Supernova Environmental Impacts
Proceedings IAU Symposium No. 296, 2013
A. Ray & R. A. McCray, eds.

doi:10.1017/S174392131300937X

The dusty debate: core-collapse supernovae and dust

Rubina Kotak

Astrophysics Research Centre, Queen's University, Belfast, BT7 1NN, Northern Ireland
email: `r.kotak@qub.ac.uk`

Abstract. Dust plays an important role in our understanding of the near and distant Universe. The enormous amounts ($\gtrsim 10^8\,M_\odot$) of dust observed at high redshifts have forced us to revisit the commonly-invoked sites of dust production. Although core-collapse supernovae are the prime candidates for cosmic dust production, their actual contribution to the dust budget has been the subject of much debate in recent years. Here, I will discuss results from several vigorous observational campaigns aimed at quantifying the amount of dust produced by core-collapse supernovae. Although sample sizes are still modest, I will attempt to put the role of supernovae as dust producers into perspective.

Keywords. core-collapse supernovae, dust, echoes

1. Introduction

Numerous studies in recent years have emphasised the important role that dust plays in our understanding of the near and distant Universe. Dust formation in the interstellar medium (ISM) has been shown to be extremely inefficient, so the preferred site for dust formation is in the atmospheres of evolved, low-mass ($M \lesssim 8\,M_\odot$) stars from where it is transported into the ISM via stellar winds. This mechanism however, fails to explain the presence of dust at high redshifts as the evolutionary time-scales of these low-mass stars (up to 1 Gyr) begin to become comparable to the age of the Universe. Furthermore, the IR luminosities of $z > 6$ quasars e.g. Bertoldi *et al.* (2003), Dwek *et al.* (2007) imply enormous dust masses ($10^8\,M_\odot$). The short time-scales required for dust enrichment make core-collapse supernovae rather natural candidates for dust producers in the early Universe.

It has long been hypothesized (Cernushi *et al.* 1967, Hoyle & Wickramasinghe, 1970, Tielens *et al.* 1990) that the physical conditions in the ejecta core-collapse supernovae may lead to the condensation of large amounts of dust. A combination of factors form the basis for this presumption: (i) core-collapse supernova ejecta contain large amounts of refractory elements from which dust grains could form; (ii) cooling of the ejecta occurs by adiabatic expansion augmented, in some cases, by molecular emission; (iii) dynamical instabilities in the ejecta results in regions of enhanced density which may further aid the process of grain-growth self-shielding.

Early attempts at modelling dust condensation in supernova ejecta (e.g. Tielens *et al.*, 1990) were easily able to generate substantial amounts (0.1-1 $M_\odot$) of dust. However, see e.g. Cherchneff *et al.* (these proceedings) who point out severe deficiencies in the treatement of grain condensation and growth in earlier work.

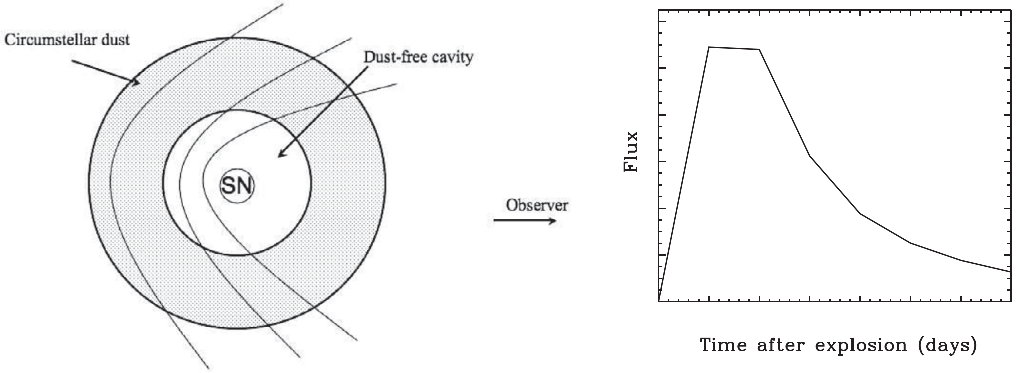

Figure 1. Left: Schematic illustration of an echo arising due to the explosion of a supernova in a dusty circumstellar medium. The series of paraboloids delineate the emitting volume which changes as a function of time. Adapted from Dwek (1983). **Right:** Example of a light curve resulting from a configuration such as that shown in the left-hand panel. Note the characteristic flat-top of the resulting light curve.

2. Observations

The observational support for the hypothesis that grains condense in substantial amounts in core-collapse supernovae is remarkably meagre. Two of the most compelling ways of detecting dust are: (i) the attenuation of spectral lines at optical/near-IR wavelengths in the nebular phase (see e.g. Fig. 16 in Meikle *et al.*, 2011); (ii) thermal emission from dust grains. Until recently, the strongest evidence for dust formation in supernova came from SN 1987A which showed a strong mid-IR excess that was accompanied by a decrease in optical emission and a blueward shift of emission line profiles (Lucy *et al.*, 1989, Danziger *et al.* (1989), Wooden *et al.*, 1991). However, even for this very well-studied albeit peculiar object, recent claims of large ejecta dust masses are controversial and model-dependent.

While the attenuation of spectral lines at late times is a relatively unambiguous signature of the presence of dust, it is difficult to derive quantitative measures of the amount and nature of the dust. As warm grains emit most strongly in the mid-IR, this is the ideal wavelength range for following dust condensation in real time. However, ground-based mid-IR observations are challenging – if not unfeasible – for the vast majority of supernovae. Even for SN 1987A (at only ∼50 kpc), most of the mid-IR data came from the *Kuiper Airborne Observatory* (Wooden *et al.*, 1991). Since the launch of the *Spitzer Space Telescope* , with vastly superior sensitivity and spatial resolution compared to previous instrumentation, this situation has been changing dramatically.

2.1. *Near-infrared echoes*

When studying the thermal emission from dust, it is important to bear in mind that even if a near- or mid-IR "excess" is detected, it might not necessarily be due to new dust that has condensed in the ejecta. Thermal emission may arise from pre-existing dust in the circumstellar medium e.g. due to a dusty wind from the progenitor star which has been heated by the flash from the supernova, resulting in an infrared echo (Bode & Evans, 1979, Dwek, 1983). Shock heating due to ejecta-circumstellar matter interaction may be another mechanism which gives rise to an echo. A schematic diagram of a configuration that would give rise to an echo is shown in Fig. 1.

Clearly, an infrared echo could potentially mask any signature of newly condensing dust, given that the magnitude of this effect. However, in general, emission due echoes

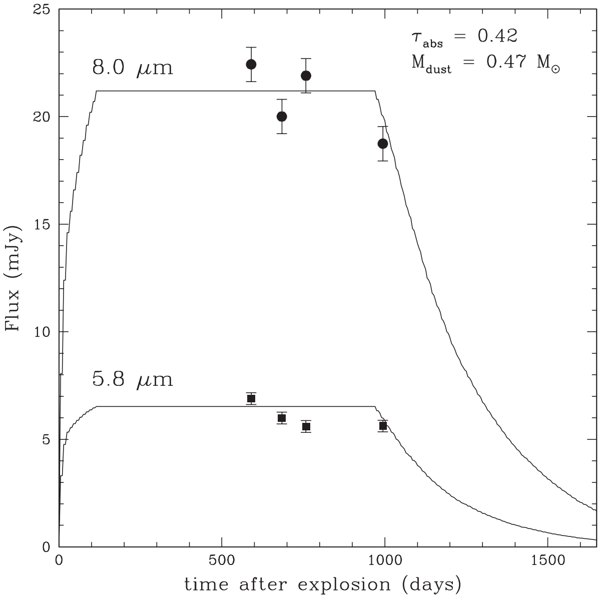

Figure 2. Dereddened 5.8 and 8.0μm photometry of SN 2002hh compared with synthetic light curves generated by an infrared echo model with a dust mass of 0.47 $M_\odot$. The dust temperature at the inner boundary was 345 K during the IR echo plateau phase. Taken from Meikle *et al.* (2006).

tends to appear earlier in the evolution of a supernova, compared to dust formation, which tends to occur at epochs of several hundred days. A caveat, of course, is the geometry and spatial extent of the circumstellar matter. Given the characteristic light curves that arise from echoes, one way of potentially distinguishing between pre-existing and new dust is to monitor the light curve to determine its shape (see Fig. 1). In situations where there is contribution to the infrared luminosity from both an echo, and new dust, the situation is complicated, and detailed modelling is required. Meikle *et al.* (2006) report the first detection of an IR echo in the most common of supernova types, the type-IIP supernova SN 2002hh (see Fig. 2). However, given the complexity of the field around the supernova, it was not possible to conclusively establish whether the echo was due to dusty pre-existing circumstellar matter, or a dusty molecular cloud.

2.2. *The case of SN 2004et*

Extensive mid-IR observations such as those of SN 2004et (Kotak *et al.*, 2009) allow us to witness – in real time – the formation of new ejecta dust (see Fig. 3). Very late-time observations reveal the likely effect of an interstellar infrared echo, which may well dominate the emission longward of $\sim 25\mu$m for this supernova.

The evolution of the spectral energy distributions (Fig. 3) point to infrared emission from dust. Consideration of the (evolution of) the model parameters further allows one to rule out an early-time echo as the source of the mid-infrared luminosity.

The models shown in Fig. 3 are based on a spherical, uniform sphere of isothermal dust grains, following the escape probability treatment of Lucy *et al.* (1989). A typical grain size distribution is used for a mix of refractory materials as predicted by models of dust condensation in supernovae.

In order to estimate the amount of dust, the mass of dust is increased until an adequate match to the spectrum is obtained. In order to be conservative, we model the spectra for

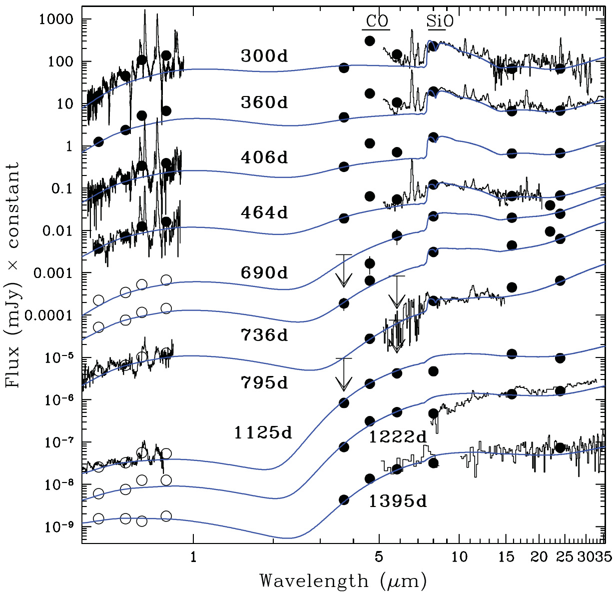

Figure 3. Spectral energy distributions of SN 2004et. The smooth (blue) lines show the model fits, including a hot blackbody component, and a cold (interstellar infrared echo) component to account for the early, and late-time behaviours, respectively. The optical spectra are from Sahu *et al.* (2006). The open circles indicate estimated optical fluxes obtained by the interpolation or extrapolation of the light curves. Adapted from Kotak *et al.* (2009).

the most optically thin case that will still provide an adequate fit to the spectra. This approach was first tested on SN 1987A, and yielded dust masses consistent with other studies.

Interestingly, for SN 2004et, the success of the model (Fig. 4) in reproducing the 8-14 μm feature not only lends further support to the newly-formed silicate dust scenario, but also provides an additional constraint on the model at each epoch in that the optical depth had to be adjusted to match the visibility of this feature. Thus, in spite of the high optical depth, the derived dust masses for SN 2004et (few $\times 10^{-4} M_{\odot}$) are actual values, rather than lower limits.

As with SN 1987A (Spyromilio *et al.* 1988, Wooden *et al.*, 1993), emission due to SiO and CO is clearly evident in SN 2004dj, Kotak *et al.* (2005), and SN 2005af Kotak *et al.* (2006). Also, a cool dust continuum provides a good match to the spectra. The same pattern holds for SN 2005af, with strong molecular emission at earlier epochs (~200 d), which is replaced by a strong cool continuum at later times (~600 d). Our dust mass estimate for SN 2005af comes to $\sim 4 \times 10^{-4} M_{\odot}$. In the latter spectrum, there is a hint of an even cooler component, which might increase this estimate somewhat.

The estimates obtained from the method described above represent the amount of directly detected dust. It is currently difficult to determine how much more dust may be present in optically-thick clumps. This problem was already identified in the context of SN 1987A (Lucy *et al.* 1989, Wooden *et al.*, 1993). The problems persists even at wavelengths as long as (24 μm, the extent of most of our data). However, for most – if not all – of our *Spitzer* targets, current indications are that the clumps are optically-thick in the mid-IR regime before significant dust condensation occurs.

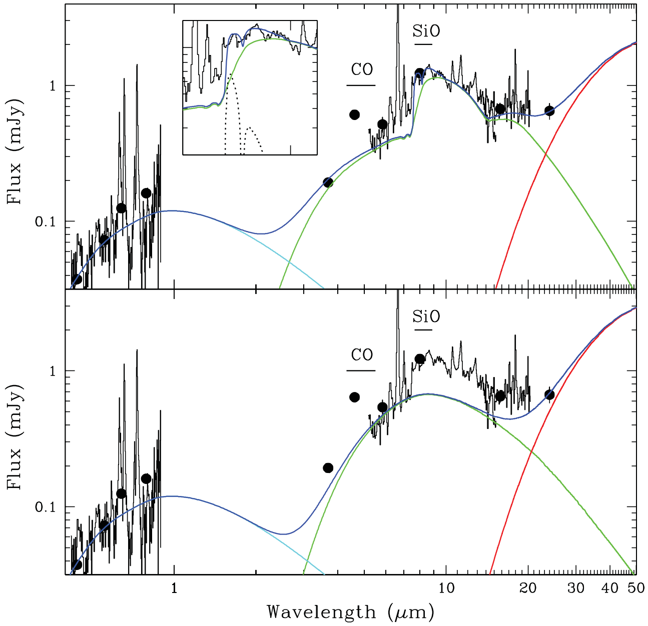

Figure 4. Day 464 observations (black) of SN 2004et compared with models. The upper (main) and lower panels show the isothermal dust models: green for silicate and amorphous carbon grains, respectively. The total model spectrum (blue) also comprises hot (blackbody: cyan) and cold (interstellar IR echo: red) components. The upper panel model also contains a contribution from the SiO fundamental. The inset shows the separate SiO contribution (dotted line). It can be seen that a superior match to the spectrum is achieved with the combined silicate dust and SiO model, as compared with the amorphous carbon dust model. Taken from Kotak *et al.* (2009).

3. Summary

From a sample of well-observed type II-P supernovae in the mid-IR, we find that all objects formed some dust. Less than a decade ago, there was only scant evidence for dust condensation in the ejecta of the most common type of core-collapse supernova.

Grain formation models predict that carbon, silicate, and magnetite grains should be present in substantial quantities, with the silicate grains probably dominating. Our sample of core-collapse supernovae all show evidence of strong emission due to CO, or SiO, or both at epochs as early as ∼100 d. Thus, although our sample size remains small, all of the supernovae that showed evidence for dust condensation, also showed evidence of strong molecular emission at earlier epochs. Thus, molecular emission may well be the harbinger of dust formation.

Current estimates of the amount of dust remain small for type II-plateau supernovae, the most common local type of core-collapse SN with ejecta dust masses in the range of 10^{-3} to $10^{-5} M_\odot$. This is 10–100 times lower than needed to account for the dust seen at high redshifts. In most – but not all – cases, the estimates are lower limits, and some dust may well exist in optically-thick clumps. Although low-mass AGB stars may account for some fraction of the deficit, it is unlikely that they could account for the entire cosmic dust budget. However, this scenario depends heavily on the assumed initial mass function, star formation history, and dust formation efficiency, all of which are difficult to constrain observationally. The recently-revived proposition (e.g. Draine 2009) that dust grains might be able to survive and grow in the ISM may go some way towards allieviating the problems outlined here. Nevertheless, much work remains to be done in assessing the dust production in core-collapse supernovae which is currently limited mainly by mid-IR facilities.

References

Bertoldi, F. *et al.* , 2003, *A&A*, (Letters) 406, 55
Bode, M. & Evans, A., 1979, *A&A*, 73, 113
Cernushi, F. *et al.* , 1967, *Ann. d'Astrophys*, 30, 1039
Cherchneff, I. *et al.*, these proceedings.
Danziger, J. *et al.*, 1989, *IAUC*, 4746, 1
Draine, B., 2009 *ASPC*, 414, 453
Dwek, E., 1983, *ApJ*, 274, 175
Dwek, E., Galliano, F., & Jones, 2007, *ApJ*, 662, 927
Hoyle, F. & Wickramasinghe, N. C., 1970, *Nature*, 226, 62
Kotak, R., *et al.* 2005, *ApJ*, (Letters) 628, 123
Kotak, R., *et al.* 2006, *ApJ*, (Letters) 651, 117
Kotak, R., *et al.* 2009, *ApJ*, 704, 306
Liu, W. & Dalgarno, A., 1994, *ApJ*, 428, L769
Lucy, L. B. *et al.* , 1989, *Structure and dynamics of the ISM, ed. Springer*, 164
Meikle, W. P. S., *et al.* , 2006, *ApJ*, 649, 332
Meikle, W. P. S., *et al.* , 2011, *ApJ*, 732, 109
Sahu, D. K. *et al.*, 2006, *MNRAS*, 372, 1315
Spyromilio, J., *et al.* 1988, *Nature*, 334, 327
Tielens, A. G. G. M., *et al.* 1990, *NASA Conf. Publ.*, 3061, 59

Discussion

VINK: What about dust in supernova remnants?

KOTAK: The picture is more confusing when remnants are considered. For example, for the young SNR 1E 0102.27219, analyses of mid-IR data by different groups result in dust mass estimates that vary greatly: Stanimirovic *et al.*(2005) find no more than $8 \times 10^4 M_{\odot}$ at ~120 K associated with the remnant, while Sandstrom *et al.* (2009) derive dust masses of a few $\times 10^3 M_{\odot}$. Direct evidence for large quantities of dust in SNRs is weak. On the other hand, there are many SNR studies that have emphasised the role of SNRs in the destruction of dust grains.

BOUCHET: It would be good to have an idea where in the ejecta the dust is forming, i.e. Within what velocity of outflow? For instance, for SN87A we got a velocity from the line profiles < 1870 km / sec. Have you this kind of information for other SNe

KOTAK: Yes, we generally do. For the cases where dust is forming in the ejecta of SNE 2004dj (Meikle *et al.* 2011), 2004et (Kotak *et al.* 2009, Sahu *et al.*. The dust forms in slow-moving ejecta $< 2000 km\ s^{-1}$.

SUTARIA: A Spitzer survey made an estimate of dust from type-IIn SNe, using (mainly) archival data. Can you please comment on the veracity of that result?

KOTAK: There have certainly been mid-SR detections based on archival data. The number of available epochs of data per SN is limited it is therefore difficult to determine contributions due to IR echoes.

VINK: A comment: The high dust mass in Cas A reported by Dunne *et al.* was based on an error. One of their lower limits on flux was a flux point and hence there was not much cold dust. For Kepler's SNR the dust seems to originate from the AGB star that formed a companion of the progenitor (Williams *et al.*.)

Ray: Is there an estimate of the Pre-SN dust in various cases of SNe?

Kotak: Yes, in "pure" echo cases, the parameters required to fit the observed fluxes are available, including the dust mass.