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Dust grains from the heart of supernovae

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Abstract

Dust grains are classically thought to form in the winds of asymptotic giant branch (AGB) stars. However, there is increasing evidence today for dust formation in supernovae (SNe). To establish the relative importance of these two classes of stellar sources of dust, it is important to know the fraction of freshly formed dust in SN ejecta that is able to survive the passage of the reverse shock and be injected in the interstellar medium.

We have developed a new code (GRASH_Rev) which follows the newly-formed dust evolution throughout the supernova explosion until the merging of the forward shock with the circumstellar ISM.

We have considered four well studied SNe in the Milky Way and Large Magellanic Cloud: SN1987A, CasA, the Crab Nebula, and N49. For all the simulated models, we find good agreement with observations and estimate that between 1 and 8% of the observed mass will survive, leading to a SN dust production rate of $(3.9 \pm 3.7) \times 10^{-4} M_{\odot} \text{yr}^{-1}$ in the Milky Way. This value is one order of magnitude larger than the dust production rate by AGB stars but insufficient to counterbalance the dust destruction by SNe, therefore requiring dust accretion in the gas phase.

1 Introduction

It is observationally and theoretically well established that a considerable amount of dust is efficiently formed in regions around asymptotic giant branch (AGB) stars. This process is classically considered as the primary source of dust grains in galaxies, and the typical formation timescale in the Milky Way is $\sim 3 \times 10^9$ yr.

In contrast, supernova (SN) explosions in the interstellar medium (ISM) trigger shock waves that are able to quickly process dust grains and are considered the dominant mechanism of dust destruction in the ISM. Recent theoretical and observational work on interstellar dust destruction in shock waves led to an estimated dust lifetime much shorter than the assumed dust formation timescale from AGB stars.

Although SNe are believed to be efficient interstellar dust destroyers, there is increasing observational evidence today for the formation of non-negligible quantities of dust grains in

the ejecta of SNe. Given the relatively short timescale between the explosion of two SNe, this would lead to an effectively shorter timescale for dust formation.

In this work we present a new code called GRASH_Rev that treats dust processing in a supernova explosion. This code couples all the dust processing included in the GRASH_EX code (Bocchio et al. 2014) with the dynamics and structure of the SN as modelled by Bianchi & Schneider (2007, BS07) but extending it to include the full dynamics of dust grains within the ejecta and in the surrounding ISM.

2 Supernova sample

Only in four core-collapse SNe it has been possible to estimate the amount of dust in the ejecta, using observation from Spitzer and Herschel: SN 1987A, Cassiopeia A, Crab Nebula and SNR N49. We obtain their main physical properties from the literature: the type of SN, the explosion energy (E_{ex}), the mass of ^{56}Ni , the progenitor mass (M_{prog}), the estimated metallicity (Z) of the progenitor star, the age, the number density of the circumstellar ISM (n_0) and the measured dust mass associated with the ejecta (M_{dust}).

A comparison between the dust mass observed in these objects and the amount and composition of dust that our model predicts gives constraints on the ongoing physical processes. This makes our model reliable and allows us to predict the amount of dust that will be released into the ISM.

3 The GRASH_Rev code

Starting from a homogeneous set of solar metallicity pre-supernova models with masses in the range [13-120] M_{\odot} (Chieffi & Limongi 2013) simulated by means of the FRANEC stellar evolutionary code (Limongi & Chieffi 2006), we have selected the most suitable model for each SN according to their physical properties. These four selected models are then used as input for the dust formation code (BS07), where classical nucleation theory in steady state conditions was applied. Here we use the latest version of dust formation model, which implements an upgraded molecular network, as described in detail in Marassi et al. (2015). We follow the formation of six different dust grain species: amorphous carbon (AC), corundum (Al_2O_3), magnetite (Fe_3O_4), enstatite (MgSiO_3), forsterite (Mg_2SiO_4) and quartz (SiO_2).

We then adopt the analytical solution described by Truelove & McKee (1999) and Cioffi et al. (1988) to characterise the SNR evolution from the early ejecta-dominated phase through the pressure-driven snowplough phase until the velocity of the shock front becomes low enough (~ 10 km/s) and the remnant merges with the ISM.

The dynamics of dust is entirely governed by its coupling to the gas, which in the GRASH_Rev code is described as the combination of the collisional (direct) and plasma drag. We then consider four main physical processes: sputtering due to the interaction of dust grains with particles in the gas; sublimation due to collisional heating to high temperatures; shattering into smaller grains due to grain-grain collisions and vapourisation of part of the colliding grains during grain-grain collisions.

4 Results

We ran simulations for the four SNe considered and follow the dust mass evolution. In Fig. 1 we show the time evolution of the dust mass following the SN explosion. The dust mass estimated using GRASH_Rev simulations are in good agreement with the observations, except for SNR N49 for which the dust mass predicted by GRASH Rev is $\sim 15\%$ larger than the upper mass limit of the range of values inferred from observations. The resulting dust yields depend on the progenitor mass, explosion energy and the age of the SN, and lie in the range $4 \times 10^{-4} - 4 \times 10^{-2} M_{\odot}$.

5 Discussion and conclusions

Given the rather large uncertainties on measurements of dust masses, our models appear to reproduce the dust masses in the four SNe well. The average effective dust yield is estimated to be $(1.55 \pm 1.48) 10^{-2} M_{\odot}$. When compared to dust destruction efficiencies in SN-driven interstellar shocks that were recently estimated by theoretical models (Bocchio et al. 2014; Slavin et al. 2015) and observations (Lakićević et al. 2015), this implies that SNe may be net dust destroyers, pointing to grain growth in the ISM as the dominant dust enrichment process both in local galaxies and at high redshifts.

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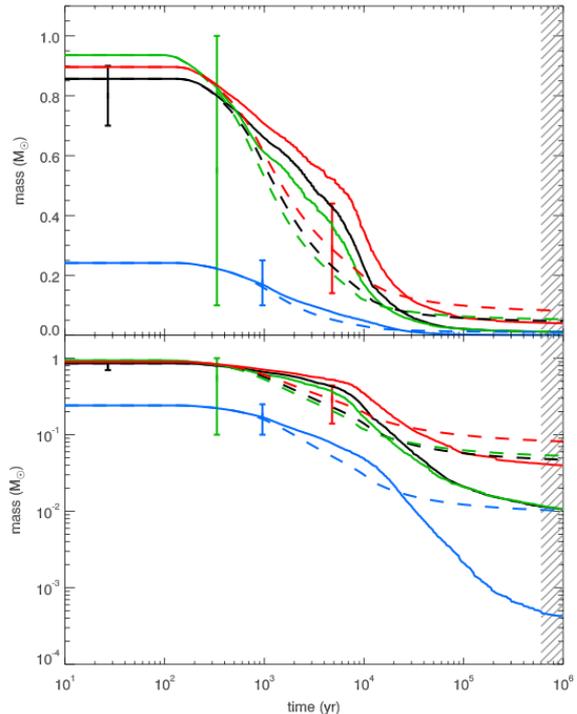


Figure 1: Dust mass evolution as a function of time (1987A: black, CasA: green, Crab: blue and N49: red). Solid and dashed lines are GRASH_Rev and BS07 results. Data points are observed dust masses and the shaded region indicates the time interval when dust processing fades out.