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In my Beginning is my End: Dust Destruction in the Cassiopeia A Supernova Remnant

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It has been demonstrated by observations that young supernovae (SNe) are indeed able to efficiently synthesize dust. However, it is unclear how much of the freshly formed dust can reach the interstellar medium and contribute to the observed emission. At the same time, SNe represent the major agent responsible for dust destruction. Because SNe are possibly the only viable dust factory in the early Universe, it is extremely important to establish the fate of the newly formed dust. Our work explores the possibility that a significant fraction of any dust formed after the explosion is destroyed within the supernova remnant itself. In the Cassiopeia A supernova remnant, dust emission has been observed associated with optical knots containing recently formed material. The dust present in such clumps is threatened by the reverse shock traveling through the ejecta toward the center of the remnant. The shock is able to disrupt the clumps and will inject the dust grains into a hot gas, where they will be eroded and possibly destroyed by thermal and inertial sputtering. We present a model that describes the propagation of the reverse shock into the supernova cavity and evaluates the modifications in the grain size distribution due to the encounter with the reverse shock. This is the first step required to quantify the amount of dust ultimately able to survive. Our model accounts for the variation of the physical properties of both the shock and the ejecta across the remnant. In particular, this means taking explicitly into consideration, for the first time in this kind of studies, the effect of clumping of the ejecta.

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1. Introduction

It is widely accepted that dust is mainly formed at high densities and temperatures in the ejecta of evolved stars such as those populating the Red Giant Branch and the Asymptotic Giant Branch (RGB and AGB stars). However, the detection of dust at very high redshift ($z > 6$) [1] when RGB and AGB stars did not have time to evolve [e.g. 2, 3, 4], raises questions about the origin of cosmic dust in the distant universe. From an evolutionary point of view, young supernovae (SNe) could represent a viable source of dust in high redshift galaxies. Recent observations with Herschel [5] and ALMA [6] have revealed the presence of a large amount of freshly formed dust in the inner ejecta of SN 1987A (0.4 $M_\odot$ – 0.7 $M_\odot$ and > 0.2 $M_\odot$ respectively). These detections are in agreement with coagulation models [7, 8] which predict the formation of 0.1 $M_\odot$ – 1 $M_\odot$ of dust and confirm that SNe are indeed efficient dust factories. At the same time, SNe represent the major agent responsible for dust destruction [9]. Thus, these observations rise a fundamental question about the fate of the dust: how much is injected into the interstellar medium and can therefore be detected in galaxies at all redshifts? The dust resides in the supernova cavity and is heavily processed by the reverse shock propagating toward the centre of the remnant [10, 11, 12, 13]. The first step to quantify the amount of dust able to reach the interstellar medium is to establish which modifications of the initial grain size distribution are induced by the encounter with the reverse shock. We have estimated this processing in the Cassiopeia A supernova remnant (Cas A SNR), where the reverse shock is clearly in action. Our study shows: i) how the reverse shock shapes the size distribution of the newly formed dust and ii) how the presence of clumpy ejecta affects the timescale for dust processing.

2. The model: evolution of Cas A and properties of the ejecta

In Cas A, dust emission has been observed associated with optical clumps containing recently formed material. Using *Spitzer* observations, Rho et al. [14] studied the hot dust associated with the shocks, inferring a dust mass of 0.02 $M_\odot$ – 0.054 $M_\odot$. Emission from cold ($\sim$35 K) dust in Cas A has been detected by Barlow et al. [15] using *Herschel* while Dunne et al. [16] report the clear detection of > 0.4 $M_\odot$ of dust in Cas A as directly probed through sub-millimetre polarimetry. To establish the fate of this newly formed dust, we have developed an analytical model which describes the propagation of the reverse shock into the supernova cavity and evaluates the destruction of the dust grains [17]. With respect to previous studies like e.g., Bianchi & Schneider 2007 [11], our model for the evolution of Cas A specifically reproduces the X-ray signatures from the remnant (e.g., radius and velocity of the forward and reverse shocks). Starting from the work of Truelove & McKee [18] and Laming & Hwang [19], we have developed the solutions for in-homogenous ejecta (clumps immersed in smooth ejecta characterized by a uniform core surrounded by a power-law envelope) expanding into a non-uniform medium. These solutions are significantly different with respect to the uniform case considered so far. In terms of dust destruction, we have evaluated separately inertial and thermal sputtering, which occur in different environments (clumps and smooth ejecta respectively). The presence of clumpy ejecta modifies the timescale for dust processing, with observational consequences which we are currently evaluating.

To describe the dynamical evolution of the Cas A SNR we refer to the analytical treatment of Truelove & McKee [18]. This seminal work focused on the evolution of supernova ejecta expanding into an uniform density ambient medium. Following Appendix A in Truelove & McKee [18] we generalize this treatment to a general power-law ambient media (described by an index s: $\rho(r) = \rho_s r^{-s}$). Then, referring to the work of Laming & Hwang [19] we consider the specific case of $s = 2$ appropriate for Cas A, i.e., ejecta expanding into a pre-supernova steady stellar wind. For the supernova ejecta we assume a density profile given by a inner uniform *core* surrounded by an external power-law *envelope* characterized by the index n, for which we adopt the value n = 9 [19, 20]. Figure 1 (left panel) shows our result for the velocity of the reverse shock, $v_{\rm r}$, calculated as a function of the time elapsed since the explosion of the supernova progenitor. For 2004 (333 yr after the explosion) we find $v_{\rm r} \sim 1600$ km s^{-1}, consistent with the measured values [21].

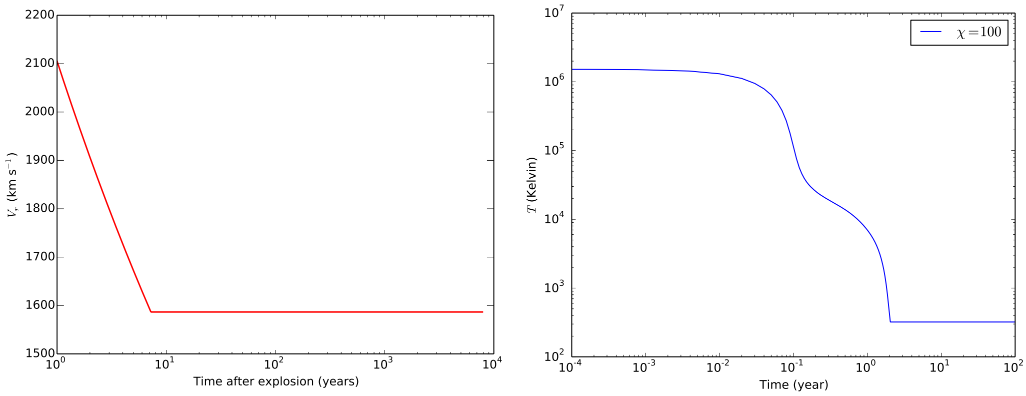

Figure 1: *Left* – Velocity of the reverse shock, $v_{\rm r}$, as a function of the time elapsed since the progenitor of Cas A exploded as a supernova. *Right* – Temperature profile of the dense ejecta clouds in Cas A as a function of time, assuming for the clouds a density contrast χ = 100 with respect to the smooth ejecta.

For the density distribution of the ejecta we consider a more realistic situation where over-dense clouds (density $n_{\rm c}$ = 100 cm^{-1}) are embedded into a smooth and tenuous medium (density $n_{\rm s}$ = 1 cm^{-1}). The value of the density contrast $\chi = n_{\rm c}/n_{\rm s}$ is thus 100. The typical radius of an ejecta cloud is $R_{\rm c}$ = 7.5$\times$10^{16} cm. All these assumptions are consistent with observations [21, 22, 23]. When the reverse shock encounters an ejecta cloud, it generates a *cloud shock* which propagates into the cloud with velocity $v_{\rm c} = v_{\rm r}/\sqrt{\chi}$. For $v_{\rm r}$ = 1600 km s^{-1}, we have $v_{\rm c}$ = 160 km s^{-1}. The *cloud crushing time* $t_{\rm cc}$ is defined as $t_{\rm cc}$ = $R_{\rm c}/v_{\rm c}$ and represents an indicator of the timescale for cloud disruption by the cloud shock. For $v_{\rm c}$ = 160 km s^{-1} we have $t_{\rm cc}$ = 150 yr. After 3$t_{\rm cc}$ the cloud is completely fragmented and dispersed into the smooth ejecta. It should be noted that the time required for the reverse shock to *pass* the cloud is much shorter: 2 $R_{\rm c}/v_{\rm r}$ = 30 yr.

The ejecta clouds contains 80% – 90% of oxygen [23]. The cloud shock propagating into the ejecta clouds heats the ejecta up to $\sim$1.5$\times$10^6 K. Such a high abundance of oxygen implies that the shocked cloud cools down very quickly. Figure 1 (right panel) shows the temperature evolution of the shocked cloud calculated using the cooling function for an O-rich shocked gas with $v_{\rm c}$ = 150 km s^{-1}, very close to our value of 160 km s^{-1} [22]. It takes only two years for the temperature of the ejecta in the clouds to drop below 1000 K. For the smooth ejecta we assume a composition of O, Ne, Mg, Si, S, Ar and Fe as determined by Hwang & Laming [24]. The reverse shock heats up the smooth ejecta to a temperature of $\sim 2\times 10^8$ K. In this case the cooling time is $\sim 4\times 10^5$ yrs, much longer than the timescales of the other considered processes. Therefore we can assume that the cooling is negligible and that the smooth ejecta remain hot.

3. The model: dust processing by the reverse shock

The cloud shock generated by the impact of the reverse shock with an ejecta clump propagates into the clump itself and heats the gas up to $\sim 1.5\times 10^6$ K. Because of the very high content of oxygen, the shocked gas cools down to temperatures below 10^3 K. Under these "low-temperature" conditions, the fresh dust residing in the clump is affected by inertial sputtering, i.e., the ejection of atoms from the grain surface due to collisions with energetic ions, where the velocity of the ions is due to the relative motion between the grains and the gas. Inertial sputtering erodes the grains, resulting in the modification of the initial grain size distribution. At the same time, the propagation of the cloud shock causes the fragmentation of the clump. After $3t_{cc}$ the cloud is completely dispersed and the dust, whose size distribution has been modified by inertial sputtering, is released into the smooth ejecta. Here the temperature is much higher (2×10^8 K), therefore the dominant erosion mechanism is thermal sputtering, where collisions arise from the thermal motion of the gas. To calculate the post-shock grain size distribution, we use the formalism from Tielens et al. [25]. This is the same adopted by Jones et al. [26] to study in a very general way the destruction of interstellar dust grains by supernova *forward* shocks. For simplicity, we assume that all the grains in the SN ejecta are silicates in the form of SiO_2. For comparison, we also evaluate the effects of sputtering on carbonaceous grains (graphite/amorphous carbon) under the same conditions. For these two kind of grains we adopt the sputtering parameters from [25].

4. Results and Conclusions

The post-shock grain size distribution from our calculations is presented in Figure 2. The left panel shows the fractional abundance, $f(a)$, as a function of the radius of the grain, a. For each radius, the fractional abundance is defined as the fraction of dust grains having that radius. For the initial grain size distribution (black dotted line) we have assumed the classical MRN distribution [27]. The results presented here refer to the situation where the reverse shock encounters an ejecta cloud in 2004 (333 years after the supernova explosion). Results for impacts occurring at different stages of the evolution of the remnant will be presented in our forthcoming paper [17]. Cas A is expected to produce silicate dust [28]. The behaviour of carbonaceous dust (graphite) under the same conditions is shown for comparison. The solid lines (blue for graphite, red for silicates) represent the grain size distribution resulting from the inertial sputtering which occurs in the ejecta clumps. It can be noted that inertial sputtering shifts the initial distribution towards smaller radii, thus maintaining the initial slope. The processing of the dust in the ejecta clouds occurs during $3t_{cc}$ (450 yr). After this lapse of time, the cloud is completely disrupted and the dust with the modified size distribution (solid lines) is released into the hot smooth ejecta. In the hot gas, the dust is processed via thermal sputtering. The final grain size distribution after an infinite interval of time is shown by the dashed lines. The effect of thermal sputtering is much more dramatic than the one

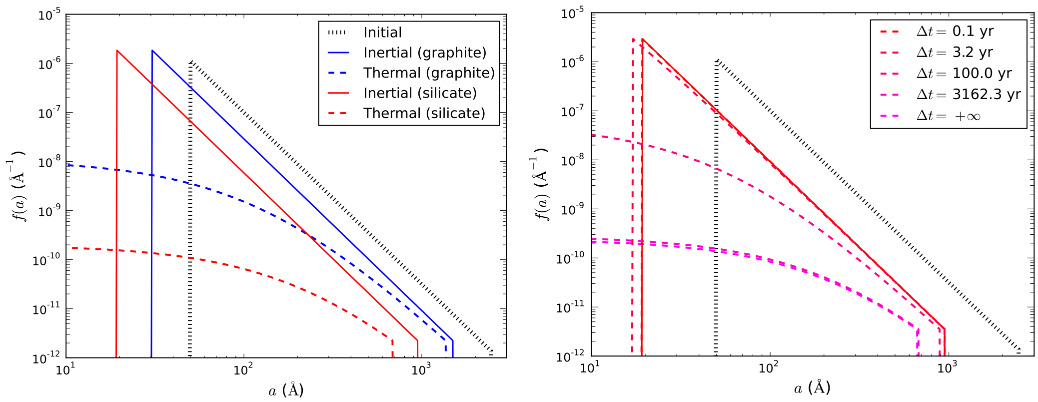

Figure 2: *Left* – Size distribution of the freshly formed dust in the ejecta of Cas A. The reverse shock enters the ejecta cloud in 2004. The initial grain size distribution is modified by inertial sputtering inside the clump and by thermal sputtering in the smooth ejecta. *Right* – Evolution of the size distribution for silicate dust in the ejecta of Cas A. The initial grain size distribution in the clouds and the distribution released into the smooth ejecta are the same as in the left panel. The dashed lines show the grain size distribution at the time corresponding to $(333 + 450 + \Delta t)$ years after explosion.

of inertial sputtering, resulting in a reduction of at least 60% of the initial radius of the grains. For both inertial and thermal sputtering, silicate grains are more affected than carbonaceous grains.

The time evolution of the size distribution for silicate dust is shown in the right panel of Figure 2. The initial grain size distribution in the clouds (333 years after explosion – black dotted line) and the distribution released into the smooth ejecta (333 + 450 years after explosion – solid line) are the same as in the left panel. The different colors of the dashed lines identify the grain size distribution resulting from thermal sputtering at different times, corresponding to $(333 + 450 + \Delta t)$ years after the explosion of the progenitor star of Cas A. The distribution for $\Delta t = \infty$ is almost coincident with the distribution for $\Delta t \sim 3100$ yr. Therefore, this latter value can be used as an indicator of the typical timescale for dust processing in the hot ejecta, for dust which initially resides in a dense clump and then encounters the reverse shock in 2004. The results for impacts occurring at different stages of the supernova evolution are expected to be different.

The details of the model, our full suite of results and a detailed discussion of our findings will be presented in our upcoming paper [17]. From these preliminary results we can nevertheless already draw some interesting conclusions. Our model for the evolution of Cas A can be easily adapted to other young supernova remnants such as SN 1987A, SN 1006, Tycho and Kepler, and allows us to study the processing of dust under the different physical conditions corresponding to the various evolutionary stages of the remnants. Processing by the reverse shock, in particular via thermal sputtering, strongly modifies the dust grain size distribution towards small radii, resulting in a substantial erosion of the grains with consequent release of elements into the gas phase. The presence of inhomogeneities in the ejecta, i.e. the dense clumps where the dust initially resides, introduces not only an additional processing of the dust (via inertial sputtering in the clumps), but also a delayed injection of the dust into the hot smooth ejecta where most of the processing occurs. The dust residing in a cloud which has encountered the reverse shock few years after the supernova explosion, has not been released yet into the smooth ejecta. Therefore, its size distribution should be similar to the initial one.

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