow range, i.e. $0.3 \sim 1$Gyr. This provides a rigorous constraint on the age of the object like SN 2006X. We will discuss it in the next section.
4. Discussion and Conclusions

4.1. the age of SN 2006X

SN 2006X is the first case that show a variable Na I D line in its spectral, which clearly shows a signal of CSM (Patat et al. 2007). Patat et al. (2007) also noticed a relatively low expansion velocity of the CSM (~ 50 km/s). The low expansion velocity seems to imply that the progenitor of SN 2006X belongs to a WD + RG systems. However, Hachisu et al. (2008) showed that under the assumption of the optically thick wind, the WD + MS system also may produce the low-velocity CSM. In this paper, we show that if SN 2006X is from a WD + MS system with the optically thick wind, the age of its progenitor is smaller than 1 Gyr, which implies that there is star formation during the recent 1 Gyr in its host galaxy. The host galaxy of SN 2006X, NGC 4321 (M100), is a well-studied spiral galaxy (e.g. Ho et al. 1997) and SN 2006X locates near one of its arms (Wang et al. 2008). As one of the largest spiral galaxies in the Virgo cluster, it produced SNe 1901B, 1914A, 1959E, 1979C, and 2006X in roughly the last century and shows significant signal of star formation at present (Kanpen et al. 1993, 1996). Recently, Blondin et al. (2009) found a similar signal to that of SN 2006X in another
SNe Ia (SN 1999cl) in archives. Its host galaxy, NGC4501 (M88), is also a spiral galaxy and SN 1999cl locates at one of its arms (Krisciunas et al. 2000). During the last 1 Gyr, the star formation is significant in the galaxy (Wong & Blitz 2002). The host galaxy of SN 2007le (NGC 7721) is a Sc galaxy, and a recent star formation is also expected (Iglesias-Páramo et al. 2006; Simon et al. 2009). So, all the supernovae fulfill the age constraint from WD + MS system.

4.2. Progenitor system

Following the study of Meng, Chen & Han (2009), in this paper, we show the evolution of birth rate of supernovae like SN 2006X by assuming that if a SN Ia explode at the optically thick wind phase, it is a 2006X-like supernova. Based on the assumption, we can reproduce the birth rate of 2006X-like objects. Please keep in mind that we only consider the case of WD + MS channel in this paper. However, the progenitor of SN 2006X is still an open question. Patat et al. (2007) suggested that the progenitor of SN 2006X belongs to WD + RG system such a RS Oph based on the velocity of absorptions line of Na I D. Lü et al. (2009) designed a WD + RG model with an aspherical stellar wind and equatorial disk, and then they may explain some properties of SN 2006X. However, the birth rate of 2006X-like objects obtained in Lü et al. (2009) is too low (less than 1%) to compare with that observed. Based on the assumption of the optically thick wind and a mass-stripping effect, Hachisu et al. (2008) argued that the progenitor of SN 2006X should be a WD + MS system and they also can well explain the properties of SN 2006X. Although the treatment of binary evolution in Meng, Chen & Han (2009) is different from that in Hachisu et al. (2008), Meng, Chen & Han (2009) obtained similar results for the SNe Ia exploding at the optically thick wind phase, e.g. there is no supernova explosion at the optically thick wind phase when the initial mass of CO WD is smaller than 0.9 $M_\odot$. So, considering the results in this paper, all the properties of SN 2006X can be explained by the WD + MS channel with the optically thick wind, including its birth rate and its age. Then, we suggest that the progenitor of supernovae like SN 2006X is WD + MS system, not WD + RG system.
References

[1] Blondin, S., Prieto, J.L., Patat, F., Challis, P., Hicken, M., Kirshner, R.P., Matheson, T., Modjaz, M., 2009, ApJ, 693, 207
[2] Branch, D., Fisher, A., Nugent, P., 1993, AJ, 106, 2383
[3] Chen, W., Li, X., 2007, ApJ, 658, L51
[4] Chen W., Li X., 2009, ApJ, 702, 686
[5] Hachisu, I., Kato, M., Nomoto, K., ApJ, 1996, 470, L97
[6] Hachisu, I., Kato, M., Nomoto, K., Umeda, H., 1999a, ApJ, 519, 314
[7] Hachisu, I., Kato, M., Nomoto, K., 1999b, ApJ, 522, 487
[8] Hachisu I., Kato M., Nomoto K., 2008, ApJ, 679, 1390 (arXiv: 0710.0319)
[9] Hamuy , M. et al., 2003, Nature, 424, 651
[10] Han, Z., Podsiadlowski, P., Eggleton, P.P., 1995, MNRAS, 272, 800
[11] Han, Z., Podsiadlowski, Ph., 2004, MNRAS, 350, 1301
[12] Han, Z., Podsiadlowski, Ph., 2006, MNRAS, 368, 1095
[13] Han, Z., 2008, ApJ, 677, L109
[14] Hillebrandt, W., Niemeyer, J.C., 2000, ARA&A, 38, 191
[15] Ho, L.C., Filippenko, A.V., & Sargent, W.L.W., 1997, ApJS, 112, 315
[16] Hurley, J.R., Pols, O.R., Tout, C.A., 2000, MNRAS, 315, 543
[17] HUR02 Hurley, J.R., Tout, C.A., Pols, O.R., 2002, MNRAS, 329, 897
[18] Iben, I., Tutukov, A.V., 1984, ApJS, 54, 335
[19] Iglesias-Páramo J., Buat V., Takeuchi T.T. et al.2006, ApJS, 164, 38
[20] Kanpen, J.H., Cepa, J., Beckman, J.E., Soledad del Rio, M., Pedlar, A., 1993, ApJ, 416, 563
[21] Kanpen, J.H., Beckman, J.E., Cepa, J., Nakai, N., 1996, A&A, 308, 27
[22] Kippenhahn, R., Weigert, A., 1967, ZA, 65, 251
[23] Krisicunmas, K., Hastings, N.C., Loomis, K., McMillan, R., Rest, A., Riess, A.G., Stubbs, C., 2000, ApJ, 539, 658
[24] Langer, N., Deutschmann, A., Wellstein, S. et al., 2000, A&A, 362, 1046
[25] Leibundgut, B., 2000, A&ARv, 10, 179
[26] Li, X.D., van den Heuvel, E.P.J., 1997, A&A, 322, L9
[27] Lü, G., Zhu, C. Wang, Z., Wang, N., 2009, MNRAS, 396, 1086, arXiv:0903.2636
[28] Meng, X., Chen, X., Han, Z., 2009, MNRAS, 395, 2103, arXiv: 0907.2753
[29] Meng, X., Chen, X., Han, Z., Yang, W., 2009, RA&A, accepted, arXiv: 0907.2753
[30] Meng, X., Yang, W., Geng, X., 2009, PASJ, accepted, arXiv: 0908.2480
[31] Nomoto, K., Thielemann, F-K., Yokoï, K., 1984, ApJ, 286, 644
[32] Nomoto, K., Umeda, H., Hachisu, I. Kato, M., Kobayashi, C., Tsujimoto, T., 1999, in Truran J., Niemeyer T., eds, Type Ia Supernova :Theory and Cosmology.Cambridge Univ. Press, New York, p.63
[33] Nomoto, K., Uenishi, T., Kobayashi, C. Umeda, H., Ohkubo, T., Hachisu, I., Kato, M., 2003, in Hillebrandt W., Leibundgut B., eds, From Twilight to Highlight: The Physics of supernova, ESO/Springer serious “ESO Astrophysics Symposia” Berlin: Springer, p.115
[34] Patat, E. et al., Science, 317, 924
[35] Perlmutter, S. et al., 1999, ApJ, 517, 565
[36] Riess A.G., Filippenko A.V., Challis P. et al., 1998, AJ, 116, 1009
[37] Simon J. D., Gal-Yam A., Gnat O. et al. 2009, ApJ, 702, 1157
[38] Wang B., Meng X., Chen X., Han Z., 2009a, MNRAS, 395, 847
[39] Wang B., Chen X., Meng X., Han Z., 2009b, ApJ, 701, 1540
[40] Wang, L., 2005, ApJ, 635, L33
[41] Wang, X. et al., 2008, ApJ, 675, 626
[42] Webbink, R.F., 1984, ApJ, 277, 355
[43] Whelan, J., Iben, I., 1973, ApJ, 186, 1007
[44] Willems, B., Kolb, U., 2004, A&A, 419, 1057
[45] Wong, T. & Blitz, L., 2002, ApJ, 569, 157
[46] Yungelson, L., Livio, M., Tutukou, A. Kenyon, S.J., 1995, ApJ, 447, 656