Stellar Evolution and Stellar Death

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Circumstellar silicate emission features in the 10µm spectra of O-rich AGB stars.

Evolved stars (red giants, M supergiants, WR stars, etc.) are known to be significant sources of dust particles.

But what are the dominant sources of dust in our Galaxy?
As a result of Spitzer SAGE Survey measurements of dust mass loss rates, the dominant stellar dust contributors to the metal-poor LMC and SMC dwarf galaxies will soon be known.

For the much more massive Milky Way Galaxy, the dominant silicate and carbon-dust contributors are still uncertain, due to current uncertainties in distances, total population numbers and mass loss rates. The availability of accurate parallaxes from the GAIA Mission (2012-19) for more than two hundred million stars in the MW and beyond will transform this situation.
Sylvester et al. (1999) ISO spectra

Sequence running from pure emission 10 and 18μm silicate profiles (e.g. Mira) to pure absorption profiles (OH/IR stars) represents a sequence of increasing mass loss rate.
NGC 6302 – a massive O-rich Type I PN

A likely descendant of an extreme OH/IR star. It has a massive edge-on dust disk which completely obscures the central star, whose effective temperature is estimated from photoionization modelling to exceed 200,000 K.
JWST-MIRI stops at 28 μm. Herschel-PACS starts at 57 μm. In between, there are many crystalline silicate bands, plus the crucial 44 μm crystalline ice band (also the [O III] 52 μm line). Only SOFIA will be able to observe these.
Forsterite 69\,\mu m band temperature dependence (Bowey et al. 2002)
The temperature from the peak wavelength of the 69μm forsterite band is well-correlated with the continuum dust temperature and is an excellent dust thermometer that can be used by Herschel-PACS and by SOFIA for studies of post-MS and pre-MS objects.
Log L/L\(_{\odot}\) from Iben & Renzini (ARAA, 1983)

* NGC 7027
NGC 6302

* IRC+10216
GL 2688
* W Hya

* NGC 7293
AFGL 915 = HD 44179 = The Red Rectangle reflection nebula (C-rich)
Polycyclic Aromatic Hydrocarbons (PAHs)

from Puget & Leger (1989)
(see also Allamandola, Tielens & Barker, 1989)
Sloan et al. (2007) found the PAH emission features in the IRS spectrum of the carbon star HD 100764 to peak at longer wavelengths than for any other source. They also found a strong correlation between the peak wavelength and the effective temperature of the exciting source.
AFGL 618: blue-shifted and red-shifted 2.12\(\mu\)m H\(_2\) contours (imaging-FTS; Cox et al. 2003), superposed on HST WFPC-2 H\(\alpha\) image
ISO SWS mid-IR spectrum of GL 618 – detection of C₆H₆ (benzene), C₆H₂ and many other hydrocarbons (Cernicharo et al., 2001)
Detection of benzene and other complex hydrocarbons in the Spitzer IRS spectrum of the proto-PN SMP LMC 11 (Bernard-Salas et al. 2006): LMC analogue to AFGL 618.

An example of a potential target for higher spectral resolution studies by SOFIA and by JWST-MIRI.

SMP11 is close to the saturation limit (0.5 Jy) of JWST MIRI's R=3000 mode.

For JWST MIRI in imaging mode, SMP11 would be detectable at 10σ in 10^4 sec out to D=18 Mpc at 18 μm; out to 38 Mpc at 10 μm; and to 47 Mpc at 7.5 μm. MIRI lo-res 5-10 μm spectroscopy would yield 10σ per res^n element in 10^4 sec at D=14.5 Mpc.
Case study: the intergalactic stellar population of the Virgo Cluster (D=14 Mpc)

Background: the discovery of intergalactic PNe

Up to 500 Lsun is emitted in the narrow (15 km/s) [OIII] 5007A line → use narrow filter.
Planetary nebulae in the intracluster regions of galaxy clusters

Arnaboldi et al. (1996) measured velocities for 19 PNe in the outer regions of the giant elliptical galaxy NGC 4406, in the southern Virgo extension region. Although this galaxy has an RV of -227 km/s, three of the PNe had RV’s close to 1400 km/s, the mean RV of the Virgo cluster. It was concluded that they were intracluster PNe.

Theuns & Warren (1997) discovered ten PN candidates in the Fornax cluster, in fields well away from any Fornax galaxy - consistent with tidal stripping of cluster galaxies. They estimated that intracluster stars could account for up to 40% of all the stars in the Fornax cluster.

Mendez et al. (1997) surveyed a 50 arcmin² area near the centre of the Virgo cluster, detecting 11 PN candidates. They estimated about 4x10⁹ solar masses in their survey area and that such a population could account for up to 50% of the total stellar mass in the Virgo cluster.

Follow-up observations have confirmed large numbers of intergalactic PN candidates in Virgo. However, they represent a tiny tip of a very large iceberg. How to sample more of the iceberg?
For PN LMC SMP 8, $\rightarrow 10\sigma$ in $10^4$ sec with MIRI imaging for distance of:

D=19 Mpc with 7.7 and 11.3\,\mu m filters
D=13 Mpc with 18\,\mu m filter

For PN LMC SMP 36, $\rightarrow 10\sigma$ in $10^4$ sec with MIRI imaging for distance of:

D=44 Mpc with 7.7\,\mu m filter
D=23 Mpc with 11.3\,\mu m filter
For C-star MSX SMC 159, $\rightarrow 10\sigma$ in $10^4$ sec with MIRI imaging for distances of:

D=29 Mpc with 5.6\,\mu m filter
D=23 Mpc with 7.7\,\mu m filter
D=12 Mpc with 11.3\,\mu m filter

Similar sensitivity limits for O-rich AGB stars

IRS spectrum from Sloan et al. (2006)

With the JWST Tunable filter Imager (R=100), a C-star like MSX SMC 159 would give $10\sigma$ in $10^4$ sec out to D= 24-29 Mpc, for wavelengths from 2\,\mu m to 4\,\mu m.

There are at least 20-30 AGB stars for every PN, so there should be many detectable AGB stars in Virgo Cluster fields, allowing the total stellar population to be determined, as well as their gas and dust mass inputs into the intracluster medium.
Exploring the spectra of gas and dust in the 200-600 μm region

ISO LWS 50-200 μm water line spectrum of VY Cma
(self-obscured M supergiant)
Continuum-subtracted ISO LWS spectra: the noxious atmospheres of IRC+10 216 and GL 2688
The 200-650 μm range is the last largely unexplored region of the astronomical spectrum. The HIFI and SPIRE spectrometers onboard Herschel will observe a large number of targets in this wavelength region. HIFI will obtain complete spectral scans at R = 10^6 for a number of archetypal O-rich and C-rich sources, including IRC+10216, leading to a complete line inventory.

The SPIRE FTS will obtain spectra at up to R=1000 for a large number of O-rich and C-rich sources from 200-650 μm, searching particularly for new dust features that may be present.

These features may also occur in the spectra of star forming regions and galaxies, but the best place to isolate and identify them is in the spectra of objects with known chemistries, around which they have formed.

In addition, the continuum spectral properties of different dust species, particularly their emissivity laws, have yet to be fully characterised in this spectral region.
The `missing mass’ problem for intermediate mass stars

An `average’ planetary nebula has a central star mass of 0.6 Msun and a nebular mass of 0.3 Msun. Population modelling predicts a typical main sequence progenitor mass of 1.3 Msun, so about 0.4 Msun appears to have been lost during earlier stages of evolution.

A much greater discrepancy exists for intermediate mass progenitors. Populations of white dwarfs have been found in open clusters which have main sequence turn-off masses of 6-8 Msun (e.g. in NGC 2516; see Weidemann 2000). So, 5-7 Msun must have been lost in order to allow such stars to get below the Chandrasekar limit, yet the most massive PNe (e.g. NGC 6302, NGC 7027) contain no more than 2 Msun of nebular material. So when was the rest of the mass lost (and how do the stars know about the Chandrasekar limit?)

The most sensitive method to search for ejected material around evolved stars is to image the FIR/submm emission from dust particles in the ejecta that are being heated by the interstellar radiation field to temperatures of 20-30K.
IRC+10216 (CW Leo) 1.25x1.25 arcmin

3.7x3.7 arcmin

Figure 1: LEFT: Multiple-shells around the archetypical carbon star CW Leo observed by the CFHT in the V-band (left, FoV 223 × 223") and the HST WFPC2 V-band (right, smooth radial profile subtracted, 75 × 75") (Mauron & Huggins 2000, also see their 2006 paper). RIGHT: IRAM sub-mm interferometric data of TT Cyg (Olofsson et al., 2000) at a resolution of 2".

↔ Y CVn at 90μm (ISO)  
8.3 x 34.8 arcmin

↔ Y CVn at 160μm  
10.5 x 35.5 arcmin

Figure 2: ISO observations of Y CVn (Izumiura 1996) at a resolution of 44" (top panel) and 89" (bottom panel).
NGC 6720
(M 57)

Major axis Diameter: 90 arcsec
H$_2$ v=1-0 S(1)
2.122μm image of Ring Nebula

(MPIA Omega, Calar Alto)

5x5 arcmin FOV
Detecting and determining the masses of extended dust shells with Herschel via multi-wavelength photometric imaging

Aim: to trace the mass loss history of evolved stars. Shells produced by past mass loss events over periods of up to 40,000 years can be detected via their dust emission (heated by the IS radiation field), the most sensitive tool available (the gas is much more difficult to detect). Multi-wavelength photometry $\rightarrow$ fluxes $\rightarrow$ dust temperatures $\rightarrow$ dust masses.

SPIRE will obtain 30x30 arcmin scanned maps for 27 targets at 250, 350 and 520 $\mu$m. PACS will obtain similar sized maps at 70 and 110 $\mu$m.

The targets will include AGB stars (O-rich and C-rich), post-AGB objects and PNe. High galactic latitude targets are favoured, to minimise background confusion.
Where does the dust in high-z SCUBA galaxies originate?

Bertoldi et al. (2003) detected redshifted warm dust emission at mm wavelengths from three QSOs with $z > 6$, i.e. dust had formed less than 1 Gyr after the Big Bang.

Only massive stars would have had sufficient time to evolve. Which massive star phase is the dust source? LBVs? WR stars? Core-Collapse SNe?

SCUBA 450-μm contours superimposed on a UKIRT UFTI K-band image, from Stevens, Ivison, Page & Smail
Ejecta nebulae around Luminous Blue Variables can contain large masses of dust, as in the cases of eta Car and AG Car (though not in the case of P Cygni)

M1-67: an LBV ejecta nebula around a WN8 Wolf-Rayet star
Massive WC9 Wolf-Rayet stars often show hot featureless dust emission (~900K). How does such dust form?

Keck aperture-mask 2.27\(\mu\)m imaging of a rotating pinwheel plume of dust emission from the WC9+OB binary WR104. The dust is formed in the compressed shock interaction region (hotspot) between the two stellar winds. The relative motions of the two stars creates an Archimedean spiral.

from Tuthill et al. (2002)
Galactic Centre Quintuplet Cluster (contains 5 very luminous stars)

False-colour images of Q 2 at 3.08 μm, July 1999 (A) and Q 3 at 2.21μm, August 1998 (B) and at 3.08 μm, July 1999 (C)

ALMA can image the dust in the submm, plus search for molecular emission from the hot-spot shocked wind compression region.

Pre-solar meteoritic grain inclusions include examples that are dominated by r-process isotopes, indicating a supernova origin.

from http://presolar.wustl.edu/work/grains.html#SurfaceProperties
Onion-skin structure of a pre-supernova massive star

O-rich grains and C-rich grains can form in different layers of the ejecta
Optical and KAO IR spectrophotometry of SN 1987A, illustrating the onset of thermal dust emission by day 615. From Wooden et al. (1993).
From dust nucleation modelling, Todini & Ferrara (2001) predicted that 0.08-1.0 solar masses of dust should condense in the ejecta of a typical high-redshift core collapse supernovae within a few years of outburst, corresponding to a condensation efficiency for the available refractory elements of $> 0.2$. Similarly high condensation efficiencies appear to be required (Morgan & Edmunds) to explain the $\sim 10^8$ solar masses of dust deduced to exist in high redshift QSOs.

Prior to the launch of the Spitzer Space Telescope, for the handful of SNe for which dust formation had been inferred, the derived mass of newly formed dust had usually amounted to no more than a few $x 10^{-4}$ solar masses (e.g. KAO and ground-based observations of SN 1987A).
Determining the mass of newly formed dust in young supernova remnants:

From SCUBA submm maps, Dunne et al. (2003) and Morgan et al. (2003) claimed that 1-2 solar masses of new, cold (T = 18 K) dust were present in the young Cas A and Kepler SNRs.

However, Krause et al. (2004) argued that most of the submm emission observed from Cas A originated from a foreground molecular cloud that could be seen in CO.

Herschel Guaranteed Time will be used to obtain PACS and SPIRE photometric and spectroscopic maps of five galactic SNRs with ages of less than 1000 yrs (Cas A, Kepler, Tycho, Crab and 3C58)
Three methods for detecting the formation of dust in young (<1000 days) supernovae ejecta:

(1) detection of thermal IR emission from the newly formed dust. However, the use of this method alone can be compromised by pre-existing nearby dust (e.g. circumstellar dust), which can be heated by the supernova light flash.

(2) detection of a dip in the SN light curve that can be attributed to extinction by newly formed dust. Pre-existing dust cannot produce such a dip.

(3) detection of the development of a red-blue asymmetry in the SN emission line profiles, attributable to the removal by newly formed dust of some of the redshifted emission from the far side of the SN ejecta (Lucy et al. 1989).

Method (1) is normally required if dust masses are to be derived, but it ought to be supported by one or both of (2) and (3).
Hα profile evolution for SN 1998S (from Leonard et al. 2000; see also Pozzo et al. 2004, who estimated that $10^{-3} \ M_{\text{Sun}}$ of dust had formed)
The initial detection of SN 2002hh in SINGS IRAC images was confirmed by higher angular resolution Gemini Michelle imaging.
SN 2002hh, Type IIP, D = 5.9 Mpc

- The SED is reasonably well fit by a 290 K BB, which indicates a minimum emitting radius, $R \approx 10^{17}$ cm and $L = 1.6 \times 10^7 L_{\text{Sun}}$.

- For the IR, a more realistic $\lambda^{-1}$ emissivity gives $R = 5 \times 10^{17}$ cm.

- $R$ is far too large for the emitting dust to have formed in the ejecta (would have taken $> 10$ yrs for material to reach this radius).

- Infer dust was already there.

- Dust modelling with MRN grain size distributions and $r^{-2}$ density distributions: Dashed (red) curve: amorphous carbon (AC); Dotted (blue): 25% AC and 75% amorphous silicates; Dash-dot (green): same, with a dense constant density shell at the inner edge of the $r^{-2}$ wind.

- All three models have total dust masses in the range 0.10 – 0.15 $M_{\text{Sun}}$. 

Barlow et al. 2005

Day 600
SN 2002hh is a Type IIP (plateau) supernova, whose very extended optical light curve is explicable in terms of the just-resolved light echo revealed by the HST ACS/HRC F606W images below.

Preliminary analysis indicates the echo has occurred from a thick dust distribution that is located about 2-8 light years, i.e. (2-8) \( \times 10^{18} \) cm, in front of the SN.
Gerardy et al. (2006)

Spitzer IRS spectrum of SN 2005df at day 135, showing emission lines from radioactive cobalt and nickel.

Spitzer IRS spectrum of SN 2005 at day 214, showing the 8μm v=1-0 bandhead of gaseous SiO. By analogy to SN 1987A, this is believed to be a precursor to dust formation.

Kotak et al. (2006)
SN 1999bw in NGC 3198

Discovered April 15, 1999 - Type IIn, D = 14.5 Mpc

- SINGS Legacy data observed in May 2004 (day 1843) with IRAC and with MIPS in December 2004 (day 2063).

reported by Sugerman et al. 2004.

SINGS IRAC 8 μm at day 1843, 0.75/pixel
5 years after outburst, the source coincident with SN 1999bw had fluxes of 10, 37, 116 and 206 $\mu$Jy at 3.6, 4.5, 5.8 and 8.0$\mu$m, which could be fitted by a 450 K blackbody.

For D=14.5 Mpc, $L = 1.6 \times 10^5 L_{\odot}$ and the minimum (BB) emitting radius is $1.6 \times 10^{16}$ cm, which could be reached by ejecta dust moving at 1000 km/s during the 5 years since core collapse.
SN 1999bw, Type IIb, D = 14.5 Mpc


8 µm flux evolution

Decline of 8 µm flux - faded by factor of ~2 over c.700 days.

5.8 µm flux faded by factor of ~3 over same period.
Supernova SN 2003gd in NGC 628 (Messier 74)

Day 499
SN 2003gd, Type IIP, D = 9.3 Mpc

Further evidence for dust condensation in the SN ejecta ...

Asymmetric blue-shifted emission lines - dust forming in the ejecta preferentially extinguishes emission from receding (i.e. red-shifted) gas.

Increase in optical extinction - as evidenced by the dip in the light curve of SN 1987A scaled to the fluxes of SN 2003gd (red circles).

Additional extinction by dust is inferred to have occurred after day 500 for both SNe, corresponding to 0.25 - 0.5 mags at R on day 499 for 2003gd and 0.8 -1.9 mags on day 678.
Clumpy SN ejecta models calculated with dusty-MOCCASIN using a mother-grid of $61^3$ cells; mother cells that contain clumps are resolved by a subgrid of $5^3$ cells. (from Ercolano et al. 2007)
SN 2003gd, Type IIP, D = 9.3 Mpc

- Observations point to dust forming within the ejecta of SN 2003gd, beginning 250-493 days after outburst.

- Estimating the dust mass: 3-D Monte-Carlo RT code MOCASSIN (Ercolano et al. 2005) - Smooth and clumpy dust distributions modelled.

- Summary of the lower (smooth) and upper limits (clumpy) to the dust mass estimates for the 2 epochs are shown in the table below.

<table>
<thead>
<tr>
<th>Day</th>
<th>Model</th>
<th>$A_R$</th>
<th>$M_{\text{dust}}(M_{\odot})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>499</td>
<td>Smooth</td>
<td>0.40</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>499</td>
<td>Clumpy</td>
<td>0.65</td>
<td>$1.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>678</td>
<td>Smooth</td>
<td>1.48</td>
<td>$2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>678</td>
<td>Clumpy</td>
<td>1.22</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

- Clumpy modelling at day 678 indicates condensation efficiency of $\leq 0.12$, close to the 0.2 needed to account for the dust content of high-z galaxies.

(from Sugerman et al. 2006)
SN 2004dj, Type IIP, D = 3.3 Mpc

- Observed with Spitzer over a number of epochs from day 90 to day 996 (PI’s: Van Dyk, Meikle, and Sugerman), and with Gemini Michelle in the N’ filter at days 614 and 967.

- Fading evident in the mid-IR
SN 2004dj, Type IIP, D = 3.3 Mpc

- 690 K BB fit to day 996 IRAC data => minimum emitting radius of \( \sim 0.8 \times 10^{17} \text{cm} \) for a distance of 3.3 Mpc, and \( L = 26 \times 10^7 L_{\odot} \), which indicates min. ejecta speeds of circa 9000 km/s.

- This is just plausible, but is it more likely we are seeing an IR echo from a CS shell?
Thermal IR studies of CCSNe – results so far

<table>
<thead>
<tr>
<th>SN</th>
<th>D</th>
<th>Progenitor mass (M\textsubscript{Sun})</th>
<th>Dust formation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987A</td>
<td>0.05</td>
<td>16-22</td>
<td>Yes</td>
</tr>
<tr>
<td>1999bw</td>
<td>14.5</td>
<td>unknown</td>
<td>Yes; but very late</td>
</tr>
<tr>
<td>2002hh</td>
<td>5.9</td>
<td>8-14</td>
<td>only pre-existing dust seen</td>
</tr>
<tr>
<td>2003gd</td>
<td>9.3</td>
<td>6-12</td>
<td>Yes</td>
</tr>
<tr>
<td>2004dj</td>
<td>3.3</td>
<td>12-15</td>
<td>maybe; but CS dust more likely?</td>
</tr>
<tr>
<td>2004et</td>
<td>5.9</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>2005cs</td>
<td>8.0</td>
<td>7-12</td>
<td>No</td>
</tr>
</tbody>
</table>

All of the above were Type II SNe, from supergiant progenitors with masses <20 M\textsubscript{Sun}. No Type Ib or Ic SNe (believed to originate from H-deficient WR stars descended from even more massive stars) have been close enough for similar studies to be carried out (no Type Ia’s either).

JWST MIRI’s much greater sensitivity will enable SNe out to 200 Mpc to be detected at mid-IR wavelengths, corresponding to a volume 8000x larger than for Spitzer. So MIRI will be able to observe very large numbers of SNe of all classes, photometrically and spectroscopically.
Spitzer images of Supernova SN2002hh in NGC 6946, (day 590).

Gemini-N Michelle 11µm image (day 698)
The use of archival images from the HST and from ground-based 8m-class telescopes has allowed the precursors of nearly 20 core-collapse SNe to be identified in the last few years (Smartt et al.; van Dyk et al.) – all were Type II (H-rich) and all were associated with supergiant stars with M < 20 Msun. The precursors of CCSNe from more massive stars have been more difficult to identify.

The supergiant precursors of Type II SNe have $M_V$ in the range $-6$ to $-7$, whereas WC Wolf-Rayet stars have $M_V \sim -4$ and WO stars have $M_V \sim -2$. So much deeper, high angular resolution imaging of a significant sample of galaxies would be needed to identify such precursors. A better option might be to carry out deep surveys for WR stars for a significant sample of galaxies (using filters to isolate the strong WR emission features), in order to obtain a complete WR census in advance of future Type Ib and Ic events.

Some massive CCSNe could have luminous LBVs as their immediate precursors. Pastorello et al. (2007) found that the Type Ic SN 2006jc had an LBV-like outburst two years before the SN event.