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Dust masses in the ejecta of SN 1993J, SN 1987A, SN 1980K and Cas A from modelling their red-blue optical line profile asymmetries

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Abstract. Newly-formed dust masses in the ejecta of core-collapse supernovae (CCSNe) have generally been inferred by fitting their near-IR and mid-IR SEDs yielding small dust mass estimates of $<10^{-3}$ $M_\odot$. However, observations of a few CCSNe in the far-IR by Herschel and ALMA have indicated far higher cold dust masses ($0.1 - 1.0\,M_\odot$). If representative of the wider CCSN population, this could potentially account for the dust masses seen in the early Universe. Unfortunately, there are now few instruments capable of detecting CCSN far-IR dust emission so other techniques must be exploited. The late-time optical and near-IR line profiles of many core-collapse supernovae exhibit a red-blue asymmetry caused by red-shifted emission from the receding parts of the ejecta, which must traverse the dusty interior of the ejecta, experiencing greater extinction than the blue-shifted emission. We present Monte Carlo line transfer models of asymmetric optical line profiles in the late-time spectra of SN 1987A, SN 1980K, SN 1993J and Cas A using the new code DAMOCLES (Bevan & Barlow, 2016). We derive dust mass estimates at late times of $0.08 - 0.18\,M_\odot$ for SN 1993J, $0.12 - 0.3$ $M_\odot$ for SN 1980K and $\sim 1.1\,M_\odot$ for Cas A. We also discuss a series of models of the [OI] and Hα line profiles for SN 1987A over a range of epochs. The derived dust masses as a function of epoch are consistent with continuous dust formation during the first few decades of ejecta evolution and final dust mass estimates of $0.4 - 0.7\,M_\odot$. We conclude that dust masses $> \sim 0.1 M_\odot$ have formed in the ejecta of CCSNe supporting the case that they are the dominant sources of dust in the early Universe.

Key words. supernovae: general - supernovae: individual: SN 1980K, SN 1987A, SN 1993J, Cas A - ISM: supernova remnants - radiative transfer

1. Introduction

The large quantities of dust observed in some high redshift galaxies may have been produced by supernovae from massive stars, although a high dust formation efficiency of $0.1 - 1.0\,M_\odot$ per supernova appears to be required (Morgan & Edmunds, 2003; Dwek et al., 2007). Quantitative determinations of the masses of dust formed in the ejecta of core-collapse supernovae (CCSNe) have normally relied on modelling their thermal infrared dust emission spectra, (e.g. Dwek et al., 1983; Wooden et al., 1993; Sugerman et al., 2006; Gomez et al., 2012; Matsuura et al., 2015). However, even with the enhanced sensitivities of modern thermal infrared instruments it has been difficult to detect extragalactic supernovae at wavelengths $> 8\,\mu$m more than three years after outburst.

An alternative method to determine dust masses in CCSN ejecta was proposed by Lucy et al. (1989) to analyse the optical spectra of SN 1987A, whose Hα and [O I] line profiles at $t > 2$ yr showed pronounced red-blue asymmetries, with their peak line emission shifted bluewards from line centre. This was interpreted and modelled as due to greater extinction by newly formed dust of redshifted photons emitted from the far side of the ejecta relative to blue-shifted photons emitted from the approaching side. They noted an additional effect, whereby energy lost by dust-scattered photons can lead to a red emission wing extending to higher velocities than the largest velocity seen at the blue edge of the line profile.

Blue-shifted line emission can be a common and long-lasting feature of the optical spectra of some CCSNe at both early times (e.g. SN 2006jc Smith et al. 2008), SN 2005ip, SN 2006jd (Stritzinger et al., 2012) and SN 2010jl (Gall et al., 2014)) and at late times (e.g. Milisavljevic et al. 2012). If these lines can be modelled then it may be possible to determine the masses of dust in SN ejecta and supernova remnants (SNRs). This is particularly useful at late-time epochs ($\gtrsim 5$ years) where CCSNe are not currently accessible at mid-infrared and longer wavelengths.

2. The DAMOCLES code

In order to exploit the above phenomena to derive SN dust masses from their observed late-time emission line profiles, we have developed a Monte Carlo line transfer code, DAMOCLES, that models line photons subjected to scattering and absorption by dust in expanding ejecta (Bevan & Barlow, 2016). The emitting material can have arbitrary velocity and density distributions and the code can handle a wide range of grain species and grain size distributions.

We have modelled the Hα line and [O I] λ6300,6363 Å doublet of SN 1987A at

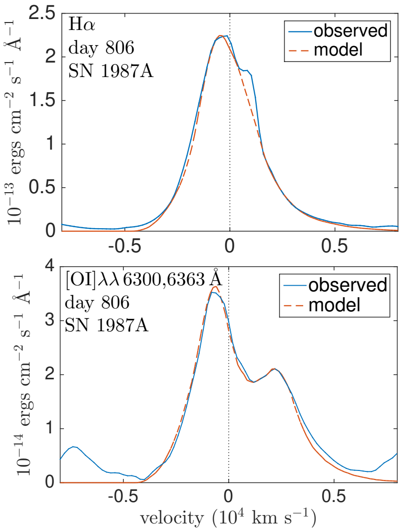

Fig. 1. The best-fitting clumped models for the Hα and [O I] $\lambda\lambda$6300,6363 Å lines of SN 1987A at day 806.

a range of epochs in addition to the late-time emission line spectra of SN 1980K and SN 1993J. We also modelled the asymmetric line profiles seen in the optical spectrum of the ~330-year old Galactic SNR Cassiopeia A, whose integrated spectrum was shown by Milisavljevic et al. (2012).

In the models discussed here, we adopted a velocity profile $V(r) = \frac{V_{max}}{R_{max}} r$ and treated the following variable parameters: the maximum velocity V_{max}, the ejecta radius ratio R_{in}/R_{out}, the dust optical depth τ, the dust albedo ω and the density profile index β where $\rho \propto r^{-\beta}$.

In all models, the ejecta occupies a shell with inner radius R_{in} and outer radius R_{out}. Packets are emitted according to a smooth density profile assuming recombination or collisional excitation such that $i(r) \propto \rho(r)^2 \propto r^{-2\beta}$. Initially the dust is considered to have a smooth density distribution coupled to the gas. In further models, dust is located entirely in clumps of size $R_{out}/25$. The clumps are distributed stochastically between R_{in} and R_{out} according to a distribution $\propto r^{-\beta}$ where $i(r) \propto r^{-2\beta}$. The number of clumps used is determined by the clump volume filling factor of $f = 0.1$.

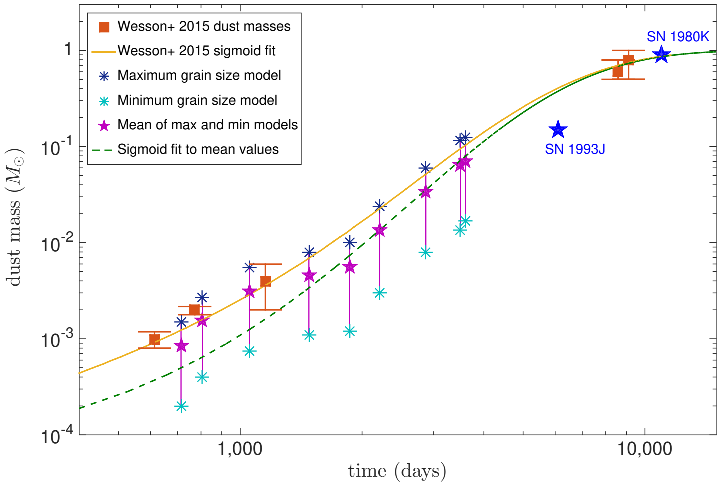

Fig. 2. Derived dust masses for SN 1987A as a function of epoch. *Red squares and yellow line* - dust masses derived by Wesson et al. (2015) from their photometric SED modelling of SN 1987A and their sigmoid fit to these values. *Dark and light blue asterisks* - maximum ($a = 3.5\,\mu$m) and minimum ($a = 0.6\,\mu$m) dust masses respectively for the [O I] models for $t \leq 1478$ days and for the Hα models for $t \geq 1862$ days. *Purple stars* - predicted dust masses (mean of the maximum and minimum estimates). *Dashed green line* - sigmoid fit to our predicted dust masses. *Blue stars* - our dust mass estimates for SN 1993J and SN 1980K.

3. Line profile models for SN 1987A

We collated optical spectra of SN 1987A from the archives of the AAT, CTIO, HST and VLT (see Bevan & Barlow (2016) for more details).

Using DAMOCLES, we modelled the evolution of the Hα and [O I] λ6300,6363 Å line profiles between days 714 – 3500, enabling us to place constraints on the evolution of newly formed dust in the ejecta of SN 1987A. After day ~3600 the Hα profile begins to become dominated by emission from the reverse shock (Fransson et al., 2013). The [O I] doublet becomes too weak to model after day ~1500.

Even at the earliest epochs there is a substantial wing on the red side of the Hα line profile that requires a minimum albedo of $\omega \approx 0.5$ to fit. This necessitates grains larger than $0.6\,\mu$m to have formed by day 714, while by day 3604 grain radii as large as $\sim 3.5\,\mu$m reproduce the extended red scattering wings seen in several of the lines. Our best-fitting clumped amorphous carbon models indicate steady growth from a dust mass of 7×10^{-5} $M_\odot$ at day 714 to a dust mass of the order of $0.1 M_\odot$ by day 3604 (see Figure 1 for an example line profile fit). We derive a sigmoid fit to our dust mass data that predicts a current dust mass of $0.68 M_\odot$, in line with current SED-based dust mass estimates for SN 1987A (e.g. Matsuura et al. (2015), see Figure 2). Since SN 1987A's present dust mass is several times larger than the ~ 0.1 $M_\odot$ we predict by day 3604, a substantial fraction of the current dust mass must have condensed after this epoch, in agreement with the conclusions of Wesson et al. (2015). For further details regarding the SN 1987A line profile models please refer to Bevan & Barlow (2016).

4. Line profile models for SN 1980K, SN 1993J and Cas A

The presence of dust in the ejecta of SN 1980K was postulated by Milisavljevic et al. (2012) based on the observed blue-shifting of the optical line profiles, still present even in very late-time spectra (30 years). Our modelling of SN 1980K focussed on the Hα line and the [O I] λλ6300,6363 Å doublet in this spectrum at 30 yr (Milisavljevic et al., 2012). Both of these line profiles exhibited a very strong blue-shifted asymmetry and were sufficiently distinct that they provided the best options for modelling purposes.

Given the strong oxygen forbidden lines in the spectrum of SN 1980K, a silicate-dominated dust composition, rather than amorphous carbon, seems likely and so we adopt our clumped silicate dust models which imply a dust mass of $0.12-0.30\,M_\odot$ at year 30 with grains of radius $a = 0.1\,\mu$m.

SN 1993J exhibited strong line asymmetries at late times (16 years post-outburst) and we were therefore interested to investigate the presence, or otherwise, of dust in the ejecta as postulated by Fransson et al. (2005) and Milisavljevic et al. (2012). SN 1993J exhibited its strongest line asymmetries in the oxygen lines and in particular we focussed our modelling on the [O II] $\lambda\lambda$ 7319,7330 and [O III] $\lambda\lambda$4959,5007 doublets. Since SN 1993J's spectrum is dominated by oxygen lines, we prefer our silicate dust models to those that used amorphous carbon, implying a clumped dust mass of $0.08-0.15\,M_\odot$ for SN 1993J at year 16 using a grain size of $0.04\,\mu$m.

In the case of Cas A, asymmetries in the ejecta require the modelled [O I] $\lambda\lambda$6300,6363 Å, [O II] $\lambda\lambda$7319,7330 Å and [O III] $\lambda\lambda$4959,5007 Å doublets to be shifted by $\sim$700 – 1000 km s^{-1}. The modelled profiles do not allow for a grain size to be determined. However, adopting a dust composition of 50% amorphous carbon and 50% silicate grains yields an estimated dust mass of $\sim 1.1\,M_\odot$. For further details regarding these models, please refer to Bevan et al. (2017).

5. Conclusions

Our aim throughout our modelling of these objects has been to investigate the feasibility that dust causes the red-blue asymmetries observed in the optical line profiles from CCSNRs and then to determine the dust masses in their ejecta. Whilst the derived dust masses are dependent on clumping structures and dust composition, at these late stages we find that significant dust optical depths (typically 0.5 - 2) and large dust masses ($0.1 - 1.1\,M_\odot$) are required to account for the degree of blue-shifting observed.

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