The Impact of Type Ia Supernova Explosions on their Companions in Binary System

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Abstract

Using a simple analytic method, we calculate the impact effect between the ejecta of a SN Ia and its companion to survey the influence of initial parameters of the progenitor’s system, which is useful for searching the companion in a explosion remnant. The companion models are obtained from Eggleton’s evolution code. The results are divided into two groups based on mass transfer stage. For a given condition, more hydrogen-rich material is stripped from the envelope of a Hertzsprung-gap companion than that of a main-sequence companion, while a larger kick velocity and a larger luminosity are gained for a main-sequence companion. The kick velocity is too low to significantly affect the final spatial velocity of the companion, which is mainly affected by the initial parameters of the progenitor systems. The spatial velocity of the stripped material has an upper limit within the range of 8000 - 9500 km/s, which only depends on the total kinetic energy of the explosion. The stripped mass, the ratio of the stripped mass to the companion mass and the kick velocity of the companion all significantly depend on the initial companion mass and orbital period. Our model may naturally explain the spatial velocity of the star G in the remnant of Tycho’s supernova, while an energy-loss mechanism is needed to interpret its luminosity.

Keywords: supernova: general - supernova: individual: SN 1572

1 Introduction

Type Ia supernova (SNe Ia) have been successfully used to determine cosmological parameters, e.g. $\Omega_M$ and $\Omega_\Lambda$ (Reiss et al. [1998]; Perlmutter et al. [1999]), although we do not know about the exact nature of SNe Ia, especially about their progenitors. The most widely accepted model is a single degenerate Chandrasekhar mass model, in which a carbon-oxygen white dwarf (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 (Whelan & Iben [1973]). The companion may be a main-sequence star (WD+MS) or a red-giant star(WD+RG) (Yungelson et al. [1995]; Li et al. 1997; Hachisu et al. 1999a, 1999b; Nomoto et al. 1999; Langer et al. 2000). Hachisu & Kato (2003a, 2003b) argued that supersoft X-ray sources, which belong to the WD+MS channel, may be good candidates for the progenitors of SNe Ia. Observation of the remnant of SN 1572 (Tycho’s supernova)
favors the model of WD+MS and suggests that a star named star G is likely to be the companion of Tycho’s supernova (Ruiz-Lapuente et al. [2004]; Branch 2004).

In the single degenerate model, the supernova ejecta collides into the envelope of its companion and strips some hydrogen-rich material from the surface of the companion (Cheng 1974; Wheeler et al. 1975; Fryxell & Arnett 1981; Taam & Fryxell 1984; Chugai 1986; Livne et al. 1992; Langer et al. 2000). The stripped hydrogen-rich material may reveal itself by narrow H$\alpha$ emission or absorption lines in later-time spectra of SNe Ia (Chugai 1986; Filippenko 1997). Marietta et al. (2000) ran several high-resolution two-dimensional numerical simulations of the collision between the ejecta and the companion, which is a MS star, a subgiant (SG) star or a red giant (RG) star. They found that about 0.15 $M_\odot$ - 0.17 $M_\odot$ of hydrogen-rich material is stripped from a MS or a SG companion and there is no difference between the two companions. After the impact, the companion gains a small kick velocity and its luminosity will rise dramatically to as high as 5000 $L_\odot$. However, the SG companion model in M00 was gained by adjusting the entropy profile of the companion to simulate the effect of binary mass transfer and the MS companion model in M00 was represented by a 1.0 $M_\odot$ solar model. Their companion models were not from a detailed binary evolution calculation and the study was only for $Z = 0.02$, which lead the results to be different from an actual case. In this paper, we use some companion models obtained from the Eggleton’s evolution code (1971, 1972, 1973), which are more realistic than that in M00, to examine the effects of some initial parameters on the collision by a simple analytic method.

2 Method and Results

2.1 Method

We consider the case where a CO WD accretes matter from its companion which may be a MS star or a Hertzsprung-gap (HG) star. When the CO WD increases its mass to close to the Chandrasekhar mass, i.e. 1.378 $M_\odot$ (Nomoto, Thielemann & Yokoi 1984), it explodes as a SN Ia. Using the method of Han & Podsiadlowski (2004), we get 23 companion models for different metallicities which are listed in table 1. Then, the changes in the secondary structure due to mass transfer are taken into account naturally. An optically thick wind (Hachisu et al. 1996) is used to calculate the mass loss and angular moment loss from the binary system. The prescription of Hachisu (1999a) about hydrogen accretion is adopted to calculate the growth of the WD mass. The mass accumulation efficiency for helium-shell flashes is from Kato & Hachisu (2004). We changed one initial parameter and fixed the others to test the effect of different parameters on the final results. In table 1 we see that the mass transfer between a CO WD and its companion may begin as the companion is a MS star or a HG star. Note that the definition of HG stars in this paper is similar to that of the
SG model in M00. Evolving these binaries, we get the companion models as the WD mass increases to 1.378 $M_\odot$. After the explosion, a large amount of material is ejected as a series of spherically expanding shells and impact on the surface of the companion. The leading edge of these expanding shells collides into the envelope of the companion with a velocity $V_{SN,z}$ at $t_0 = a/V_{SN,0}$, where $a$ is the orbital separation of the binary system at the moment of the explosion and it is deduced from Eggleton’s equation (Eggleton [1983]) by assuming that the companion radius $R_{SN}$ equals the critical radius of its Roche lobe $R_{cr}$. We assume that the density in each spherical shell is uniform and that each shell moves at a fixed velocity $V_{SN} = a/t$, where $t$ and $t_0$ both take the moment of the explosion as the zero point of time. The density of the expanding shell at a distance $r = a$ from the explosion center is scaled as

$$\rho_{SN} = \frac{3M_{SN}}{4\pi a^3} (\frac{t}{t_0})^3,$$

(1)

after $t \geq t_0$, where $M_{SN}$ is the total mass of the CO WD at explosion, i.e. 1.378 $M_\odot$ (Chugai [1986]). The definitions of the density and the velocity are similar to those of M00. Then, the total kinetic energy of the ejecta is

$$E_k = \int_{t_0}^{\infty} \frac{1}{2} \rho_{SN} \cdot V \cdot dt \cdot 4\pi a^2 \cdot V^2 = \frac{3}{10} M_{SN} V_{SN,0}^2,$$

(2)

and the total momentum of the ejecta is

$$P_t = \int_{t_0}^{\infty} \rho_{SN} \cdot V \cdot dt \cdot 4\pi a^2 \cdot V = \frac{3}{4} M_{SN} V_{SN,0},$$

(3)

where $M_{SN}$ is the total mass of the ejecta. As shown in Fig. 1, the ejecta mass which collides into the $i$th slab in the envelope is calculated by

$$M_{i,SN} = M_{SN} \cdot \frac{R_{2,i}^2 - R_{2,i-1}^2}{4a^2},$$

(4)

where $R_{2,i}$ is the radius of the $i$th slab stripped from the companion. Then, the momentum of $M_{i,SN}$ is $P_i = \frac{3}{4} M_{i,SN} V_{SN,0}$. Assuming that the ejecta and the envelope material leave with the same velocity $v$ along the same direction of the ejecta velocity, we may get $v$ by momentum conservation. If $v$ exceeds the escape velocity $V_{esc}$ of the companion, the envelope material is stripped. Then, the amount of the stripped material is the sum of all the material in these stripped slabs. Since only the kinetic properties of the ejecta are considered, the composition of the ejecta is not considered. After the impact of the ejecta, a shock like a bowl develops (Fryxell & Arnett [1981]; M00). However, our method is unable to calculate the effect of the shock. We discuss whether our simplification is reasonable or not in the next subsection. The kinetic energy of the supernov ejecta is assumed to be $1 \times 10^{51}$ erg, which corresponds to the lower limit of the kinetic energy of normal SNe Ia (Gamezo et al. [2003]).

If the supernova ejecta injected into the companion envelope can not strip the material from the surface of the companion, i.e. $v < V_{esc}$, the ejecta will settle
in the companion and the momentum of the ejecta transfers to the companion. The companion then gains a kick velocity \( V_{\text{kick}} \) (Cheng [1974]; M00). During this process, some material reverses to the explosion center and the companion gains an added momentum (Fryxell & Arnett [1981]; M00). We neglect this effect because it does not significantly affect the final results (Fryxell & Arnett [1981]; M00). The kick velocity is gained by the conservation of linear momentum. Note that the ejecta is not always parallel to the axis between explosion center and companion center. However, we take the momentum of the ejecta settled in the companion as the ejecta’s momentum paralleled to the axis and neglected the effect of angle on the momentum paralleled to axis because the angle is very small.

2.2 discussion of the method

It is well known that a shock will develop after the impact of the ejecta. A large part of the material in the companion’s envelope will be heated by the shock and then be vaporized from the surface of the companion if their velocities exceed the escape velocity. So, the method used in this paper is very simple. To examine whether our method is reasonable or not, we use the same analytic method in this paper to calculate the models in M00. We re-calculated the model in Li & van den Heuvel ([1997]), using their method to get the SG model used in M00, and calculated the stripped mass using our analytic method, which is shown by a triangular point in Fig. 2. Here, the kinetic energy of the supernova ejecta is also from the W7 model of Nomoto et al. ([1984]) as used in M00. The stripped mass from our SG model is smaller than that of M00, but the difference is not very significant. We also calculate a 1 \( M_\odot \) solar model used in M00 by Eggleton’s stellar evolution code, and calculate the stripped mass from this MS model using the same analytic method in this paper. \( a/R_2 \) is changed according to M00, not from Eggleton’s equation (Eggleton [1983]). The results are shown by filled squares in Fig. 2. A similar linear relation between \( \log(\delta M) \) and \( \log(a/R_2) \) is gained as indicated by M00. However, the stripped mass in our model is smaller than that in M00 for small \( a/R_2 \) and larger than that in M00 for large \( a/R_2 \), which is derived from our simple method. Since the conservation of linear momentum and the completely inelastic collision are applied, and the shock induced in the secondary envelope by the impact of the ejecta is not considered, the effect of ablation induced by the shock is not considered. For the simple method, most of the energies which should be used to heat the secondary envelope and to vaporize the material in the envelope are lost with the stripped material for small \( a/R_2 \), while for large \( a/R_2 \), a part of energy which should heat the secondary envelope but were not used to strip the material are collected to strip the material from the surface of the companion in our model. Although the stripped mass in our models is different from that of M00, our method can give a similar trend to M00. We also use the same model as M00 and method in this paper to calculate the kick velocity of the companion. The results are shown in Fig. 3. The difference between our results and that of M00 is very small for all the models. This is a natural result since
the kick velocity is mainly decided by the collision section of the companion for a given companion model. We also gain a similar linear relation between \( \log(V_{\text{kick}}) \) and \( \log(a/R_2) \) to that indicated by M00. Then, although the stripped mass is different from that of M00, the kick velocity may be correct. Since we only want to discuss the trend of the effect of some initial parameters, in this context, it is not unreasonable for our method to do this. However, a fact must be emphasized that since \( \log(a/R_2) \) concentrates in the range of (0.35-0.5) in our models, the stripped mass in our models should be taken as a lower limit for a real case, especially for MS models.

2.3 results

The stripped mass \( \delta M \) and the ratio of \( \delta M \) to the companion mass \( M_{SN} \) at explosion are presented in panels (a) and (b) of Fig. 4. Although there is no obvious difference between the MS and HG companions, the results seem to be divided into two groups based on the mass transfer stage. For a given \( a/R_2 \), the stripped mass \( \delta M \) of the MS models is always smaller than that of HG ones. Also, \( \delta M/M_{SN} \) of MS models is always slightly smaller than that of HG ones at a certain \( M_{SN} \). These differences are derived from the different structure of the companions. If the mass transfer begins as the companion is in the HG, the companion has a denser core and a more expanded envelope than the MS companion. Then, the binding energy is smaller and the material in the envelope is easier to strip off.

The kick velocities of the companions are shown in panel (d) of Fig. 4. \( V_{\text{kick}} \) is low and has little influence on the spatial velocity of the companion, which is consistent with the numerical simulation (Fryxell & Arnett [1981]; M00). In Fig. 4 we see that \( V_{\text{kick}} \) is relevant to the mass-transfer stage: \( V_{\text{kick}} \) of a HG companion is always smaller than that of a MS one at a certain \( M_{SN} \). However, it is difficult to tell when the mass transfer begins only according to a given kick velocity. There seems to exist a peak value at a position of \( M_{SN} \approx 1.0 M_\odot \). More calculation is needed to test whether this peak value is real or not.

After the impact, the companion accretes a part of the ejecta and will be puffed up, and its luminosity will increase sharply. At the same time, the hydrogen-burning quenches because of its lower central temperature and density and the companion is similar to a pre-main-sequence star (M00). Because it is difficult to estimate the thermal time scale of the companions in this situation, we simply assume that the time scale for the companion to recover its thermal equilibrium is \( 10^4 \) yr (M00) for all of the models. Note however the thermal timescale actually depends on the properties of the companion’s envelope before SN Ia explosion (Podsiadlowski [2003]), and our assumption oversimplifies the problem. According to virial theorem, we assume that half of the kinetic energy of the ejecta accreted by the companion is radiated by photon energy. The companion’s luminosity is estimated via the half of the kinetic energy being divided by \( 10^4 \) yr. The results are shown in panel (c) of Fig. 4 which are well consistent with the numerical simulation of M00. The luminosity depends slightly on the mass transfer stage. For a given \( a/R_2 \), the luminosity of the MS
models is slightly larger than that of the HG ones. The luminosity decreases with \( a/R^2 \), which is a natural result since the collision section of the companion decreases with \( a/R^2 \). Because of the rough estimation of the thermal time scale here, we do not discuss the relation between the luminosity and the initial parameters of the binary system.

No obvious evidence shows that the stripped mass, \( \delta M \), the ratio of the stripped mass to companion mass, \( \delta M/M_{2}^{SN} \), and the kick velocity, \( V_{\text{kick}} \), depend significantly on the initial metallicity and the initial WD mass. The initial companion mass \( M_{2}^i \) and the initial orbital period \( P^i \) affect the final result as shown in Fig. 5. In that figure, we see that both \( \delta M \) and \( \delta M/M_{2}^{SN} \) increase with \( M_{2}^i \) and \( P^i \), and \( V_{\text{kick}} \) increases with \( M_{2}^i \) while it decreases with \( P^i \). These facts are relevant to the evolutionary degree of the companion at explosion – a more massive star evolves more quickly and has a less compact envelope at a given stage. Meanwhile, larger \( P^i \) results in the companion being further away from zero age main sequence (ZAMS) and the companion also has a less compact envelope at explosion. The matter in this less compact envelope will be stripped off more easily. For the same evolutionary reason, a larger \( M_{2}^i \) and a smaller \( P^i \) result in a larger collision section.

The \( V_{\text{kick}} \) is not high compared to the orbital velocity, \( V_{\text{orb}} \). The ratios of \( V_{\text{kick}}/V_{\text{orb}} \) locate in the range of 0.25 to 0.5. The spatial velocity, \( V_{2}^{SN} = \sqrt{V_{\text{kick}}^2 + V_{\text{orb}}^2} \), of the companion after an explosion is mainly decided by the initial parameters of the progenitor, except for metallicity. The spatial velocity increases with the companion mass and decreases with the WD mass and the period, which are natural results of binary evolution. The spatial velocity ranges from 120 km/s to 200 km/s and the velocity of star G (about 136 km/s) is located in this range.

3 Discussion and Conclusion

By numerical simulation, Marietta et al. (2000) performed an excellent detailed study of the impact of a supernova’s ejecta on its companion. The study shows that there is no difference for the stripped mass \( \delta M \) and for the ratio of \( \delta M/M_{2}^{SN} \) between MS companions and SG companions. The simple analytic solution in this paper is similar to the result of numerical simulations. However, there seem to be two groups based on the mass-transfer stage – both \( \delta M \) and \( \delta M/M_{2}^{SN} \) from SG models are always larger than those from MS models at certain conditions, i.e. at a fixed \( a/R_2 \) or \( M_{2}^{SN} \). This fact indicates that the companion structure is important to discriminate \( \delta M \) and \( \delta M/M_{2}^{SN} \) during SNe Ia explosions. It is possible that the process of mass transfer has a significant effect on the final result. We did not find the linear relation between \( \log(\delta M) \) and \( \log(a/R_2) \) or between \( \log(V_{\text{kick}}) \) and \( \log(a/R_2) \) in Fig. 4 as given by M00. This result is also relevant to the choice of the companion model and this is because Marietta et al. (2000) simply changed \( a/R_2 \) for the same companion model to examine the effect of \( a/R_2 \). The importance of the companion structure is also verified by the fact that we can gain a similar relation to M00 by adopting a similar
assumption of M00.

A caveat must be emphasized that the kinetic energy of the supernova ejecta translates into the thermal energy of the companion envelope and a part of the material in the envelope is heated and is vaporized to escape from the companion, which may increase the stripped mass (Fryxell & Arnett 1981; M00). We do not consider this effect in the analytic solution although this effect may affect the stripped mass significantly (Fryxell & Arnett 1981; M00). Therefore, as discussed in subsection 2.2, $\delta M$ in our models is only a lower limit. Note that our analytic method may have oversimplified the physics of the interaction between the ejecta and the companion star, e.g. we did not calculate the effect of the shock formed between the ejecta and the companion star. In this context, our results may be taken as a qualitative one giving the trend of real case.

However, Leonard (private communication 2007) showed the amount of the stripped mass may be less than 0.01 $M_\odot$ as derived from observation, although this result relies on the model of M00. The contradiction between the observation of Leonard and the prediction of M00 might be from the companion model used by M00, especially the effect of the mass transfer on the structure of the companion. For a realistic case, before SN Ia explodes, most material in the companion’s envelope has transferred onto the CO WD. At the same time, the radius of the companion decreases (Langer et al. 2000). These facts make the companion more compact than that of a star with the same mass while without mass transfer, such as a solar model used in M00. It is more difficult to strip material from the envelope of a compact companion and the stripped mass in M00 should therefor be lower. The result that the stripped mass in this paper is lower than that in M00 might go in the right direction, showing the importance of the companion models.

We do not find the dependence of the $\delta M$, $\delta M/M_{SN}^2$, and $V_{kick}$ on the metallicity. However, the result depends on an assumption that the mass of the evaporated material is independent of the metallicity. Since there is not any numerical simulation or analytic method to test this assumption, we have no way to estimate the effect of the metallicity on the evaporation by our simple method. Chugai (1986) showed that for the given explosion energy of a SN Ia, the mass of the evaporated material is proportional to $(\rho a^3)^{-0.5}$, where $\rho$ is the density of the companion’s envelope at the explosion and $a$ is the orbital separation at the explosion. Increasing $(\rho a^3)^{-0.5}$ leads more mass evaporated. According to our calculation, there is no systemic effect of the metallicity on $\rho a^3$ and $\rho a^3$ is mainly decided by the mass transfer. Then, it is plausible that there is no correlation between the metallicity and the $\delta M$, $\delta M/M_{SN}^2$, $V_{kick}$.

The effect of the kinetic energy of supernova ejecta can be examined by changing the kinetic energy. If $E_k = 1.5 \times 10^{51}$ erg, which corresponds to the upper limit of the kinetic energy of normal SNe Ia (Gamezo et al. 2003), $\delta M$ increases by about 0.01 $M_\odot$ compared with that of $E_k = 1.0 \times 10^{51}$ erg, the luminosity of the companion increase by about 20% to 30% and the kick velocity also increases slightly. An interesting phenomenon is that there is a maximal spatial velocity at infinity for the stripped material and this maximal
velocity only depends on the kinetic energy of the supernova ejecta. It is in the range of 8000 km/s to 9500 km/s for an $E_k$ of $1.0 \times 10^{51}$ erg to $1.5 \times 10^{51}$ erg. However, almost for all the models, the special velocities of a half of the stripped materials are less than 1100 km/s. This is roughly consistent with the numerical simulation (820 km/s and 890 km/s for MS and SG models, respectively (M00)).

By the same analytic method, we use a polytropic stellar model of $1 \, M_\odot$ to examine the influence of companion structure on the results. These results are plotted in Fig. 4 as a solar symbol. For a given condition, $\delta M$ and $\delta M/M_{SN}$ are much larger than that of our MS models and even larger than that of our HG models. $L$ and $V_{kick}$ increase by a factor of 2-9 and 3-8, respectively. These differences indicate that the values of $\delta M$, $L$ and $V_{kick}$ are overestimated by using a polytropic stellar model. Note the fact that we can gain similar results to M00 by using models similar to those of M00, especially for kick velocity. So the influence of companion structure is very important. The different structures between the MS models and the SG models result in different stripped mass, luminosity and kick velocity. Then, the difference between our results and that in M00 might be from the different structure of the companion.

Star G is likely to be the companion of Tycho’s supernova and it has a lower spatial velocity and luminosity compared to theoretical predictions (Canal et al. [2001]; Marietta et al. [2000]). Our model may naturally interpret the spatial velocity of Star G, while the luminosity of Star G is lower than the prediction of our model and than that of the numerical simulation of M00 (by about 3 orders of magnitude). Although this result may be partly from our approximation of the thermal timescale of the companion, it may still reflect the fact to some extent. Podsiajlovsky ([2003]) showed that if the energy injected into the companion’s envelope is larger than $10^{47}$erg, the luminosity of the companion after $10^3$yr is higher than that of Star G by at least one order of magnitude. Noting that the energy injected into the companion’s envelope in all of our models is much larger than $10^{47}$erg and considering that the time since Tycho supernova (SN 1572) exploded is less than 500 yr, we suggest that an energy-loss mechanism might be needed to explain the low luminosity of Star G. Much effort is needed to solve this problem.

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Table 1: Initial parameters, i.e. metallicity (Column 2), WD mass (Column 3), companion mass (Column 4) and orbital period (Column 5) for our binary system model. The stage when mass transfer begin is shown in Column 6.

| $N_{\text{model}}$ | $Z^*$ | $M_{\text{WD}}/M_\odot$ | $M_{i}/M_\odot$ | $\log(P^i$/day) | Onset |
|---------------------|-----|----------------|-------------|----------------|-------|
| 1                   | 0.01| 1.00          | 2.40        | 0.60           | HG    |
| 2                   | 0.01| 1.00          | 2.40        | 0.40           | MS    |
| 3                   | 0.01| 1.00          | 2.20        | 0.00           | MS    |
| 4                   | 0.01| 1.10          | 3.20        | 0.20           | HG    |
| 5                   | 0.01| 1.10          | 2.40        | 0.40           | HG    |
| 6                   | 0.01| 1.20          | 3.20        | 0.20           | MS    |
| 7                   | 0.01| 1.20          | 2.20        | 0.20           | MS    |
| 8                   | 0.02| 0.75          | 2.00        | 0.20           | MS    |
| 9                   | 0.02| 0.80          | 2.20        | 0.40           | HG    |
| 10                  | 0.02| 1.00          | 2.20        | 0.40           | HG    |
| 11                  | 0.02| 1.00          | 2.20        | 0.00           | MS    |
| 12                  | 0.02| 1.00          | 2.40        | 0.20           | MS    |
| 13                  | 0.02| 1.00          | 2.40        | 0.40           | HG    |
| 14                  | 0.02| 1.00          | 2.40        | 0.60           | HG    |
| 15                  | 0.02| 1.10          | 3.20        | 0.20           | MS    |
| 16                  | 0.02| 1.10          | 2.20        | 0.40           | HG    |
| 17                  | 0.03| 0.80          | 2.20        | 0.40           | HG    |
| 18                  | 0.03| 1.00          | 2.20        | 0.00           | MS    |
| 19                  | 0.03| 1.00          | 2.40        | 0.40           | HG    |
| 20                  | 0.03| 1.00          | 2.40        | 0.60           | HG    |
| 21                  | 0.03| 1.10          | 2.40        | 0.20           | MS    |
| 22                  | 0.03| 1.10          | 3.20        | 0.20           | MS    |
| 23                  | 0.03| 1.10          | 2.20        | 0.40           | HG    |

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Figure 1: Schematic for the impact between the supernova’s ejecta and its companion. Supernova ejecta collides into the envelope of its companion and strips some hydrogen-rich material from the surface of the companion.
Figure 2: Comparison between the stripped masses in this paper and those of M00. Filled circles are from M00 and filled squares are our results for the MS model. Dashed line and solid line fit linearly our results of MS models and those of M00, respectively. The triangular and Hexagonal points are our result for the SG model and that of M00, respectively.
Figure 3: Similar to Fig. 2 but for kick velocity.
Figure 4: In panels (a) and (c), stripped mass, $\delta M$, and luminosity of companions, $L$, are shown as functions of the ratio of separation to the radius of companions, $a/R_2$. Panels (b) and (d) show the ratio of stripped mass to companion mass, $\delta M/M_{SN}$, and the kick velocity, $V_{kick}$, vs the companion mass at the moment of explosion. Triangles, squares and pentacles denote the cases for $Z=0.01$, 0.02 and 0.03, respectively. Filled symbols denote that mass transfer onsets at Hertzsprung gap and hollow symbols denote that mass transfer onsets at main sequence. Solar symbols are the results from a polytropic stellar model of $1\ M_\odot$. 
Figure 5: Stripped mass, $\delta M$, ratio of the stripped mass to companion mass, $\delta M/M_{SN}^2$, and kick velocity of the companion, $V_{\text{kick}}$, vs the initial companion mass, $M_i^2$, and orbital period, $\log(P_i/\text{day})$. The points linked by lines have same initial parameters excepting abscissas. The symbols are the same as in Fig. 5.