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Contribution of dust produced by binary merger ejecta *

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Abstract By means of a population synthesis code and by constructing a simple toy model of dust produced by asymptotic giant branch (AGB) stars, common envelope (CE) ejecta and binary merger ejecta, we estimate the dust product rates (DPRs) of these processes in the Milky Way. The total DPR from AGB stars is $\sim 6.7 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$, in which about 73% of dust grains are carbon, 24% are silicates and 3% are iron. The total DPR from CE ejecta is $\sim 4.2 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$, in which about 83% of dust grains are silicates, about 12% are carbon and 5% are iron. The DPR from binary merger ejecta is less than 1/3 that from AGB stars or CE ejecta, and it could even be negligible under certain circumstances. Therefore, compared with AGB stars and CE ejecta, the contribution of dust produced by binary merger ejecta to total dust grains in the Milky Way is smaller or can be negligible.

Key words: binaries: close — stars: evolution — circumstellar matter — dust

1 INTRODUCTION

The interstellar medium (ISM) of a galaxy is one of the drivers of its own evolution. Its composition determines many characteristics of the next generation of stars. Dust is one of the important ingredients of the ISM and plays a central role in the astrophysics of the ISM. It is an important component for understanding the paradigms of galaxy formation and evolution. Dust abundance is directly connected with galaxy growth through the formation of new stars.

According to a popular point of view, the stellar wind emanating from asymptotic giant branch (AGB) stars and ejecta from type II supernovae (SNe) have long been considered the main sources of dust formation (e.g., Gail et al. 2009; Dunne et al. 2003; Gall et al. 2011). Indeed, red supergiants, luminous blue variables, Wolf-Rayet stars and type Ia SNe can also produce dust. However, compared with AGB stars and type II SNe, their contribution to dust production can be neglected (e.g., Zhukovska et al. 2008; Gall et al. 2011). According to the classical theory of nucleation (Feder et al. 1966), Lü et al. (2013) suggested that the ejecta that is produced during common-envelope (CE) evolution in close binary systems can provide a good environment for dust formation and growth. Using a toy model, Lü et al. (2013) found that compared to dust production in AGB stars, the dust produced in CE ejecta can be quite significant and could even dominate under certain circumstances.

Recently, using the data from the Thermal-Region Camera Spectrograph, Nicholls et al. (2013) showed that V1309 Sco had become dominated by mid-IR emission since eruption, which indicated

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the presence of a significant amount of dust in the circumstellar environment. V1309 Sco erupted in September 2008 (Nakano et al. 2008). Subsequently, its evolution indicated it is a luminous red nova (Mason et al. 2010). Soker & Tylenda (2003) suggested that luminous red novae are produced by a binary merger. Tylenda et al. (2011) analyzed photometric data from V1309 Sco observed by the OGLE project since August 2001, and showed that it indeed originated from the merger of a contact binary. Up to now, V1309 Sco has been the first documented case of a binary merger. Furthermore, having considered that the absence of detectable mid-IR emission before the outburst, Nicholls et al. (2013) suggested that the dust around V1309 Sco was produced in an eruptive merger event.

Very recently, using the model of dust formation and growth in CE ejecta, we considered that these dust grains around V1309 Sco were efficiently produced in its progenitor-binary merger ejecta (Zhu et al. 2013). We estimated that $\sim 5.2 \times 10^{-4}\ M_{\odot}$ of dust grains around V1309 Sco were produced. In this paper, we investigate the contributions of dust formed by binary merger ejecta to interstellar dust.

In Section 2 the model of the ejecta during binary merger is described. The main results and discussions are presented in Section 3. Section 4 gives conclusions.

2 MODEL

In order to estimate dust quantities produced by binary merger ejecta, we need to know the ejecta's mass, chemical abundances, density and temperature.

2.1 Mass of Binary Merger Ejecta

In a binary system, mass transfer occurs when a star fills its Roche lobe. If the ratio of the donor's mass to the gainer's mass is larger than a certain value ($q_{\rm cr}$), the mass transfer is dynamically unstable. The most typical case involves a giant or giant-like star (donor) transferring mass to a normal star (gainer). Due to the relatively long thermal timescale, the gainer cannot accept the overflowing material. The donor envelope overfills the Roche lobe of the both stars, and forms a CE. The donor core and the gainer are contained within the CE. Owing to its expansion, the CE rotates more slowly than the orbital velocity of the donor core and the gainer, which results in friction occurring. The donor core and the gainer release their orbital energy to drive of the entire envelope, and they spiral together.

If the orbital energy is large enough that the entire envelope is ejected away, the system undergoes a CE evolution, and the donor core and gainer survive and become a close binary system. Lü et al. (2013) investigated the dust formation and growth in CE ejecta. If the orbital energy is too small, the binary probably may generate a luminous red nova, and the donor and gainer merge into a single star. There is matter ejected from the binary during the merging process. However, it is very difficult to know how much matter is ejected. Using the 3D smoothed-particle hydrodynamics code *StarCrash*, Ivanova et al. (2013) performed several numerical simulations to estimate the mass ejected during the merging process of the progenitor binary of V1309 Sco. In their simulations, the merger ejects a small fraction of the giant envelope, and the ejected mass varies from 0.03 to 0.08 $M_{\odot}$. Jiang et al. (2010) investigated the mass loss during the merging process that occurs in W Ursae Majoris binaries. They suggested that these binaries should lose a large amount of mass ($\sim$21%–33% of the total mass) during the merging process. Following Jiang et al. (2010), we assume that 25% of the total mass is ejected during the merging process, that is, the mass ejected is given by

$$M_{\rm ej} = 25\%(M_{\rm gainer} + M_{\rm donor})\,. \tag{1}$$

Of course, $M_{\rm ej}$ should be smaller than the mass of the donor's envelope.

In this work, in order to discuss the effects of $M_{\rm ej}$ on dust quantities produced by binary merger ejecta, we take different $M_{\rm ej}$: (i) Following Zhu et al. (2013), we take $M_{\rm ej} = 0.05\ M_\odot$ which is the average value of the matter ejected around V1309 Sco; (ii) We use Equation (1) to estimate $M_{\rm ej}$.

2.2 Chemical Abundances of Binary merger Ejecta

The chemical abundances of binary merger ejecta are determined by the donor's envelope. For a single star, three dredge-up processes and hot bottom burning in a star with initial mass larger than $4\ M_\odot$ may change the chemical abundances of the stellar envelope. In binary systems, mass transfer can change the chemical abundances of the stellar envelope.

In this work, we use the model of Lü et al. (2008) to simulate the chemical evolutions of ^{1}H, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{20}Ne and ^{22}Ne in the stellar envelope of a binary system. The abundance ratio of carbon to oxygen, C/O=(^{12}C+^{13}C)/(^{16}O+^{17}O), determines the dust species produced by CE ejecta. Oxygen-rich ejecta ($\rm C/O < 1$) forms silicate dust, while carbon-rich ejecta ($\rm C/O > 1$) yields amorphous carbon and a small amounts of SiC dust. We assume that other key elements (Fe, Si, Mg and S) in the stellar envelope that form dust do not change.

In this work, we take the metallicity $Z = 0.02$. The initial element abundances on the surface of the Sun are taken from Anders & Grevesse (1989).

2.3 Degrees of Condensation and Dust Quantities from Binary Merger Ejecta

When binary merger ejecta begins to expand, its temperature and mass density start to decrease, which determines the amount of dust formation and growth. However, to our knowledge, there is no comprehensive theoretical model or observational datum to describe the mass density and the temperature of binary merger ejecta.

From a theoretical point of view, the formation and growth of dust grains still represent a widely unsolved problem. Simultaneously, it is very difficult to simulate the evolutions of mass density and temperature of binary merger ejecta. In this work, we do not simulate the exact process of the formation and growth of dust grains in binary merger ejecta. Considering that dust can efficiently form and grow throughout the process of forming binary merger ejecta in the case with a high γ value (Lü et al. 2013), we roughly estimate the quantities of dust produced from binary merger ejecta by the following assumptions:

(i) For oxygen-rich binary merger ejecta ($\rm C/O < 1$), silicate grains should be produced. As Ferrarotti & Gail (2006) did, we use the degrees of condensation of the key elements for the different species to describe how much dust is formed. Based on mid-IR photometry and spectra of the merged binary V1309 Sco, Nicholls et al. (2013) showed that the best fit to the absorption features is amorphous pyroxene $\rm MgFeSi_2O_6$ grains. According to observations of interstellar gas and dust and theoretical models, Draine (2009) suggested that the Si is predominantly in amorphous silicate material whose composition is likely to be $\rm Mg_{1.1}Fe_{0.9}SiO_4$. In this work, we assume that oxygen-rich binary merger ejecta ($\rm C/O < 1$) mainly produces amorphous silicate dust ($\rm Mg_{1.1}Fe_{0.9}SiO_4$). The degrees of condensation of Si element, $f_{\rm si}$, can describe the quantity of dust by

$$M_{\rm d}^{\rm si} = M_{\rm ej} X_{\rm si} \frac{A_{\rm silicate}}{A_{\rm si}} f_{\rm si}\,, \tag{2}$$

where $M_{\rm ej}$ is the mass of ejecta produced in the binary merger, $X_{\rm si}$ is the elemental abundance of Si in binary merger ejecta by mass, and $A_{\rm silicate}$ and $A_{\rm si}$ are the molecular and atomic weight of $\rm Mg_{1.1}Fe_{0.9}SiO_4$ and Si, respectively.

(ii) Carbon-rich binary merger ejecta ($\rm C/O > 1$) forms carbonaceous grains and solid iron. There may be various candidates for carbonaceous grains (Zubko et al. 2004). However, for simplicity, following Ferrarotti & Gail (2006), we assume that carbonaceous grains are solid carbon and SiC. Based on simulations in Zhukovska et al. (2008), under the same conditions, the quantity of solid carbon is much higher than that of SiC. Therefore, in this work, we only estimate the quantities of solid carbon and iron by

$$M_{\rm d}^{\rm ca} = M_{\rm ej}\Big[12 \times (X_{\rm c}/12 - X_{\rm o}/16)\Big] f_{\rm ca} \tag{3}$$

and

$$M_{\rm d}^{\rm ir} = M_{\rm ej} X_{\rm fe} f_{\rm fe}, \tag{4}$$

respectively. Here, $f_{\rm ca}$ and $f_{\rm fe}$ are the degrees of condensation for C and Fe in solid carbon and iron, respectively.

Therefore, in the present paper, the quantities of dust produced in binary merger ejecta mainly depend on the degrees of condensation: $f_{\rm si}$, $f_{\rm ca}$ and $f_{\rm fe}$. Draine (2009) showed that the abundant elements Mg, Si and Fe reside primarily in dust, and perhaps 2/3 of element C is in dust. Similarly, Lü et al. (2013) showed that about 90% of the Si in the binary merger ejecta condenses into silicate grains in the simulations with $\gamma = 0.4$, in which γ is a parameter to describe the ejecta's temperature evolution with distance R by $T = T_0(R_0/R)^\gamma$. Here, R_0 and T_0 are the initial distance of ejecta from the star and the initial temperature of ejecta respectively. In this work, we assume that $f_{\rm si} = f_{\rm ca} = f_{\rm fe} = 0.8$.

2.4 Dust Quantities from AGB Stars and CE Ejecta

In order to discuss the contribution of dust produced by binary merger ejecta, we must estimate the dust quantities from AGB stars and CE ejecta. Considering that the dust production of SNe is very uncertain in the Large Magellanic Cloud (LMC) (Matsuura et al. 2009), we do not consider dust quantities from SN ejecta.

For AGB stars, using stellar population synthesis models, Ferrarotti & Gail (2006) calculated the quantities of dust from stars with different initial masses ($1\,M_\odot \leq M < 8\,M_\odot$) and different metallicities. Zhukovska et al. (2008) generated a more detailed grid for quantities of dust. In this work, we can calculate the dust quantities produced by AGB stars in the different models by the linear interpolation of a stellar mass with the results of $Z = 0.02$ from Zhukovska et al. (2008).

For CE ejecta, we use a method that is summarized as follows:

(i) For oxygen-rich CE ejecta ($\rm C/O < 1$), silicate grains should be produced. In this work, similar to binary merger ejecta, we assume that oxygen-rich CE ejecta ($\rm C/O < 1$) mainly produces amorphous silicate dust ($Mg_{1.1}Fe_{0.9}SiO_4$). The degrees of condensation for Si, $f_{\rm si}$, can describe the quantity of dust by

$$M_{\rm d}^{\rm si} = M_{\rm en} X_{\rm si} \frac{A_{\rm silicate}}{A_{\rm si}} f_{\rm si}\,, \tag{5}$$

where $M_{\rm en}$ is the mass of CE ejecta, $X_{\rm si}$ is the elemental abundance of Si in CE ejecta by mass, and $A_{\rm silicate}$ and $A_{\rm si}$ are the molecular and atomic weight of $Mg_{1.1}Fe_{0.9}SiO_4$ and Si, respectively.

(ii) Carbon-rich CE ejecta (C/O>1) forms carbonaceous grains and solid iron. There may be various candidates for carbonaceous grains (Zubko et al. 2004). However, for simplicity, following Ferrarotti & Gail (2006), we assume that carbonaceous grains are solid carbon and SiC. Based on the simulations in Zhukovska et al. (2008), under the same conditions, the quantity of solid carbon is much higher than that of SiC. Therefore, in this work, we only estimate the quantities of solid carbon and iron by

$$M_{\rm d}^{\rm ca} = M_{\rm en}\Big[12 \times (X_{\rm c}/12 - X_{\rm o}/16)\Big] f_{\rm ca} \tag{6}$$

and

$$M_{\rm d}^{\rm ir} = M_{\rm en} X_{\rm fe} f_{\rm fe}, \tag{7}$$

respectively.

In this work, $f_{\rm si}$, $f_{\rm ca}$ and $f_{\rm fe}$ are equal for CE ejecta and binary merger ejecta.

2.5 Basic Parameters for Population Synthesis

Like in the standard models considered in our literature (e.g., Lü et al. 2006, 2011a, 2013; Zhu et al. 2012, 2013), we use the method of population synthesis to calculate the quantities of dust produced by CE events and AGB stars in the Milky Way. We use the initial mass function in Miller & Scalo (1979) for primary components. The primary mass is generated using the formula suggested by Eggleton et al. (1989)

$$M_1 = \frac{0.19X}{(1-X)^{0.75} + 0.032(1-X)^{0.25}}\,, \tag{8}$$

where X is a random variable uniformly distributed in the range [0,1].

The mass ratio distribution is quite controversial. We only consider a constant mass ratio distribution (Kraicheva et al. 1989; Goldberg & Mazeh 1994),

$$n(q) = 1,\;\; 0 < q \leq 1\,, \tag{9}$$

where $q = M_2/M_1$.

In our work, the most important input parameter is the distribution of initial binary separations which directly determines how many binaries undergo Roche-lobe overflow. However, to our knowledge, there is no confirmed observational evidence to describe it. Yungelson et al. (1993) assumed that the distribution over initial separations, A_0, is flat over $1 < \log A_0/R_\odot < 6$. The distribution of separations is given by

$$\log a = 5X + 1\,, \tag{10}$$

where X is a random variable uniformly distributed in the range [0,1] and a is in $R_\odot$.

The model is normalized to formation of one binary with $M_1 \geq 0.8\ M_\odot\ {\rm yr}^{-1}$ (Yungelson et al. 1993; Han et al. 1995b,a; Lü et al. 2011b; Zhu et al. 2012). We use 2×10^7 binary systems in the Monte Carlo simulations. This gives a statistical error $\leq 6\%$ for the occurrence rate of Galactic binary merger events.

3 RESULTS AND DISCUSSION

We simulate the evolutions of 2×10^7 binaries with initial binary separations of $10 - 10^6\ R_\odot$. About 65% of binaries do not undergo Roche lobe mass transfer, and their evolutions are similar to the case of single stars. When they evolve into the AGB stage and produce dust, about 35% of binaries undergo Roche lobe overflow at least once, in which about 17% of them undergo a stable mass transfer and about 83% of them undergo dynamical mass transfer and form CEs. About 30% of the binaries undergo CE evolutions. About 2/3 of them can eject the whole CE, and dust can efficiently form and grow in the CE ejecta. About 1/3 of them cannot eject the CE and participate in a binary merger. In our work, binary merger ejecta can also produce dust.

In Table 1, we give our estimate of the dust production rates (DPRs) in the Milky Way from AGB stars, CE ejecta and binary merger ejecta. The total DPR from AGB stars is $\sim 6.7 \times 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, in which about 73% of dust grains are carbon, 24% are silicates and 3% are iron. The total DPR from CE ejecta is $\sim 4.2 \times 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, in which about 83% of dust grains are silicates, 12% are carbon and 5% are iron.

Table 1 DPRs of C-rich and O-rich AGB stars, C-rich and O-rich CE ejecta, and C-rich and O-rich binary merger ejecta are given in units of $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$. Gas injection rates (GIRs) are from AGB stars.

O-rich DPR	C-rich DPR	Iron DPR	GIR
AGB	stars		
16.2	49.5	2.0	35.1
CE ejecta ($10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$)			
35.1	5.2	1.9	10.6
Binary merger ($10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$)	ejecta		
$M_{\mathrm{ej}} = 0.05\ M_\odot$			
0.6	0.008	0.001	0.2
$M_{\mathrm{ej}} =$ Eq. (1)			
11.9	0.2	0.07	3.5

In the simulation with $M_{\mathrm{ej}} = 0.05\ M_\odot$, compared with AGB stars and CE ejecta, the DPR from binary merger ejecta is negligible. However, M_{ej} calculated by Equation (1) usually is much larger than 0.05 $M_\odot$. In the simulation with $M_{\mathrm{ej}} =$ Eq. (1), the DPR from binary merger ejecta is $\sim 1.2 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, which is about 18% and 29% of the DPRs from AGB stars and CE ejecta, respectively. Therefore, the DPR from binary merger ejecta greatly depends on the mass ejected during the merging process.

As Table 1 shows, in our simulations, the DPR of carbon grains originating from C-rich AGB stars is much higher than that of silicate grains from O-rich AGB stars in the Milky Way, which is consistent with that in Zhukovska et al. (2008). However, Weingartner & Draine (2001) estimated that total volume per H atom in the carbonaceous and silicate grain populations in the Milky Way, LMC and Small Magellanic Cloud. The volumes per H atom of the carbonaceous and silicate grain populations in the Milky Way are $\sim 1.4\times10^{-27}$ cm^3 H^{-1} and $\sim 4.2\times10^{-27}$ cm^3 H^{-1}, respectively. Considering the ideal graphite density of 2.24 g cm^{-3} and the silicate density of 3.5 g cm^{-3}, we can estimate that ~82% of dust grains in the Milky Way are silicate grains. Therefore, we consider that most of the silicate grains in the Milky Way are produced by O-rich CE ejecta. A detailed work about this is being prepared. When compared to AGB stars and CE ejecta, dust from binary merger ejecta is less or can even be negligible.

3.1 Properties of Binary Systems Producing Dust

Binaries have more complicated evolutions than single stars. In our work, not only AGB stars and CE ejecta but also binary merger ejecta can produce dust. In this section, we take $M_{\mathrm{ej}} =$ Eq. (1) during the merging process as an example to discuss the properties of binary systems producing dust.

Figure 1 shows the time evolution of accumulated dust masses produced by AGB stars, CE ejecta and binary merger ejecta in the Milky Way. Obviously, CE ejecta and binary merger ejecta produce dust earlier than AGB stars.

The time of dust formation depends on stellar mass. Figure 2 illustrates the contribution of stars with different masses to DPR. In binary systems, stars which can undergo CE evolutions have a wide range of mass (from $\sim 1\ M_\odot$ to more than 20 $M_\odot$) in a Hubble time, but the range of mass for AGB stars is between $1\ M_\odot$ and $8\ M_\odot$. Therefore, as Figure 1 shows, CE ejecta and binary merger ejecta can produce dust earlier than AGB stars. C-rich CE ejecta mainly originates from stars with masses of $\sim 1\ M_\odot - 6\ M_\odot$, while C-rich binary merger ejecta forms in stars with masses of $\sim 1\ M_\odot - 4\ M_\odot$. This discrepancy results from the following: the binary systems that can participate in a binary merger should have close binary separations, so there is not enough space for massive stars to evolve into C-rich stars.

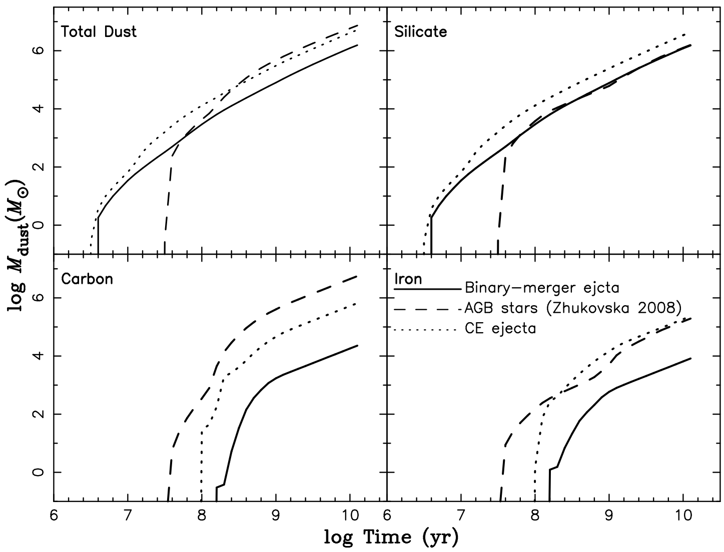

Fig. 1 Time evolution of accumulated dust masses produced by AGB stars, CE ejecta and binary merger ejecta in the Milky Way with a constant star formation rate. The four panels are for total, silicate, carbon and iron dust, respectively.

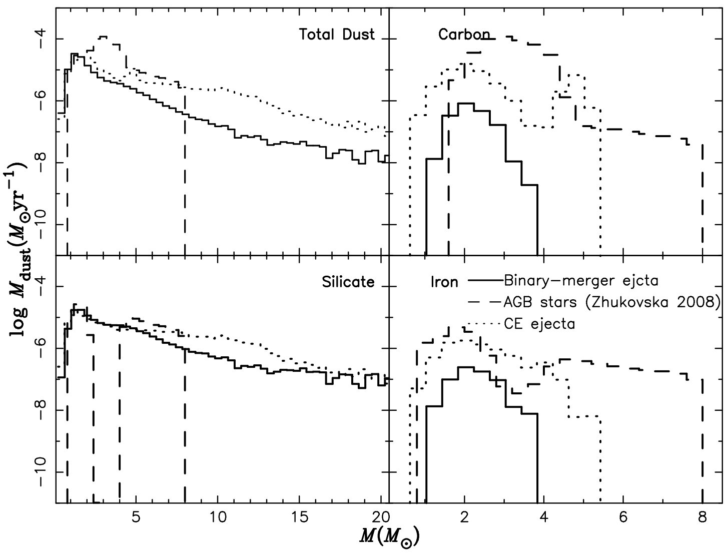

Fig. 2 The contribution of stars with different masses to DPR.

Figure 3 shows the contribution of stars with different initial binary separations to DPR. CE ejecta and binary merger ejecta mainly come from these binaries in which initial binary separations are between $\sim 10^1 - 4 \times 10^3 \; R_\odot$. In binary systems, it is possible for a star to evolve into a C-rich star when the binary separation is wide enough, but CE evolution can only occur when binary separation is narrow enough. Therefore, C-rich CE ejecta and C-rich binary merger ejecta originate

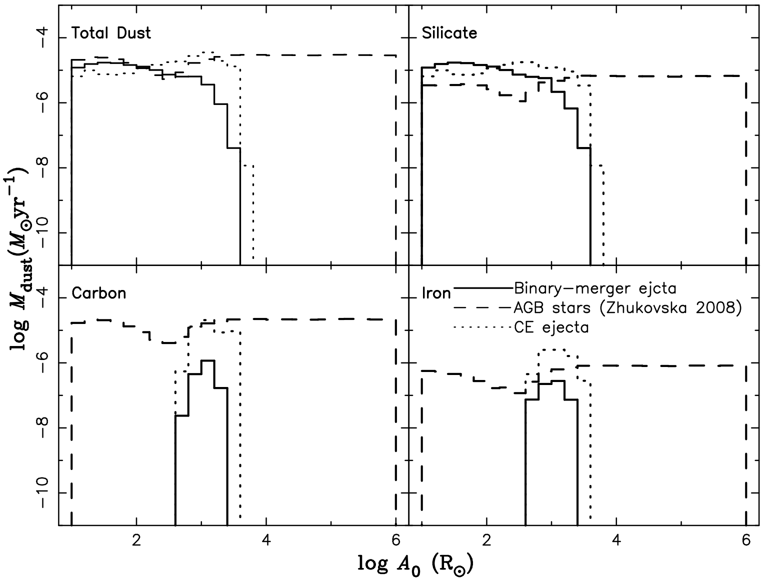

Fig. 3 The contribution of stars with different initial binary separations with respect to DPR.

from these binaries with initial binary separations of $\sim 4 \times 10^2 - 4 \times 10^3\ R_\odot$. Binary systems in which AGB stars produce dust have a distribution of initial separations wider than those in which CE ejecta and binary merger ejecta produce dust.

4 CONCLUSIONS

Unlike the LMC, to our knowledge, there is no observation that has estimated the DPR in the Milky Way because dust in the Galactic disk obscures possible observations. Up to now, we cannot compare our results with any observational value, but using a toy model we predict the DPR in the Milky Way. Based on our simulations, the total DPR from AGB stars is $\sim 6.7 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, in which about 73% of dust grains are carbon, 24% are silicates and 3% are iron. The total DPR from CE ejecta is $\sim 4.2 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, in which about 83% of dust grains are silicates, about 12% are carbon and 5% are iron. The DPR from binary merger ejecta is less than 1/3 that of those from AGB stars or CE ejecta, and it could even be negligible under certain circumstances.

Therefore, compared with AGB stars and CE ejecta, the contribution of dust produced by binary merger ejecta to total dust grains in the Milky Way is smaller or can be negligible. It is well known that dust formation and growth, CE evolution and chemical evolution of stars are open problems. However, by using the toy model in this paper, we consider that the dust formation and growth in binary systems deserve much more attention of the observers and astrophysicists.

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