DUST FORMATION IN THE EJECTA OF COMMON ENVELOPE SYSTEMS

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ABSTRACT

The material that is ejected in a common-envelope (CE) phase in a close binary system provides an ideal environment for dust formation. By constructing a simple toy model to describe the evolution of the density and the temperature of CE ejecta and using the AGBDUST code to model dust formation, we show that dust can form efficiently in this environment. The actual dust masses produced in the CE ejecta depend strongly on their temperature and density evolution. We estimate the total dust masses produced by CE evolution by means of a population synthesis code and show that, compared to dust production in asymptotic giant branch stars, the dust produced in CE ejecta may be quite significant and could even dominate under certain circumstances.

Key words: binaries: close – circumstellar matter – dust, extinction – stars: evolution

1. INTRODUCTION

Dust is one of the important ingredients of the interstellar medium (ISM). It plays a central role in the astrophysics of the ISM, from the thermodynamics and chemistry of the gas to the dynamics of star formation. It affects the thermal and chemical balance of the ISM by reprocessing the radiative output from stars, providing photoelectrons which heat gas, and depleting the gas of refractory elements, which are important cooling agents in the ISM (e.g., Nozawa et al. 2007). In addition, dust changes the spectra of galaxies: radiation at short wavelengths is attenuated, and energy is radiated in the infrared. Bernstein et al. (2002) estimated that 30% or more of the energy emitted as starlight in the universe is re-radiated by dust in the infrared.

From a theoretical point of view, the formation and growth of dust grains is still a widely unsolved problem (e.g., Gail & Sedlmayr 1999; Ferrarotti & Gail 2006; Gail et al. 2011). There are numerous efforts under way trying to understand the processes involved (e.g., Gail & Sedlmayr 1999; Todini & Ferrara 2001; Draine 2009). Until now, it has been assumed that dust mainly originates from the stellar winds of asymptotic giant branch (AGB) stars and supernova (SN) ejecta. Gail and his collaborators investigated the formation and growth of dust grains produced by AGB stars (e.g., Gail & Sedlmayr 1999; Ferrarotti & Gail 2006; Gail et al. 2009), while Todini & Ferrara (2001), Nozawa et al. (2003), and Bianchi & Schneider (2007), among others, have studied the condensation and survival of dust grains in SN ejecta.

Common envelopes (CEs) form as a result of dynamical timescale mass exchange in close binaries and play an essential role in their evolution (see, e.g., Paczynski 1976; Iben & Livio 1993). In most cases, CE evolution involves a giant star transferring matter to a normal or a degenerate star on a dynamical timescale. The giant envelope overfills the Roche lobes of both stars and engulfs the giant core and its companion. During the CE phase, orbital energy is transferred to the CE via dynamical friction between the orbiting components and the non-corotating CE. If enough orbital energy is deposited in the CE before the components merge, the whole envelope can be ejected on a dynamical timescale. The CE ejecta then rapidly expand. According to the classical theory of nucleation (Feder et al. 1966), the saturation pressure in most cases falls more rapidly than the pressure of the vapor, and the vapor becomes supersaturated when saturated vapor expands adiabatically. The formation of dust grains from the gas phase can occur from vapor in a supersaturated state. Therefore, CE ejecta provide a potentially important environment for the formation of dust grains. To our knowledge, there is no investigation of dust formation in CE ejecta to date.

In this paper, we investigate dust grain formation and growth in CE ejecta. Section 2 describes the model for the CE ejecta, and Section 3 gives the input parameters for the dust modeling. The main results are presented in Section 4 and discussed in detail in Section 5. In Section 6 we estimate the total dust masses produced using population synthesis modeling, and Section 7 summarizes our main conclusions.

2. THE MASS DENSITY AND TEMPERATURE OF COMMON ENVELOPE EJECTA

In general, a CE system contains a gainer (a normal star or compact object) and a donor composed of a giant envelope and a giant core. The CE ejecta are formed from the ejected giant envelope. In general, dust formation and growth is determined by the density and temperature evolution of the CE ejecta. Unfortunately, our understanding of CE evolution is still rather poor despite numerous efforts to improve our understanding (e.g., Ricker & Taam 2008; Ge et al. 2010; Deloye & Taam 2010). To first-order approximation, we assume that the whole giant envelope is ejected as CE ejecta on a dynamical timescale. We use the EZ code (Paxton 2004), derived from Eggleton’s STARS code (Eggleton 1971), to simulate the giant’s structure and evolution. In this work, “giant envelope” refers to the region in the star in which the hydrogen abundance (by mass) is larger than 0.5. In the EZ code, the giant envelope is divided into ~100 zones. The mass density and the temperature in every zone are noted by \( \rho_0 \) and \( T_0 \), respectively. These determine the initial conditions for the CE ejecta.

After the giant envelope has been ejected, it begins to expand, and the density and temperature start to decrease.

1. The evolution of mass density. The mass density \( \rho \) is represented by \( \rho = \frac{M_{\text{ej}}}{4\pi R^2 V} \), where \( M_{\text{ej}} \) and \( R \) are the mass-ejection rate and the radial distance of the ejected matter, respectively, and \( V \) is the velocity of the ejected matter. According to Harper (1996), the main characteristic of the cool winds of evolved K and early M giants is that their terminal velocities are lower than the surface escape velocity.
velocity, typically, $V_{\infty} \leq (1/2)V_{esc} = (1/2)\sqrt{2GM/R}$, where $V_{esc}$ is the escape velocity at the stellar surface, $R_s$ is the stellar radius, and $G$ is the gravitational constant; $M_s = M_{\text{gainer}} + M_{\text{donor}}$, where $M_{\text{gainer}}$ is the mass of the gainer and $M_{\text{donor}}$ is the mass of the donor. If the velocity of the CE ejecta at infinity is similar to the terminal velocity of the cool wind from the red giant, energy conservation can be used to determine $V$ as a function of distance $R$ from the giant from $(1/2)(V^2 - V_\infty^2) = GM/R$. Considering the stellar structure of a red giant, we assume, for simplicity, that $V$ approximately equals $\sqrt{2GM/R}$, that is, $V$ is the escape velocity at $R$. It is difficult to determine $M_{\text{ej}}$ for CE ejecta. Since we assume that the giant envelope is ejected on a dynamical timescale, we assume for each layer within the CE ejecta that $M_{\text{ej}} = \rho_04\pi R_0^2V$, where $R_0$ is the initial distance of this layer to the stellar center. Therefore, the evolution of the density in each layer can be represented by

$$\rho = \left( \frac{R_0}{R} \right)^{3/2} \rho_0. \quad (1)$$

2. The evolution of temperature. The expansion of the CE ejecta leads to the cooling of the gas. At the beginning, most of the hydrogen atoms in the giant envelope are fully ionized except for hydrogen near the giant’s photosphere. As the temperature decreases, hydrogen recombines, gradually turning ionized hydrogen nuclei into hydrogen atoms and releasing the recombination energy in the process. Here, to first-order approximation, we only consider the recombination of hydrogen. The released energy can partly be absorbed by the CE ejecta and be used to drive the CE expansion further (Han et al. 1995) or be lost from the CE ejecta (e.g., by radiation). However, it is difficult to accurately describe the efficiency of this process. For simplicity, we introduce a parameter $\gamma$ to describe the temperature evolution in each layer:

$$T = \left( \frac{R_0}{R} \right)^{\gamma} T_0, \quad (2)$$

where $T_0$ is the initial temperature. The degree of ionization of the hydrogen atoms is determined by the Saha equation

$$\frac{n_+n_e}{n-n_e} = \frac{2}{\sqrt{\pi^2 m_e k_B T}} \exp \left( \frac{-\varepsilon}{k_B T} \right), \quad (3)$$

where $n$, $n_+$, and $n_e$ are the density of hydrogen atoms, hydrogen ions, and electrons, respectively. In the case of pure hydrogen, $n_+ = n_e$. The constants $h$, $k_B$, and $m_e$ are the Planck constant, the Boltzmann constant, and the mass of the electron, respectively. The ionization energy of hydrogen is given by $\varepsilon$ and equals 13.6 eV. The temperature $T$ is given by Equation (2). As the temperature decreases, the degree of ionization of hydrogen, $n_+/n$, also decreases. In this work, we take $n_+/n = 1$% as the boundary between the regions where hydrogen is fully ionized and where it is partially ionized or atomic. The distance of this boundary from $R_0$ is denoted as $R_{cr}$, and the temperature of the CE ejecta at $R_{cr}$ is $T_{cr}$. Once most of the ionized hydrogen has recombined, the gas in the CE ejecta will be similar to the gas at the surface of the red giant. Following Gail & Sedlmayr (1999), we refer to Lucy (1971, 1976) to calculate the temperature evolution from

$$T^4 = \frac{1}{2} T_{cr}^4 \left( 1 - \sqrt{1 - \frac{R_{cr}^2}{R^2} + \frac{3}{2} \frac{\tau_l}{R^2}} \right), \quad (4)$$

where $\tau_l$ is defined by

$$\frac{d\tau_l}{dR} = -\rho \kappa_T \frac{R_{cr}^2}{R^2}. \quad (5)$$

Here, $\kappa_T$ is the flux-averaged mass extinction coefficient and is calculated by a simple superposition of the extinction of the different dust species and the gas (see details in Gail & Sedlmayr 1999).

In summary, the expansion of the CE ejecta is split into two zones. In the inner zone ($R < R_{cr}$), the evolution of the CE ejecta’s temperature is given by Equation (2). In this zone, the CE ejecta temperature is high enough for hydrogen to be fully ionized so that dust cannot form. In the outer zone ($R > R_{cr}$), the temperature’s evolution is described by Equation (4). In this zone, the temperature of the CE ejecta has dropped so that ultimately dust grains can form.

3. A DUST MODEL FOR THE COMMON ENVELOPE EJECTA

As mentioned in the last section, we assume that the structure of the CE ejecta in the outer zone, where $R > R_{cr}$, is similar to that in the stellar wind from an AGB star. With the CE ejecta expanding, its temperature and pressure decrease, and some tiny seed nuclei can form in the cooling gas. However, the nucleation of seed nuclei from the gas phase is a difficult problem. The AGBDUST code does not consider this problem and assumes that the seed nuclei already exist. Condensation of dust can occur on the surface of the seed nuclei. Then, dust starts to grow. Gail & Sedlmayr (1999) and Ferrarotti & Gail (2001, 2002, 2003, 2005) have investigated the condensation and growth of dust grains in the stellar wind from AGB stars using the AGBDUST code. In this work, we use the same code for dust formation in CE ejecta. In the AGBDUST code, the condensation and growth of dust grains is affected by the following input parameters (other input parameters that are not specifically mentioned are taken to have the default values as in Ferrarotti & Gail 2006).

1. Chemical composition. The chemical composition has a large effect on dust formation. In this paper, we investigate dust formation in CE ejecta formed in binary systems in which giants are on the first giant branch (FGB). Due to the first dredge-up, the chemical abundances in the envelopes of FGBs star are different from the initial abundances, which are taken from Anders & Grevesse (1989) for the Sun. The effects of the first dredge-up are a reduction of $^{12}$C by approximately 30% and no change in the $^{16}$O abundance at the stellar surface (Iben & Renzini 1983). For Fe, Mg, and Si, which are some of the key elements for dust formation, the abundances are not changed substantially. Therefore, the abundance ratio of carbon to oxygen by number (C/O) in the CE ejecta is approximately 0.4. According to Gail & Sedlmayr (1999), the most abundant dust species formed in the circumstellar matter (where C/O < 1) are olivine- and pyroxene-type silicate grains and iron grains.

2. Temperature. The temperature of the CE ejecta is determined by Equations (2) and (4) and is affected by the parameter $\gamma$, a parameter that is quite uncertain. Based on
Figure 1. Initial temperature and density profiles of the envelopes of giants (at different evolutionary stages as indicated) as a function of relative mass coordinate. The results of model calculations by Fransson & Chevalier (1989), Kozasa et al. (1989) adopted an adiabatic index \( \gamma_{\text{ad}} = 1.25 \) for the early stage of SN explosions. For an adiabatically expanding perfect gas, \( \rho T^{1/\gamma_{\text{ad}}} = \text{constant} \). We assume that the temperature evolution of the CE ejecta in the inner zone is similar to that in the early stage of an SN explosion. This implies \( \gamma = 0.375 \) in Equation (2). In this work, in order to check the effects of this parameter on the dust-formation process, we simulate cases with \( \gamma = 0.2, 0.3, \) and \( 0.4 \).

3. The mass density. The mass density is determined by Equation (1). The density profile will also be affected by the geometry of the CE ejecta. Sandquist et al. (1998) showed that the mass loss in the orbital plane is about five times larger than in the polar direction. It is beyond the scope of this paper to simulate such more realistic structures. Specifically, in this work we assume that the CE ejecta expand spherically.

4. The stellar luminosity and mass. The stellar luminosity is taken to be the luminosity of the FGB star, and the mass is the mass of the binary, including the FGB star and the degenerate companion. However, their effects are weak because the region of dust formation is far away from the binary system.

4. RESULTS

Using the EZ code, we simulate the evolution of 10 stars with initial masses of 1.0, 1.25, 1.5, 1.7, 2.0, 2.5, 3.0, 4.0, 5.0, and 7.0 \( M_\odot \), respectively. Their companions are assumed to be degenerate stars of 1.0 \( M_\odot \). We assume that they experience a CE phase immediately when they overflow their Roche lobes on the FGB, ejecting their whole envelopes. The density and the temperature of the CE ejecta depend on the parameter \( \gamma \), and the initial temperature and density profiles \( T_0 \) and \( \rho_0 \). \( T_0 \) and \( \rho_0 \) are given by the EZ code and depend on the evolutionary state of the giant. In order to examine the effects of \( T_0 \) and \( \rho_0 \) on dust formation, we calculate the dust masses produced in the CE ejecta which originate from giants at the top of the FGB and at the base of the FGB, respectively. Figure 1 shows \( T_0 \) and \( \rho_0 \) at every level of the giant envelope at the top of the FGB and at the base of the FGB.

Figure 2 shows the amount of dust produced (in \( M_\odot \)) in the CE ejecta in these models for different values of \( \gamma \). As the figure demonstrates, \( \gamma \) and the evolutionary state of the giant dramatically affect the dust masses produced. In particular, varying \( \gamma \) from 0.2 to 0.4 introduces an uncertainty for the dust masses of up to a factor of \( \sim 10^7 \). Different \( T_0 \) and \( \rho_0 \) profiles, i.e., varying the evolutionary state from the base of the FGB to the top of the FGB, introduce a variation of up to a factor of \( \sim 10^5 \), but this depends strongly on the mass of the giant.

The dust masses mainly depend on the temperature and the mass density of the CE ejecta. In order to show the effects of \( \gamma \), \( T_0 \), and \( \rho_0 \), we give the temperature, mass density, and relative distance of the CE ejecta produced by an FGB star of 1.0 \( M_\odot \) at \( R_c \) in Figure 3. Obviously, a higher \( \gamma \) results in a smaller \( R_c \) for the same \( T_0 \) and \( \rho_0 \), and the CE ejecta have a higher density (see the right panels or the left panels in Figure 3). According to Gail & Sedlmayr (1999), a higher mass density results in a higher degree of dust condensation in the stellar...
Figure 2. Dust masses as a function of initial stellar mass. FG2006 refers the results in Ferrarotti & Gail (2006). The circles give the dust masses in the models calculated.

Figure 3. Temperature, density, and relative distance as a function of relative mass coordinate of the CE ejecta at $R_{cr}$. The left panels are for the CE ejecta produced by a star with $1 \, M_\odot$ at the top of the FGB. The right panels are for the CE ejecta produced by a star with $1 \, M_\odot$ at the base of the FGB. The solid and dashed curves represent $\gamma = 0.4$ and $\gamma = 0.325$, respectively.

wind. Thus, in the simulation with a high $\gamma$, the CE ejecta offer a very favorable environment for the formation and growth of dust grains. Similarly, a lower $T_0$ also results in a smaller $R_{cr}$ for the same $\gamma$ (see Figure 3), and the CE ejecta have higher density at $R_{cr}$. Again dust grains can easily form and grow in the CE ejecta in this case. In contrast, a low $\gamma$ and a high $T_0$ result in a large $R_{cr}$, and the mass density of the CE ejecta becomes too low to lead to efficient dust production.

Beyond $R_{cr}$, the CE ejecta enter the zone where dust may form. Figure 4 gives the quantities of olivine- and pyroxene-type silicate grains and iron grains produced by the CE ejecta. Due to the small sticking efficiency for quartz (Gail & Sedlmayr 1999), its quantity in dust grains is negligible. In our simulations, the silicates mainly consist of olivine and pyroxene whose proportion in the dust grains is between 70% and 90%. The proportion of iron in the dust grains is between ~10% and 30%.

As Figure 4 shows, for a small $\gamma$ and a high $T_0$, dust is mainly produced by the CE ejecta close to the stellar surface, while the whole CE ejecta can efficiently produce dust for a high $\gamma$, and a low $T_0$ and $\rho_0$.

Ferrarotti & Gail (2006) calculated the quantities of dust produced by AGB stars. This is plotted as a dot-dashed curve in Figure 2. This shows that, although dust production is comparatively unimportant in the CE models with $\gamma = 0.2$ at the base of FGB, the dust quantities produced by the CE ejecta are significant or may even dominate in other models with a higher $\gamma$. There are two main reasons for this.

1. Ferrarotti & Gail (2006) concluded that the dust condensation is efficient when AGB stars have high mass-loss rates, higher than $2 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$. For an AGB wind with a high mass-loss rate of $1 \times 10^{-5} \, M_\odot \, \text{yr}^{-1}$, the temperature and the mass density of dust-forming zones are $\sim 1.3 \times 10^{3} \, \text{K}$ and $5.0 \times 10^{-14} \, \text{g cm}^{-3}$, respectively. About 32% of the Si elements in an AGB wind condensate into olivine-, pyroxene-, and quartz-type dust, and about 4% of the Fe elements condensate into iron grains. However, in the simulation with $\gamma = 0.4$ and at the top of FGB, the temperature and the mass density of dust-forming zones in the CE ejecta are $\sim 1.1 \times 10^{3} \, \text{K}$ and $\sim 3.3 \times 10^{-11} \, \text{g cm}^{-3}$, respectively. The mass density of the CE ejecta in the dust-forming zone is much higher than that in an AGB wind and hence is very favorable for dust formation and growth. About 90% of the Si elements in the CE ejecta condensate into silicate grains, and about 50% of the Fe elements in the CE ejecta condensate into iron grains.

2. Generally, about 7% (for $M_i = 1.0 \, M_\odot$) to 70% (for $M_i = 7.0 \, M_\odot$) of the mass of an AGB star is lost at mass-loss rates in excess of $2 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$, and only this portion can efficiently produce dust. However, as Figure 1 shows, about 40% (for $M_i = 1.0 \, M_\odot$) to 80% (for $M_i = 7.0 \, M_\odot$) of the stellar mass can be ejected as...
Figure 5. Amounts of dust produced in the CE ejecta as a function of the distance to the FGB star. The left panels are for FGB stars with masses less than 2.0 \(M_\odot\), and the right panels are for FGB stars with masses larger than 2.0 \(M_\odot\).

For example, the progenitors of Type Ia SNe (SNe Ia) may have experienced CE evolution. From \textit{Hubble Space Telescope} WFPC2 imaging, Garnavich et al. (2001) proposed that SN 1998bu may have two echoes caused by dust at <10 pc and 120 ± 15 pc away from the SN: the inner echo is likely to be caused by dust from circumstellar material, while the outer component is consistent with ISM dust. SN 1998bu is an SN Ia. There are three other known SN Ia echoes, SNe 1991T, 1995E, and 2006X. Wang et al. (2008) showed that these echoes have a wide range of dust distances from <10 pc to ~210 pc, which is consistent with our results (see Figure 5). However, there are no observational data for light echoes in the majority of SNe Ia. The main reason is that it is very difficult to observe these light echoes. In the single-degenerate model, there is typically a long time delay between the CE phase and the SN explosion of between \(10^8\) and \(10^9\) yr (Han & Podsiadlowski 2004; Meng et al. 2009). In the double-degenerate model, the delay times often exceed \(10^9\) yr. In contrast, the time it takes for material to move from the binary to the zone of dust formation is only \(10–100\) yr. Dust grains formed in the CE ejecta probably have significant outflow speeds. It is difficult to determine this outflow speed. If it is \(\sim 10\) km s\(^{-1}\), dust grains will have moved far away from the binary by the time of the SN, and it will be difficult to observe light echoes. However, if a degenerate WDs explode as SNe Ia within \(10^7–10^8\) yr after the CE phase, it is possible to observe light echoes at distances of 100–1000 pc (depending on the outflow velocity). The delay time in the single-degenerate model depends on the mass of the companion of the WD. A delay time of \(\sim 10^8\) yr means that the companions of WDs have initial masses larger than \(\sim 6.0\ M_\odot\). Considering the condition for dynamical stability for mass transfer, Han & Podsiadlowski (2004) suggested that the main-sequence masses in the progenitors of SNe Ia cannot exceed \(\sim 4.0\ M_\odot\). However, using observations of the evolution of the SN Ia rate with redshift, Mannucci et al. (2006) suggested that SNe Ia have a wide range of delay times, from \(<10^8\) to \(>10^{10}\) yr. From a theoretical point of view, assuming an aspherical stellar wind in symbiotic stars, Lü et al. (2009) claimed that the initial masses of WD’s companions in progenitors of SNe Ia can exceed 6.0 \(M_\odot\).
Similarly, Wang et al. (2009) argued that the delay times of some SNe Ia from the helium-star channel are shorter than $10^8$ yr. Therefore, it may be possible in principle to observe light echoes in SNe Ia in which their progenitors are composed of WDs and massive companions.

In one of the main channels for Type Ib SNe (core-collapse SNe without hydrogen), the progenitors are believed to lose their hydrogen envelopes in a CE phase (Podsiadlowski et al. 1992). The resulting naked helium stars (which may appear as Wolf–Rayet stars) will explode after the CE ejection within $\sim 10^4–10^6$ yr. Therefore, it may be possible to observe light echoes from dust grains in SNe Ib, although their luminosities are much lower than those in SNe Ia. In fact, dust grains have been observed in the case of SN2006jc, which had a Wolf–Rayet star progenitor, though, in this case, it may be more likely that the dust was produced in the SN ejecta themselves (Smith et al. 2008; Di Carlo et al. 2008; Nozawa et al. 2008). Until now, to our knowledge, there is no direct observational evidence for dust grains in SNe Ib formed by CE ejection.

6. AN ESTIMATE OF THE DUST PRODUCED BY CE EJECTA VIA POPULATION SYNTHESIS

CE evolution often occurs in close binary systems, and the CE ejecta may provide an important contribution to the dust in the ISM. Its importance to the overall dust production can be estimated using population synthesis modeling. Similar to the main case considered in our study of symbiotic stars with WD components (Lü et al. 2006), we use the initial mass function of Miller & Scalo (1979) for the mass of the primary components and a flat distribution of mass ratios (Kraicheva et al. 1989; Goldberg & Mazeh 1994). The distribution of separations is determined by $\log a = 5X + 1$, where $X$ is a random variable uniformly distributed in the range [0,1] and the separation $a$ is in $R_\odot$.

During the CE phase, the binary experiences a dynamical spiral-in. It is generally assumed that the orbital energy that is released by the spiral-in process is used to expel the envelope of the donor with an efficiency $\alpha_{ce}$. In the theoretical calculation, the dynamical spiral-in is affected by the combined parameter $\alpha_{ce} \lambda_{ce}$, where $\lambda_{ce}$ parameterizes the envelope structure of the donor. In this work, we take $\alpha_{ce} \lambda_{ce} = 1.0$, i.e., assume that the CE ejection process is very efficient.

Using the rapid binary-star evolution (BSE) code of Hurley et al. (2002), we calculate the evolution of $10^6$ binary systems. About 20% of all binary systems undergo CE evolution and eject their envelopes. Of these, about 51% come from FGB stars, while the rest originate from stars on the AGB. For simplicity, we assume that all ejected CEs originate from the stellar envelope either at the base of the FGB or the top of the FGB. Usually, the envelopes of AGB stars have temperature lower than those of FGB stars. Therefore, this assumption may underestimate the amount of dust produced. According to Figure 2, for given input parameters, the dust masses mainly depend on the stellar mass at the beginning of the CE evolution. Using one-dimensional linear interpolation of stellar masses, we estimate the quantities of dust produced by CE evolution using this population synthesis approach. Similarly, using the results of Ferrarotti & Gail (2006), we also estimate the quantities of dust produced by AGB stars in a single starburst of $10^6$ single stars through one-dimensional linear interpolation of stellar masses.

Figure 6 presents the dust masses produced by CE evolution in a single starburst of $10^6$ binary systems or by $10^6$ single stars. Compared with AGB stars, due to the high initial temperature and slow temperature decrease, the quantities of dust produced by CE evolution are negligible in the simulation with $\gamma = 0.3$ at the base of the FGB. However, CEs produce significant amounts of dust or even dominate in the simulations with $\gamma = 0.4$ and $\gamma = 0.3$ at the top of the FGB. This demonstrates the potential importance of CE evolution to the overall dust production in the ISM.

Figure 7 shows how the dust masses produced by CEs or single AGB stars depend on the initial stellar masses. There are two peaks in the distribution of the dust quantities produced by AGB stars. The left peak is a direct consequence of the initial mass function that favors lower-mass stars, while the
right peak originates from stars with masses of 3–4 $M_\odot$ which are particularly efficient dust producers (Ferrarotti & Gail 2006). The dust produced by CEs mainly comes from the stars with masses of 1–3 $M_\odot$ due to the initial mass function.

7. CONCLUSIONS

We have investigated the dust formation in CE ejecta constructing simple models for the evolution of the CE ejecta and using the AGBDUST code to simulate dust formation. The dust masses produced by CE ejecta greatly depend on the input parameters. Compared to the dust masses produced by AGB stars, they may be significant and could even dominate under certain conditions. This demonstrates that the contribution of dust produced by CEs to the overall dust production in the ISM needs to be taken into account. The progenitors of SNe Ia usually undergo CE evolution. Due to the generally expected long delay times of SNe Ia, it is difficult to observe the dust grains formed in CE ejecta via light echoes, but it may be possible to find light echoes produced by dust grains in SNe Ia in which their progenitors are composed of WDs and massive companions. Due to the short delay times, SNe Ib may be good candidates for observing dust grains formed in CE ejecta. However, due to the still large uncertainties in modeling the CE phase, our conclusions are very preliminary and further work on its importance will be required.

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