ORIGIN OF DUST AROUND V1309 SCO

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ABSTRACT

The origin of dust grains in the interstellar medium is still an unanswered problem. Nicholls et al. found the presence of a significant amount of dust around V1309 Sco, which may originate from the merger of a contact binary. We investigate the origin of dust around V1309 Sco and suggest that these dust grains are produced in the binary-merger ejecta. By means of the AGBDUST code, we estimate that ~5.2 × 10^-4 M\(_{\odot}\) dust grains are produced with a radii of ~10^-3 cm. These dust grains are mainly composed of silicate and iron grains. Because the mass of the binary merger ejecta is very small, the contribution of dust produced by binary merger ejecta to the overall dust production in the interstellar medium is negligible. However, it is important to note that the discovery of a significant amount of dust around V1309 Sco offers a direct support for the idea that common-envelope ejecta provides an ideal environment for dust formation and growth. Therefore, we confirm that common envelope ejecta can be an important source of cosmic dust.

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

1. INTRODUCTION

One of the important constituents of the interstellar medium (ISM) is dust, which plays a crucial role in the astrophysics of the ISM from the thermodynamics and chemistry of the gas to the dynamics of star formation. The origin of cosmic dust is still an unanswered question. According to a popular point of view, dust mainly originates from the stellar wind of asymptotic giant branch (AGB) stars (Gail et al., 2009) or supernova (SN) ejecta (Dunne et al., 2003). However, Draine (2009) estimated that the dust originating from AGB stars and supernova could be only 10% of interstellar dust if their lifetimes are considered. Similarly, in the Large and Small Magellanic Clouds, Matsuura et al. (2009, 2013) and Boyer et al. (2012) found that the accumulated dust mass from AGB stars and supernova could be significantly less than the dust mass in the ISM, and they suggested that dust must be also formed by another unknown mechanism or grow in the ISM, an idea put forward by Draine & Salpeter (1979). Unfortunately, the destruction and growth processes of dust in the ISM are poorly understood (e.g., Dwek et al., 2007).

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, some authors suggested that the ejecta during common envelope (CE) evolution in close binary systems can provide a good environment for dust formation and growth (e.g., Lü et al., 2013; Ivanova et al., 2013). Lü et al. (2013) found that, compared to AGB stars, the dust quantities produced by CE ejecta may be significant or even dominated. Thus, it can be seen that the majority of dust in ISM may originate from CE ejecta. However, there is no direct evidence from observations to support their model.

Very recently, Nicholls et al. (2013) showed that V1309 Sco had become dominated by mid-IR emission since eruption, which indicated the presence of a significant amount of dust in the circumstellar environment. V1309 Sco erupted in 2008 September (Nakano et al., 2008). Subsequently, its evolution marked it as a new member of the “red novae” (Mason et al., 2010). Soker & Tylenda (2003) suggested that red novae were produced by binary merger. Tylenda et al. (2011) analyzed the data of V1309 Sco that have been photometrically observed by the OGLE project since 2001 August, and showed that it indeed originated from the merger of a contact binary. Until now, V1309 Sco is 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 the eruptive merger event.

In general, before a binary merger, the binary undergoes a CE phase that forms as a result of dynamical timescale mass exchange in close binaries and plays an essential role in their evolution (see, e.g., Paczynski 1976; Iben & Livio 1993). In most cases, CE evolution involves a giant star (donor) transferring matter to a main-sequence star or a degenerate dwarf (gainer) on a dynamical timescale. The giant envelope overfills the Roche lobes of both stars, engulfs the giant core and its companion, and forms a CE. During the CE phase, owing to its expansion, the CE rotates more slowly than the orbit velocity of the giant core and the donor, which results in friction. Then, orbital energy is transferred to the CE via dynamical friction between the orbiting components and the non-corotating CE. If the orbital energy is enough large, the whole CE can be ejected on a dynamical timescale, the binary does not merge, and a close binary is left. In this work, the whole envelope ejected is called CE ejecta. The CE ejecta rapidly expands and its temperature rapidly decreases. Lü et al. (2013) investigated whether dust forms and grows in it.

If the orbital energy is too small, the gainer and the donor merge into a single star, and part of the CE may be ejected. In order to distinguish from CE ejecta, we call the matter ejecta in this case binary merger ejecta. Compared with whole CE mass, the mass of binary merger ejecta is usually small. Using the three-dimensional 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 $M_\odot$. Ivanova et al. (2013) suggested that the binary merger ejecta rapidly cooled and potentially formed dust around V1309 Sco. In the present work, we try to simulate the dust formation and growth in the binary merger ejecta around V1309 Sco. If the merger event in V1309 Sco indeed produced a significant amount of dust, it means that dust can efficiently form and grow in the binary merger ejecta. Similarly, dust can do so in the CE ejecta. Therefore, observed dust around the V1309 Sco offers support for the new origin of cosmic dust proposed by Lü et al. (2013).

In this paper, we explain the origin of dust around V1309 Sco and show the quantity and properties of these dust grains. In Section 2, the model of the ejecta during binary merger is described. Results and discussions are given in Section 3, and Section 4 concludes.

2. DUST MODEL FOR V1309 SCO

In order to simulate the formation and growth of dust around V1309 Sco, we must look at its progenitor, which was composed of a gainer and a donor. Tylenda et al. (2011) estimated the luminosity and effective temperature of the progenitor of V1309 Sco and suggested that the donor was at the beginning of the red giant branch. According to observational constraints, Stepień (2011) computed the evolution of the progenitor binary of V1309 Sco from zero-age main sequence to binary merger. He showed that all possible progenitor systems had undergone the second Roche lobe overflow before merger. At this time, the donor was a giant star and its mass was $\sim 1.5 M_\odot$; the gainer’s mass was $\sim 0.15 M_\odot$ and binary orbital period was $\sim 1.4$ days.

Based on the popular model of binary evolution, if the donor was overflowing its Roche lobe, the progenitor would undergo a CE evolution and the donor and the gainer finally merged into V1309 Sco. During the above process, a portion of the donor’s envelope was ejected. Dust formation and growth mainly depend on the mass, temperature, and mass density of the ejecta.

2.1. Mass of Ejecta

At the beginning of the giant branch, the donor in the progenitor binary of V1309 Sco had an envelope with a mass of $\sim 1.2 M_\odot$. As the previous section described, Ivanova et al. (2013) estimated that the ejected mass during the binary merging process varies from 0.03 to 0.08 $M_\odot$.

Considering that a significant amount dust around V1309 Sco was found, we adopt an upper limit of their estimate, that is, the ejected mass equals 0.08 $M_\odot$. Ivanova et al. (2013) estimated that the mass of binary merger ejecta rapidly cooled and began to decrease. Therefore, observed dust around V1309 Sco offers support for the new origin of cosmic dust proposed by Lü et al. (2013).

After the matter is ejected, its mass density, $\rho$, is represented by $\rho = \rho_0 R_0/V_0$, where $\rho_0$ is the initial mass density, $R_0$ is the initial radius of the ejected material, and $V_0$ is the escape velocity. The matter is ejected on a dynamical timescale, we assume that $M_{ej} = \rho_0 4\pi R_0^2 V_0$, where $M_{ej}$ is the mass ejection rate and the radial distance of the ejected matter, respectively, and $V$ is the velocity of the ejected matter. We assume $V$ approximately equals to the escape velocity. Because the matter is ejected on a dynamical timescale, we assume that $M_{ej} = \rho_0 4\pi R_0^2 V_0$, where $R_0$ is the initial radius of the ejected material, and $V_0$ is the escape velocity of the ejected matter.

Lü et al. (2013) considered that the expansion of CE ejecta underwent two different zones in which the evolution of temperature is different.

In the first zone, some hydrogen atoms are ionized. As the temperature decreases, ionized hydrogens gradually turn into hydrogen atoms via releasing energy. The released energy can be partly absorbed by CE ejecta, be partly used to drive the CE (Han et al. 1995a, 1995b), or is directly lost from CE ejecta. For simplicity, Lü et al. (2013) introduced a parameter $\gamma$ to describe the temperature evolution:

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

where $T_0$ is the initial temperature. The ionization of hydrogen atom, can be given by Saha ionization equation.

In the second zone, the majority of ionized hydrogen has turned into hydrogen atoms and the gas in the CE ejecta is similar to that on the surface of the red giant. Lü et al. (2013) selected the temperature’s evolution given by Lucy (1971, 1976).
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no change in the 16O abundance at the stellar surface. Other stages of a SN explosion, this implies of the CE ejecta in the inner zone is similar to that in the early stage of SN explosions. For an adiabatically expanding perfect gas, \( \rho T^{1/(\gamma - 1)} \) = constant. If the temperature evolution of the CE ejecta in the inner zone is similar to that in the early stage of a SN explosion, this implies \( \gamma \sim 0.4 \) in Equation (2). In order to check \( \gamma \) effects on dust formation, Lü et al. (2013) carried out different simulations in which \( \gamma = 0.2, 0.3, \) and 0.4. They found that CE ejecta could efficiently produce dust in the simulation where \( \gamma = 0.4 \). We also carried out a test: If \( \gamma = 0.5 \), most of the Si, Fe, and Mg elements condense into the dust grains of silicate and iron. Considering that Nicholls et al. (2013) found a significant amount of dust in the circumstellar environment around V1309 Sco, we use \( \gamma = 0.4 \) in this work.

2.3. Dust Formation and Growth

Using AGBDUST code, Gail & Sedlmayr (1999) investigated the condensation and growth of dust grains in the stellar wind from an AGB star (Also see Ferrarotti & Gail 2001, 2002, 2003, 2005). As mentioned in Section 2.2, the binary merger ejecta in the second zone is similar to the stellar wind from AGB stars. We use AGBDUST to simulate the dust formation and growth in the binary merger ejecta. In the AGBDUST code, for a gas given temperature and mass density (the temperature and the mass density of binary merger ejecta are determined by Equations (1), (2), and (3)), the chemical abundances affect the dust species.

For a single star, three dredge-up processes and hot bottom burning in a star with an initial mass higher than 4 M_⊙ may change the chemical abundances of the stellar envelope (Iben & Renzini 1983). In binary systems, mass transfer also can change chemical abundances of the stellar envelope. Stepien (2011) showed that the progenitor of V1309 Sco had undergone two Roche lobe overflows and the giant, before the binary merger, had accreted a large amount of matter (~0.6–1.0 M_⊙) from its companion at the first Roche lobe overflow. According to the models of Stepien (2011), the giant and its companion in the progenitor of V1309 Sco had only undergone the first dredge-up. Iben & Renzini (1983) showed that the effects of the first dredge-up are a reduction of 12C by approximately 30% and no change in the 18O abundance at the stellar surface. Other key elements (Fe, Si, Mg, and S) for dust formation in the stellar envelope do not change. Therefore, if we assume that the initial abundances are similar with those on the surface of the Sun, the abundance ratio of carbon element to oxygen element (C/O) in the giant envelope is 0.4, which also is the value of C/O in the binary merger ejecta. According to Gail & Sedlmayr (1999), the most abundant dust species formed in the circumstellar matter (C/O < 1) are olivine- and pyroxene-type silicate grains, quartz, and iron grains. Before these dust grains start to condense, there must be some kind of seed nuclei. However, the formation of the seed nuclei is also a very difficult problem (e.g., Gail & Sedlmayr 1999). The AGBDUST code assumes that the seed nuclei existed and their radii are 1 nm (Gail & Sedlmayr 1999; Ferrarotti & Gail 2006). When the temperature of the binary merger ejecta cools down to a limit value, the different elements of dust species condensate on the surfaces of these seed nuclei. The details can be seen in Gail & Sedlmayr (1999) and Ferrarotti & Gail (2006).

In AGBDUST code, besides the temperature, velocity, mass density, and chemical abundances, the stellar luminosity and mass can also affect dust formation and growth. However, their effects are weak because the region of dust formation is far away from the binary system (Lü et al. 2013), therefore, we ignore them. In addition, other input parameters, such as outer radius of the zone for dust formation and the number of radial grippoints in AGBDUST code, not specifically mentioned are taken to have the default values as in Ferrarotti & Gail (2006).

3. RESULTS AND DISCUSSIONS

We simulate the dust formation and growth in the binary merger ejecta from the progenitor of V1309 Sco. The quantities produced along the donor’s mass coordinate are shown in Figure 2. According to our simulations, \(~5.2 \times 10^{-3} \) M_⊙ of dust grains are produced. Due to the small sticking efficiency of quartz (Gail & Sedlmayr 1999), its quantity in dust grains is negligible. The dust around V1309 Sco consists of olivine- and pyroxene-type silicate grains and iron grains. The proportion of
The proportion of pyroxene-type silicate grains in whole dust grains is \(~50\%\) and the proportion of pyroxene-type silicate grains is \(~30\%\).

Similar to CE ejecta, the mass density \((\sim 3.3 \times 10^{-11} \text{ g cm}^{-3})\) of the binary merger ejecta in the dust-forming zone is much higher than that \((\sim 5 \times 10^{-12} \text{ g cm}^{-3})\) in an AGB wind (Lü et al. 2013). This condition is very favorable for dust formation and growth. About 90% of the Si elements in the binary merger ejecta condensate into silicate grains, and about 50% of the Fe elements condensate into iron grains.

Nicholls et al. (2013) did not estimate the total dust mass around V1309 Sco because the observational data cannot allow us to estimate the radial extent of the dust. However, they found two particular results.

1. The temperature of the dust is warm \((\sim 800 \pm 25 \text{ K})\), which indicates that dust grains formed recently.
2. The best fit to the absorption features is amorphous pyroxene grains whose sizes are \(\sim 3 \times 10^{-4} \text{ cm}\) and shape distributions are hollow spheres.

In our simulations, the temperature of the region in which dust grains grow efficiently is \(\sim 1100–900 \text{ K}\). This is consistent with observations. However, as Figure 3 shows, the radii of different dust grains in our simulations are \(\sim 0.7–2.8 \times 10^{-5} \text{ cm}\), which is much smaller than the observational values. We consider that reasons are as follows.

1. The \textsc{AGBDUST} code assumes that all olivine-type silicate, pyroxene-type silicate, and iron grains have the shape of a solid sphere. Given a certain mass, a dust grain with a hollow sphere shape has a radius larger than that with a solid sphere shape.
2. In \textsc{AGBDUST} code, given a gas’s mass density, temperature, and chemical composition, the sizes of dust grains are affected by an artificial parameter, \(n_d\), which is the number density of seed nuclei of the different dust species. Ferrarotti & Gail (2003) suggested that a lower density number of seed nuclei seems to give dust quantities too small for the silicates and probably too big for silicate dust particle radii, which are bigger than the upper cutoff of the size distribution derived by Jura (1996). In order to better agreement with the results in Jura (1996), Ferrarotti & Gail (2003) assumed that \(n_d = 3 \times 10^{-13}N_H\), where \(N_H\) is the number of hydrogen nuclei. Correspondingly, the radii of dust grains calculated by \textsc{AGBDUST} are \(\sim 10^{-5} \text{ cm}\).

We carried out different simulations in which \(n_d\) is changed from \(3 \times 10^{-13}N_H\) to \(10^{-15}N_H\). The radii of different dust grains increases up to \(5 \times 10^{-5} \text{ cm}\), which is still much smaller than observational values.

Our simulations underestimate the radii of dust grains around V1309 Sco. The main reason may come from the different environments between the stellar wind of AGB stars and the binary merger ejecta. Larger grains require dust formation and growth to occur in a more stable environment (Nicholls et al. 2013).

Figure 4 gives the amounts of dust produced in the binary merger ejecta as a function of the distance to V1309 Sco. Based on our models, majority of dust grains form in the region of \(\sim 10^{-13}–10^{-17} \text{ cm away from V1309 Sco}\). Nicholls et al. (2013) found a significant amount of dust around V1309 Sco between 18 and 23 months after outburst. Mason et al. (2010) discovered that V1309 Sco spectra were characterized by low velocities (the emission lines FWHM and their extended wings never exceeded 150 km s\(^{-1}\) and 1000 km s\(^{-1}\), respectively). Similarly, simulating the merging process of the progenitor binary of V1309 Sco, Ivanova et al. (2013) showed that some of the ejecta were only barely faster than the local escape velocity (\(\sim 420 \text{ km s}^{-1}\)) and some get significantly more specific kinetic energy. If we assume that the ejecta velocity is \(\sim 100–1000 \text{ km s}^{-1}\), dust grains discovered by Nicholls et al. (2013) should be located in a zone of \(\lesssim 10^{14}–10^{16} \text{ cm away from V1309 Sco}\). This is agreement with our results.

4. CONCLUSIONS

The discovery of a significant amount of dust around V1309 Sco directly supports the point of view of Lü et al. (2013); that is, that CE ejecta in a close binary system provides an ideal environment for dust formation and growth. Using their toy model, we find that the ejecta of a progenitor–binary merger can efficiently produce dust and there are \(\sim 5.2 \times 10^{-4}M_\odot\) of dust grains around V1309 Sco.
Based on Han et al. (1995b), about 20% of all binary systems undergo CE evolutions, and about 40% of these CE evolutions result in binary mergers. However, as Figure 1 shows, only a tiny part of the whole envelope is ejected. Compared with CE ejecta, the contribution of dust produced by binary merger ejecta to the overall dust production in the ISM is negligible.

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