DUST FORMATION IN TYPE IIn SNe

Antonia Bevan[1], R. Wesson[1], M. J. Barlow[1], I. De Looze[1], K. Krafton[2], G. C. Clayton[2], J. E. Andrews[3], M. Matsuura[4], D. Milisavljevic[5]

[1]University College London, London, UK; [2]Louisiana State University, Baton Rouge, USA; [3]University of Arizona, Tuscon, USA; [4]Cardiff University, Cardiff, UK; [5]Purdue University, West Lafayette, USA

INTRODUCTION

The source of the large masses of dust observed in some very early Universe galaxies at redshifts z ≳ 6 has been much debated. The discovery of >0.1M⊙ of cold dust in a few nearby core-collapse supernovae (CCSNe) suggests that CCSNe could be efficient producers of dust but there are currently no telescopes that are capable of detecting cold dust in the far-IR in extragalactic CCSNe. However, dust formation in the interior of CCSNe can induce persistent asymmetries in their optical and near-infrared (NIR) emission line profiles due to greater attenuation of redshifted radiation which must traverse the dusty interior. By modelling these lines the dust mass that has formed can be inferred (Bevan+ 16).

Type IIn SNe often remain bright for years after outburst due ongoing interaction between the forward shock and dense circumstellar material allowing newly-formed dust to be traced both in emission in the IR and in extinction by modelling optical and NIR emission line profiles. We present Monte Carlo radiative transfer (MCRT) models of dust-affected line profiles tracing the evolution of dust formation in SN2010jl, SN2005ip and SN1995N, as well as independent MCRT models of their dust in emission in the IR.

TRACING DUST IN IIn CCSNe

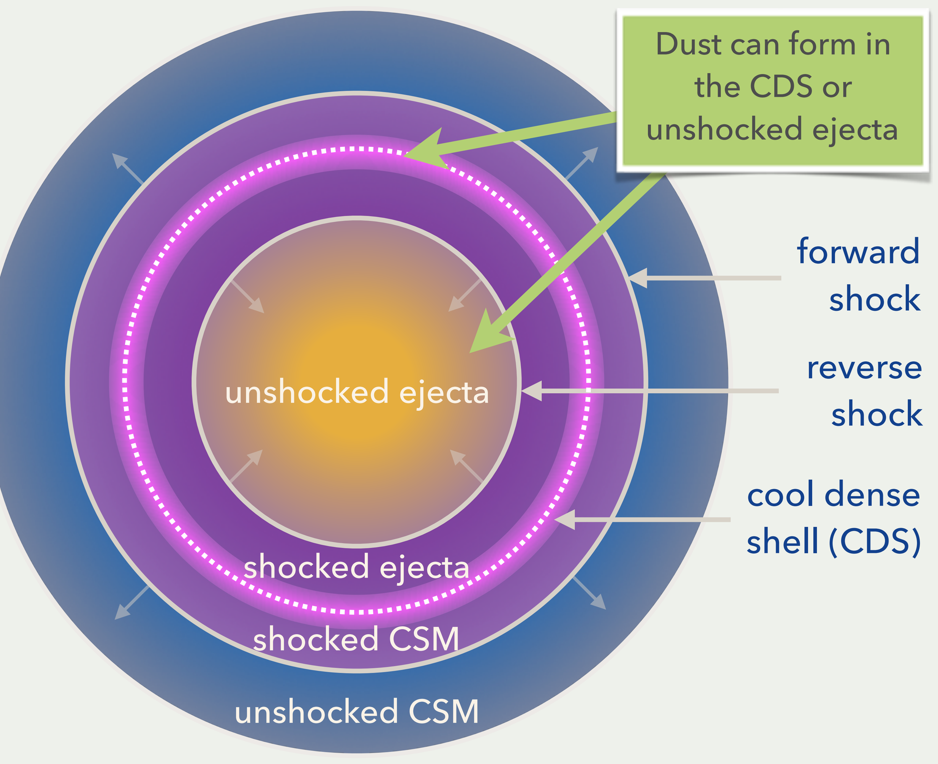

Figure 1. Graphical representation of a Type IIn interacting SN. Dust can form in the cool, dense shell (CDS) in the post-shocked region or in the unshocked ejecta.

Type IIn supernovae are surrounded by dense circumstellar material (CSM). Interaction between the blast wave and the CSM causes high energy radiation to be released and propagates a reverse shock wave back into the expanding ejecta. New dust can form either in the unshocked ejecta (as in IIP or IIL SNe) or can form in the cool, dense shell that arises at the contact discontinuity between the ejecta and CSM in the post-shocked region between the forward and reverse shocks (see Fig. 1). Type IIn SNe frequently exhibit line profiles with three distinct width components: broad emission (~15,000km/s from the expanding ejecta), intermediate emission (~2,000km/s from the post-shocked region) and narrow emission (~100km/s) from the unshocked CSM. Line emission emanating from the ejecta or post-shocked regions can only be asymmetrically attenuated by dust interior to or co-located with the emission. We have modelled the effects of dust on intermediate and broad optical and IR line profiles of three Type IIn SNe (SN2010jl, SN2005ip and SN1995N) in order to quantify the masses of dust that have formed at a range of epochs using the MCRT code DAMOCLES (Bevan+ 16, Bevan 18; see below). Where possible, we independently modelled the full optical-IR SED using the MCRT code MOCASSIN (Ercolano+ 03,05,07; see below).

DUST MODELS OF SN2010jl, SN2005ip AND SN1995N

We obtained late-time spectra (>1000d) of SN2010jl, SN2005ip and SN1995N using Gemini North and XShooter at the VLT. Combining these late-time spectra with archival spectra of earlier epochs, we modelled the progressively blueshifted optical line profiles that are present in the spectra of all three. Further evidence of dust formation in these objects comes from an observed IR excess that appeared contemporaneously. We modelled the evolution of the Hα, Hβ and He I lines profiles of SN2005ip and SN2010jl, and the [O I] 6300,6363Å and [O III] 4959,5007Å doublets of SN1995N (see poster by R. Wesson). We additionally modelled the full optical-IR SEDs of SN1995N and SN2010jl, incorporating new Spitzer data. Examples of SED and line profile fits are given in Fig. 2.

Examples of MOCASSIN fits to the optical-IR SED for SN 2010jl

Example DAMOCLES fits to optical line profiles for SN 2005ip and SN 2010jl at different epochs

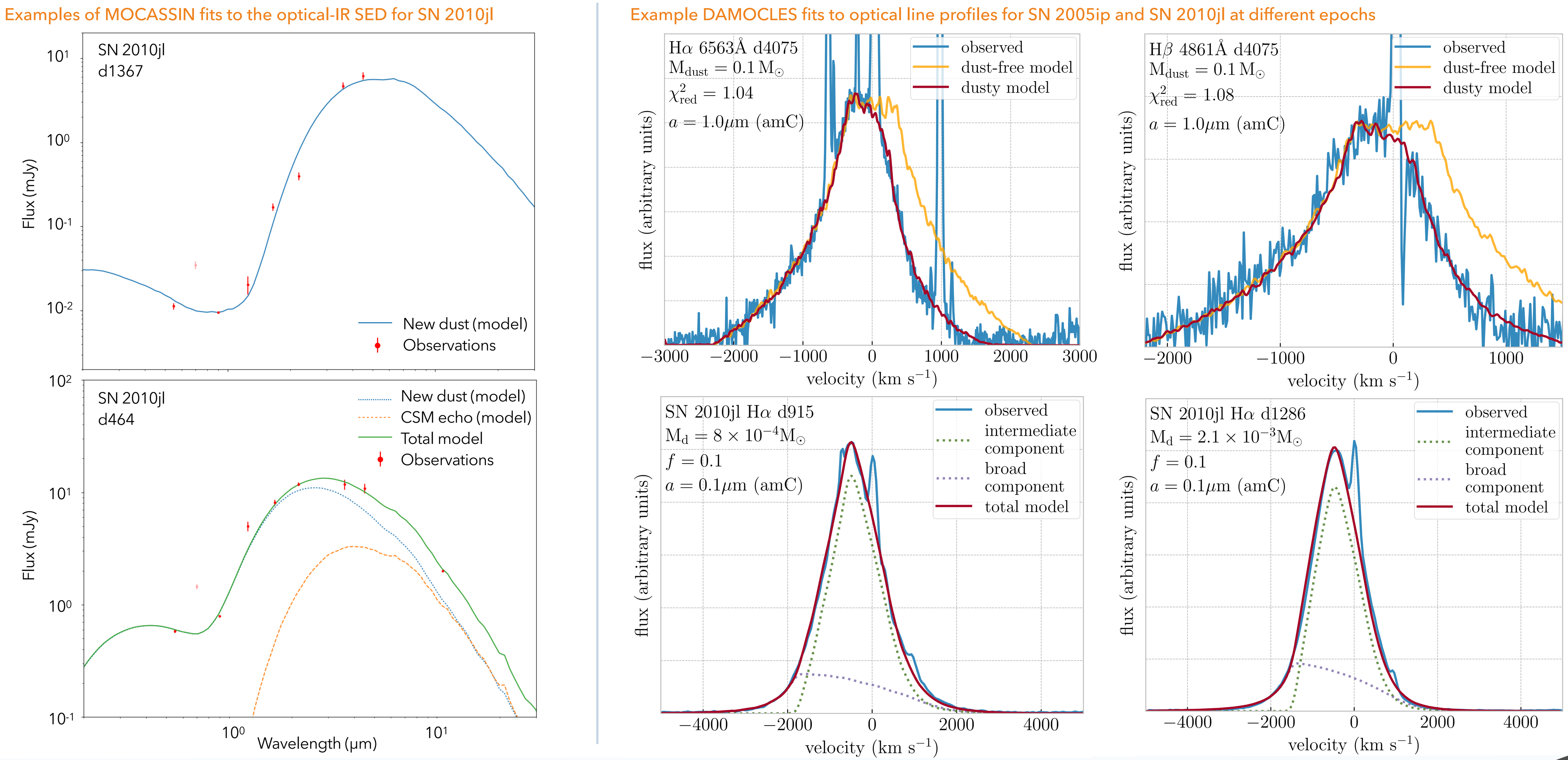

Figure 2. *Left panel:* MOCASSIN best-fits to the optical-IR SED of SN2010jl at 464 and 1367 days post-outburst. The R-band is dominated by Hα and so is excluded from the fit. A small contribution from echoing CSM dust improves the fit at 464d (Krafton+ (submitted)). *Right panel:* DAMOCLES fits to the Hα and Hβ lines of SN2005ip at 4075d, and the Hα line of SN2010jl at 915d and 1286d (Bevan+ 2019, Krafton+ (submitted)).

Dust was located entirely in clumps in the ejecta and/or post-shock region, and a variety of filling factors were investigated. Amorphous carbon grain models were investigated motivated by upper limits to the flux near 10μm precluding silicate dust. A range of grain radii were investigated. For MOCASSIN models, the heating sources were distributed on the surface of a sphere representing illumination from the interaction of the forward shock with the dense CSM. Full details of the models for SN2005ip, SN2010jl and SN1995N can be found in Bevan+ 19, Krafton+ (submitted), and Wesson+ in prep, respectively.

DAMOCLES AND MOCASSIN

DAMOCLES (**D**ust **A**ffected **M**odels **O**f **C**haracteristic **L**ine **E**mission in **S**upernovae) is a Monte Carlo radiative transfer code that models dust-affected CCSN line profiles in order to determine the masses and properties of newly-formed dust (Bevan+ 16,17,18). Any combination of dust species and grain sizes can be specified. Both dust absorption and scattering effects are treated. MOCASSIN is a 3D self-consistent MCRT code that can be used to calculate emission from dust of arbitrary species and size distributions with a given illuminating source distribution and to determine the temperature (Ercolano+ 03,05,07). Both codes allow for any arbitrary density distribution and clumps and propagate packets through a cartesian grid.

CCSN DUST MASS EVOLUTION FROM MCRT MODELS

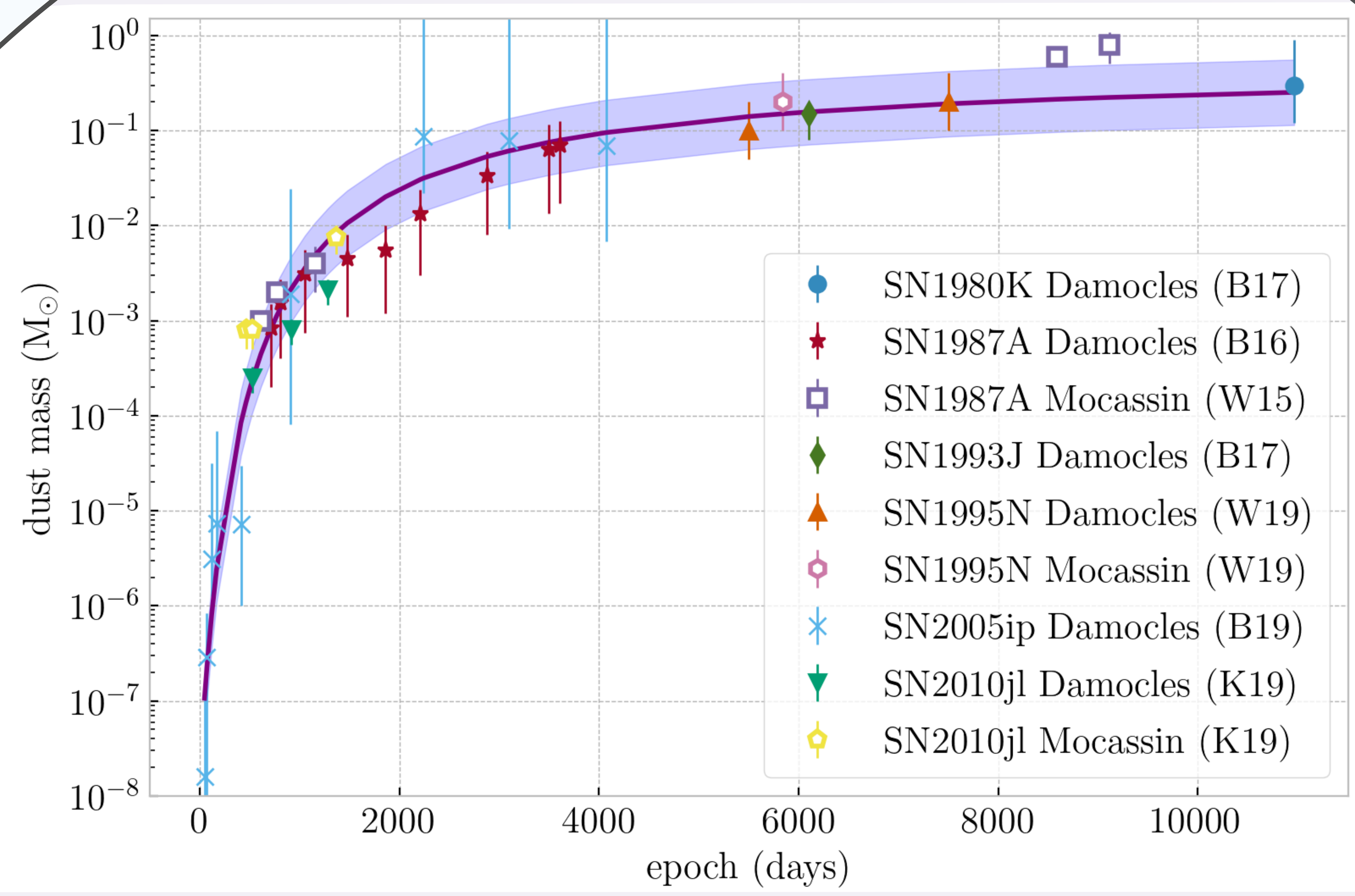

Figure 3. The evolution of dust formation in six different CCSNe from MCRT models of newly-formed SN dust in extinction (line profile models with DAMOCLES) and emission (optical-IR SED models with MOCASSIN). A best-fitting curve of the form $M_{dust} = A\exp(c/(at+b))$ is given with a 1-sigma uncertainty shaded region. The trend for dust formation in Type IIn SNe (as illustrated by SN2010jl, SN2005ip and SN1995N) is consistent with other types of CCSNe. Dust masses are published in Wesson+ 2015 (W15), Bevan+ 16 (B16), Bevan+ 2017 (B17), Bevan+ 2019 (B19), Krafton+ submitted (K19) and Wesson+ in prep. (W19).

Fits to the optical-IR SED were obtained for SN2010jl at 464, 526 and 1367d and for SN1995N at 5840d post-outburst. Line profile fits were obtained for SN2010jl at 526, 915 and 1286d, for SN2005ip at a range of epochs between 48-4075d, and for SN1995N at 5500 and 7500d. In all cases excellent fits were obtained. We plot our dust masses in Fig. 3 (above) and compare to dust masses derived using the same methodology for SN1993J, SN1980K and SN1987A (Bevan+ 16,17). A consistent trend is seen over all objects indicating a slow and steady growth rate with the majority of the dust forming after 2000d. The rate of dust formation in Type IIn SNe seems consistent with other CCSNe suggesting the dominant dust formation location is in the ejecta.

SUMMARY

We have modelled in detail the dust mass evolution in SN 2005ip, SN2010jl and SN1995N at a range of epochs spanning early (43d) to late times (4075d) by fitting the broad and intermediate width Hα, Hβ and He I lines or the [O I] 6300,6363Å and [O III] 4959,5007Å doublets using the MCRT code DAMOCLES (Bevan+ 16,18). We have also modelled the optical-IR SED using the MCRT code MOCASSIN to independently calculate the dust mass (Ercolano+ 03,05,07). We adopted spherically symmetric shell-based models with dust located in clumps. Emission emanated from either the fast-moving ejecta at early times (<200d) or from the post-shock region at later times (>200d). We find that very little dust is required to reproduce the observed line profile asymmetries at early times (~10^{-5} M⊙). However, the evolving blueshifted line profiles and persistent IR-excess demands new dust formation at later times. Both MOCASSIN and DAMOCLES models predict consistent dust masses over a wide range of epochs and objects. A slow, steady rate of dust formation is inferred from our models (see Fig. 3). There is no noticeable difference in the rate of dust formation in Type IIn SNe compared to other SN types suggesting that the majority of the dust has formed in the ejecta. Large final dust masses (~0.5M⊙) are inferred consistent with those required to account for the dust observed at high redshifts.

This project is funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant no. 694520 SNDUST)
website: www.sndust.org