Astro2020 Science White Paper

Dust in supernovae:
--- Do supernovae produce the first dust in the Universe? Are supernovae the key dust producers of galaxies?

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☒Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Sect. 1: Introduction: Why is it important to study dust? Are supernovae important source of dust?

The overall shapes of the spectral energy distributions of galaxies are often dominated by thermal emission of dust grains in the interstellar medium (ISM) within the galaxies, in particular those with on-going star formation (e.g. Helou et al. 1985; Beichman 1987; Veilleux et al. 1995; Houck et al. 2005). There has been a long-term debate on how galaxies acquire dust in the ISM, whether from stellar origins (e.g. Morgan & Edmunds 2003; Dwek & Cherchneff 2011) and/or ISM grain growth (e.g. Draine 2009; Zhukovska 2014). The next decade will be a critical time to finally untangle the threads of this debate, and come to a complete understanding of one of the key stellar sources of dust, supernovae, by measuring dust formed by one of the key stellar dust sources, supernovae (SNe).

SNe are expected to be the first objects to form dust grains in the Universe (Nozawa et al. 2003; Schneider et al. 2004; Cherchneff & Dwek 2010). High-mass stars synthesize heavy elements, such as oxygen, silicon, magnesium, and iron, which are key ingredients of dust grains, and the SN explosion expels these heavy elements into the ISM. Theoretical models predict that these elements condense into dust grains in about one year after the SN explosion, with an estimated dust mass of 25 solar masses for a 170 solar mass progenitor star (Cherchneff & Dwek 2010; Table 1). If a decent fraction of SN dust can survive the subsequent reverse shocks triggered by the SN-ISM interaction, SNe could be the dominant source of the dust in the ISM (e.g. Morgan & Edmunds 2003; Dwek & Cherchneff 2011).

Table 1: SN dust masses predicted by chemical models

Mp (Msun)	Md (Msun)	Z (Zsun)	Ref
20	0.4	1	1, 2
	0.1-0.57	0	3, 4
160	8-20	0	1,2, 3
170	25.4	0	4
200	~20	0	3

M_p: progenitor mass
M_d: dust mass
Z: metallicity

References
1: Schneider et al. (2004)
2: Bianchi & Schneider (2007)
3: Nozawa et al. (2003)
4: Cherchneff & Dwek (2010)

Sect. 2: The current status and what next?

Studies of dust in SNe started developing in 1980's. SN 1987A is the first SN where dust formation has been detected (e.g. Danziger et al 1989; Wooden et al. 1993). Dust has also been detected from Galactic SN remnants (SNRs), Cassiopeia (Cas) A and Crab Nebula (e.g. Marsden et al. 1984; Dwek et al 1987; Dunne et al 2003; Green et al. 2004), opening a new era of research into the dust formation of dust in SNe.

These past decades, the *Spitzer Space Telescope* and *Herschel Space Observatory* started measuring the dust formation in SNe, with increase in the number of detected SNe from a few to over 10 (Gall et al. 2011; Matsuura 2017). Additionally, a handful of Galactic and Magellanic Clouds SN remnants showed dust formation in the ejecta (e.g. Sandstrom et al. 2009; Chawner et al. 2019). These observations revealed that dust formation is common in core collapse SNe. Using *Spitzer* light curves of SNe starting a year after explosion, overall dust production rates of 10^{-5}- 10^{-3} solar masses per SN were inferred (e.g. Sugerman et al. 2006, Barlow et al. 2005, Kotak et al. 2009, Wesson et al. 2010, Andrews et al. 2011, Otsuka et al. 2012; Bevan et al. 2017).

In the *Herschel* HERITAGE survey (Meixner et al. 2013), Matsuura et al. (2011) detected SN1987A, with about 0.5 solar mass of dust, and determined that the submm/FIR dust continuum was from the ejecta. Indebetouw et al. (2014) and Zanardo et al. (2014) confirmed its association with the ejecta with a positive ALMA detection in spatially resolved images, and as did Matsuura et al. (2015) using follow-up Herschel observations (Fig. 1). It is still largely debated why there is a large discrepancy in inferred dust masses in early days (10^{-5}- 10^{-3} solar masses in the first couple years) and later phase (~0.5 solar mass in 20 years), which will be discussed in Sect 3.1.

In general, compositions of SN dust are largely unknown. The only known measurements of dust features are only for two Galactic SN remnants, Cas A and G54.1+0.3, showing the 21 μm feature, which may be associated with SiO_2 (Rho et al. 2008; 2018).

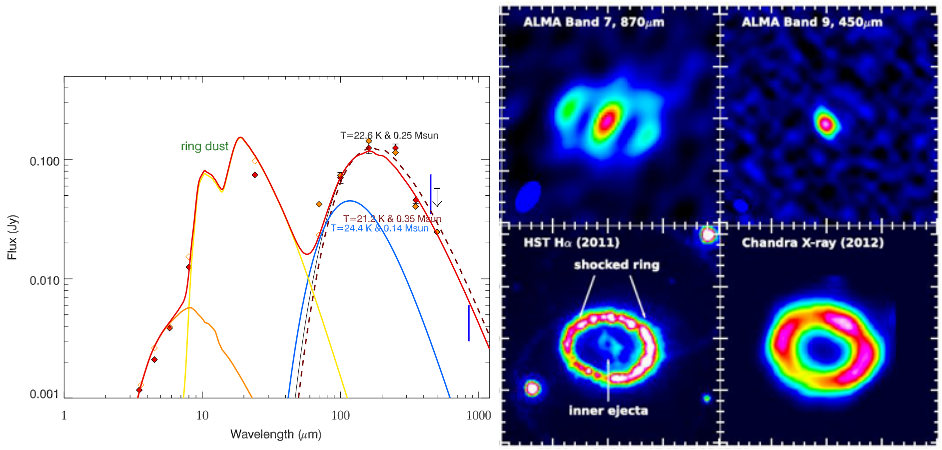

Figure 1: SN 1987A *Right:* The spectral energy distribution of SN 1987A from Spitzer and Hershel (Matsuura et al. 2011; 2015). *Left:* ALMA images confirmed the Herschel emission is due to dust in the ejecta (Band 9; Indebetow et al. 2014).

Sect. 3: What next?

Sect. 3.1: Dust from higher mass SNe - the first dust in early Universe

Although there is growing evidence that supernovae can form dust, these observations are mainly based on SN remnants in the Milky Way and Magellanic Clouds (e.g. Gomez et al. 2012; Matsuura et al. 2015; Chawner et al. 2019; Sandstrom et al. 2009) or SNe in nearby galaxies (mainly within 30 Mpc; can be up to 300 Mpc; Gall et al. 2011; Matsuura 2017). The current sample might be exposed to some bias. First, these SNe found in nearby galaxies tend to occupy the lower end of the progenitor mass range, close to 8 solar masses (Smartt 2009; Otsuka et al. 2012). The Galactic SN remnant, Cas A and SN 1987A have been suggested to have progenitor masses of about 20 solar masses (Young et al. 2006; Woosley 1988; Hashimoto et al. 1989), but these are still lower end of progenitor mass range (from 8 to >100 solar masses). Second, the metallicities of the majority of host galaxies are close to solar metallicity (Smartt et al. 2009), and their environment is not representative of extremely-low metallicity in early Universe. With high sensitivity and wide wavelength coverage from near to far infrared of the *JWST* and *Origin Space Telescope* will be able to investigate SNe in further distant galaxies (a few 100 Mpc), enabling to widen the range of metallicities and masses of sampled SNe to be significantly expanded.

Of particular interest in the context of SN dust production in the early Universe is pair-instability SNe (PISNe), which have a high mass range (Heger & Woosley 2002; Woosley et al. 2007). Pair-instability SN explosions are triggered by the instability caused by the formation of electron-positrons reducing the core pressure, opposed to core collapse. There is a debate about the range of main sequence masses of pair-instability SNe, because their progenitors' mass loss before the SN explosion is largely undetermined, and because the rotation rates, which are largely unknown, may affect mixing within the stellar core (Meynet et al. 2015), and subsequently these unknown factors affect dust yields (Marassi et al. 2019). Woosley et al. (2007) predicted about 95—260 solar masses on the main sequence, with a revised value of 120-250 solar masses by Woosley (2019). Nomoto et al. (2013) predicted about 140-300 solar mass on the main sequence.

Although the pair-instability SNe are suggested to be the sites of earliest dust production at high redshift, the challenge of pair-instability SN dust formation is their explosion energy: its explosion energy can be a few tens of times higher than a core collapse SNe (Woosley 2017). This results in a difference in expansion velocity, temperature and density of the ejecta, hence, the opacity of the gas. All these differences affect subsequent molecular formation and dust condensation in the ejecta (Cherchneff & Dwek 2010). Subtle differences in the explosion conditions appears to make a difference to SN dust formation, therefore observations of dust in high mass SNe are essential.

Superluminous SNe (SLSNe) are, as named as, SNe of luminosity of about 100 times larger than typical SN luminosity (Gal-Yan 2012; Gal-Yan 2019). Due to its large luminosity, SLSNe are thought to be massive stars in origin (Gal-Yan 2019). Superluminous SNe might be the observational counterpart of theoretically predicted pair-instability SNe (Gal-Yan 2009; 2019; Moriya et al 2019), though there is still on-going debate about the origin of this type of SNe (Nicholl et al. 2013). Superluminous SNe are often found in metal-poor galaxies (Lunnan et al. 2013). The question is if this type of SNe that is supposed to be a massive progenitor star, can form dust.

Since clearly recognized detection of superluminous SN in 2007 (SN 2007bi; Gal-Yan 2009), the detection rates of superluminous SNe has increased to a few SLSNe per year (Gal-Yan 2012). It can potentially be higher with much more sensitive deep surveys, such as those from *Euclid* (Inserra et al. 2018). The estimated frequency is 10^{-7}-10^{-8} Mpc^{-3} per year for superluminous SNe, which, as expected from their high mass stellar origins, is a much lower rate than core collapse SNe (10^{-4} Mpc^{-3} per year; Gal-Yan 2012; Pajs et al. 2017; Inserra et al. 2018). In the last two years, there was fortunate to detect two nearby super-luminous SNe, SN 2017egm at 139 Mpc (Nicholl et al 2017; Bose et al. 2018), and SN 2018bsz at 111 Mpc (Anderson et al. 2018). At that distance, it is feasible to detect dust thermal emission from superluminous SNe. Figure 1 guides a case of dust thermal emission, assuming theoretically predicted dust masses (25.4 Msun; Chercheneff & Dwek 2010) would have formed already by day 600 after the explosion. This figure demonstrates that it is feasible to detect dust from superluminous SNe at ~100 Mpc order, possibly with JWST but more likely with OST.

The caveat of this model (Fig 2.) assumes that all of theoretically predicted dust mass is already formed by day 600. However, there is an on-going debate in the nearby SNe community about the timescale of dust formation. The first possibility is that a large dust mass (25.4 solar masses) of dust can already have be formed in a 2-year time scale already, and that dust formation freezes afterwards, as the theory predicts scale (Chercheneff & Dwek 2010; Dwek et al. 2015). The second possibility is that only a small mass (10^{-6} to 10^{-4} solar masses) of dust is formed in two years, with much larger masses of condensing over 20 years of time years (Gall et al. 2014; Wesson et al 2015; Brevan & Barlow 2016; Brevan et al. 2019). The second possibility was proposed because the inferred dust mass from infrared observations of dust thermal emission, and infrared/optical line measurements of dust attenuation were several orders of magnitude low in these first couple of years. However, according to the first possibility, lower dust mass could potentially be explained by optically thick dust in early days and therefore not reflecting the true dust mass (Dwek et al. 2015). To resolve this tension further observations of SNe are required. The final dust mass formed by SNe cannot be measured without measurements of cold dust emission in far-infrared, to which the OST can make a significant contribution.

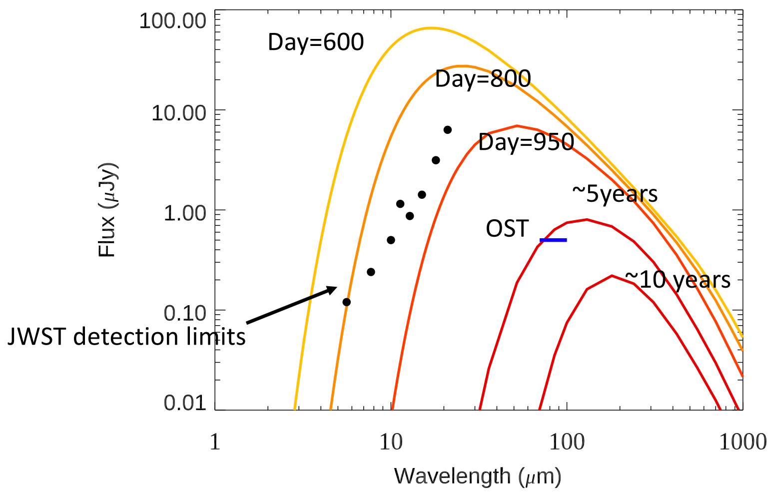

Figure 2: Simulation of 25.4 solar masses of dust emission from a SN exploded at 111 Mpc.

Sect. 3.2: Circumstellar dust, dust destruction by shocks

Of course, we have not forgotten another important question – does supernova dust survive forthcoming reverse shocks? That requires monitoring of very nearby SN remnants, such as Cas A and SN 1987A, where on-going reverse shocks, and mid- and far-infrared observations of JWST and Origin Space Telescope will provide a great opportunity for this.

Dust is not only formed in high-mass stars after the SN explosion, but also before the supernova explosion, i.e. red-supergiants, luminous blue supergiants, and Wolf-Rayet stars. After the SN explosions, the light echo and shock heated progenitor dust in SN remnants will be detected in near- to far-infrared, that could provide further insight into whether forward shocks destroy dust or not (Bouchet et al.; Dwek et al.; Matsuura et al. 2019)

Sect. 3.3: Prospect of stellar community

The upper limit of the stellar mass is largely unknown. A few stars with over 100 solar mass stars have been found in 30 Dor (Crowther et al. 2016), and now up to 200 solar masses of a star has been reported (Schneider et al. 2018). In the next decade, even more higher mass stars and SNe might be found, and understanding their properties would be an exciting topic in the future.

Sect. 4: What can be solved?

The *JWST* launch is planned in 2021, and its instruments, MIRI and NIRSpec, will be used to observe SN 1987A (JWST Guaranteed time program, PI: Wright). The goals are a) to study the evolution of the interaction of the blast wave with the ring and beyond; b) to determine the nature of the ring's hot dust component discovered by *Spitzer*; c) to search for and confirm mid-IR emission from the ~0.5 solar mass of ejecta dust that was discovered at far-IR wavelengths by *Herschel*; d) to study the evolution of the dust and molecules in the ejecta; e) to look for a remnant neutron star.

In the next decade, we expect the investigations of supernova dust production to grow with JWST measurements of SN light curves in the near to mid-IR out to 50 Mpc. JWST will measure dust production of SNe in nearby galaxies by measuring the mid-infrared light curves of SNe that will be discovered with facilities such as ZTF, ASSASN, ATLAS now, and in the future LSST. It is expected that detect of thermal dust emission from core-collapse SNe is possible out to 50 Mpc. Moreover, the detection of dust attenuated optical and near-infrared lines of SNe (Bevan & Barlow 2016) could reach out to SN dust out over 100 Mpc. These will result in a significant increase in the number of detected SNe from just over 10 (Gall et al. 2011; Matsuura 2017) to hundreds, enabling statistical analysis, such as the impact of stellar mass and metallicity on dust mass and dust composition, and how dust mass may increase in time.

JWST will be the ideal telescope at measuring the amount and composition of warm dust in the early phase's of SN dust formation. However, as with SN 1987A, we will need a long wavelength space observatory to measure the total amount of dust produced by a SN (Wesson et al. 2015). The current debate is what is the final mass of SN dust is, and when it would reach that final mass One simple interpretation from the inferred dust masses is that dust mass increases from 10^{-4} solar masses to nearly one solar mass over extended period of time (~10 yrs; Gall et al. 2014; Wesson et al. 2015). An alternative argument is that a large mass of dust is present from early times (approximately 1 year after explosion) but dust emission was optically thick, so that the mid-infrared emission might not reflect the true dust mass (Dwek & Arendt 2015). Resolving this issue would require longer wavelength infrared observations. JWST can lend some insight by detecting dust emission near 30 μm, however, the real solution will come with far-infrared facilities, such as the *Origin Space Telescope* and *SPICA*.

Sect. 5: Summary

Studies of dust in supernovae are expected to develop in forthcoming years. In the coming few years, launch of JWST can reveal

- Increasing number of ejecta dust detection from current of about 10 to hundreds
- Dust compositions of SNe
- Time evolution of thermal emission of SN ejecta dust
- Shock destruction of dust in SN remnants
- Potentially, dust formation in superluminous SNe
- Potentially, the effect of metallicities on SN dust composition and mass

In the decade, further progress is expected in the following fields

- Dust in superluminous SNe
- Final mass of dust formed by a SN
- Does dust mass and composition formed in SNe depend on progenitor mass?
- Cooling lines of ejecta, leading chemistry of dust
- What are the roles of SNe on ISM dust evolution? Dust producer or dust destroyer?

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