The Mass of Dust in the Crab Nebula: RT Models with Smooth and Clumped Dust Distributions

The Universe Explored by Herschel
ESA-ESTEC
Patrick J. Owen
Mike Barlow
Introduction

• Sub-mm observations of high redshift and metal poor galaxies have found far more dust than expected
• Core Collapse Supernovae have been proposed as the source of dust
• Predicted that 0.1-1.0 $M_\odot$ of dust needed per supernova event\([1,2]\)
• Quantifying how much dust a supernova can produce is now very important

Dust in Supernovae

• Spitzer observations have been finding $<10^{-3}\, M_\odot$ of warm dust per core collapse supernova

• Herschel observations have found 0.1 $M_\odot$ of cold dust in the ejecta of Cas A\textsuperscript{[3]} and 0.4 $M_\odot$ in SN1987A \textsuperscript{[4]} supernovae

• This is enough dust for supernovae to account for the observed mass of dust at high redshifts

\textsuperscript{[3]} Barlow et al 2010 A&A
\textsuperscript{[4]} Matsuura et al 2011 Science and ESTEC2013 talk
ESA *Herschel* and *Planck* Observations of the Crab Nebula

70, 100, 170, 250 µm
Estimating the Dust Mass in the Crab

- Amorphous Carbon
  \(0.11 \pm 0.01 \, M_\odot\) [5]

- Silicates
  \(0.24 \pm 0.32 \, M_\odot\) [5]

- Previous estimates from Spitzer
  \(2.4 \times 10^{-3} \, M_\odot\) of warm dust [6]

Issues with this estimate of the dust mass

- Fitted with only two temperature components
- Does not take into account grains of different sizes or the distribution of those sizes
- Assumes that the dust is uniformly distributed throughout the nebula
An Alternate View: Temim and Dwek 2013

- Fitted a large number of modified black bodies for grain size/temperature distribution
- Central point source
- All dust at one distance
- Rouleau & Martin (1991) 0.02 $M_\odot$ of dust with a distribution $\alpha = 3.5$ over a range 0.001-1.0 $\mu$m
Building a radiative transfer model to estimate the dust mass using MOCASSIN[7]

- Heats the dust radiatively
- Allows different grain size distributions
- Can use different sets of optical constants
- Provides a diffuse photon source
- Can model smooth, shell and clumpy density distributions

Ionisation in the Crab Nebula

- The Crab contains an inner pulsar wind nebula
- Photoionised rather than shock-ionised
- Diffuse photon source through the central 2/3 of the nebula
- Synchrotron spectrum from Hester 2006, modified to take in to account *Planck* sub-mm and mm observations
Geometry of the smooth model

[8] Hester 2006 ARAA 46
Best fits for dust mass with a smooth model

\[ a_{\text{min}} = 0.07 \, \mu\text{m} \]

\[ a_{\text{max}} = 1.0 \, \mu\text{m} \]

\[ \alpha = 2.9 \]

0.31 \( M_\odot \) of dust

Zubko AC\textsuperscript{[9]} Optical constants

Different Amorphous Carbon Optical Constants

a) Zubko AC Best Fit

\[ x^2 = 6.13 \]

b) Same parameters as a) but with Zubko BE optical constants
Fitting with Amorphous Carbon with Zubko BE optical constants

\[ x^2 = 6.21 \]

- \( a_{\text{min}} = 0.07 \, \mu\text{m} \)
- \( a_{\text{max}} = 0.2 \, \mu\text{m} \)
- \( \alpha = 2.9 \)
- \( 0.16 \, M_\odot \) of dust
- Zubko BE Optical constants
Smooth Model Best Fit Results

<table>
<thead>
<tr>
<th></th>
<th>Amorphous Carbon</th>
<th>Silicate</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>a min</td>
<td>0.07 µm</td>
<td>0.07 µm</td>
<td>0.07 µm</td>
</tr>
<tr>
<td>a max</td>
<td>1.0 µm</td>
<td>0.2 µm</td>
<td>1.0 µm</td>
</tr>
<tr>
<td>α</td>
<td>2.9±0.1</td>
<td>2.9±0.1</td>
<td>2.9±0.1</td>
</tr>
<tr>
<td>dust mass</td>
<td>0.31 M⊙</td>
<td>0.16 M⊙</td>
<td>0.30 M⊙</td>
</tr>
<tr>
<td></td>
<td>x² =6.13</td>
<td>x² =6.21</td>
<td>x² =7.01</td>
</tr>
</tbody>
</table>

Different optical properties give very different dust masses

Line Fluxes

- As well as fitting the SED, the model needs to fit the optical and IR emission line fluxes
- The smooth model (with $N_e = 450 \text{ cm}^{-3}$) fits dereddened H$_\beta$ flux
- Optical line fluxes$^{[13]}$ are fitted by varying the elemental abundances

### Line Fluxes

<table>
<thead>
<tr>
<th>Line</th>
<th>Wavelength</th>
<th>Observed</th>
<th>Modelled</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_\beta$</td>
<td>4861</td>
<td>$1.78 \times 10^{-11}$</td>
<td>$1.80 \times 10^{-11}$</td>
<td>0.99</td>
</tr>
<tr>
<td>[O II]</td>
<td>3726+3729</td>
<td>18.11</td>
<td>19.9</td>
<td>0.91</td>
</tr>
<tr>
<td>[Ne III]</td>
<td>3869</td>
<td>4.65</td>
<td>3.90</td>
<td>1.19</td>
</tr>
<tr>
<td>[S II]</td>
<td>4069</td>
<td>0.37</td>
<td>0.32</td>
<td>1.16</td>
</tr>
<tr>
<td>[O III] + H$_\gamma$</td>
<td>4363</td>
<td>0.57</td>
<td>0.50</td>
<td>1.14</td>
</tr>
<tr>
<td>He I</td>
<td>4471</td>
<td>0.37</td>
<td>0.36</td>
<td>1.04</td>
</tr>
<tr>
<td>He II</td>
<td>4686</td>
<td>0.78</td>
<td>0.87</td>
<td>0.90</td>
</tr>
<tr>
<td>[O III]</td>
<td>5007</td>
<td>11.92</td>
<td>12.4</td>
<td>0.96</td>
</tr>
<tr>
<td>H$_\alpha$</td>
<td>6563</td>
<td>2.85</td>
<td>2.92</td>
<td>0.98</td>
</tr>
<tr>
<td>[N II]</td>
<td>6548+6584</td>
<td>6.87</td>
<td>4.67</td>
<td>1.11</td>
</tr>
<tr>
<td>[S II]</td>
<td>6717+6731</td>
<td>4.31</td>
<td>4.80</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Shells: Smooth or Clumpy

All mass outside PWN Photon source
$N_e = 450 \text{ cm}^{-3}$

Mass in clumps of radius 0.1 pc
Filling factor of 0.1
Decreasing with $r$
$N_e = 750 \text{ cm}^{-3}$
### Results of Shell and Clumpy Models

<table>
<thead>
<tr>
<th></th>
<th>Amorphous Carbon</th>
<th>Silicate</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zb AC</td>
<td>Zb BE</td>
<td>Hanner</td>
</tr>
<tr>
<td>Smooth</td>
<td>0.31 M⊙</td>
<td>0.16 M⊙</td>
<td>0.30 M⊙</td>
</tr>
<tr>
<td></td>
<td>$x^2 = 6.13$</td>
<td>$x^2 = 6.21$</td>
<td>$x^2 = 7.01$</td>
</tr>
<tr>
<td>Shell</td>
<td>0.27 M⊙</td>
<td>0.11 M⊙</td>
<td>0.27 M⊙</td>
</tr>
<tr>
<td></td>
<td>$x^2 = 9.9$</td>
<td>$x^2 = 9.7$</td>
<td>$x^2 = 10.6$</td>
</tr>
<tr>
<td>Clumpy</td>
<td>0.64 M⊙</td>
<td>0.48 M⊙</td>
<td>0.60 M⊙</td>
</tr>
<tr>
<td></td>
<td>$x^2 = 11.3$</td>
<td>$x^2 = 11.5$</td>
<td>$x^2 = 13.1$</td>
</tr>
<tr>
<td>Clumpy ICM</td>
<td>0.68 M⊙</td>
<td>0.50 M⊙</td>
<td>0.63 M⊙</td>
</tr>
<tr>
<td></td>
<td>$x^2 = 11.2$</td>
<td>$x^2 = 10.9$</td>
<td>$x^2 = 13.9$</td>
</tr>
</tbody>
</table>

Different density distributions give very different dust masses.
Nebula Mass

- The model can also be used to investigate the mass of the nebula as a whole
- The smooth model is far too massive - $59 \, M_\odot$ of gas in the nebula
- The clumpy model gives a far more reasonable mass of $7.1 \, M_\odot$ of gas which is in good agreement with canonical values for the nebula of $7-12 \, M_\odot$ [14, 15]

Best Fit Results

Smooth models
0.1-0.3 $M_\odot$ of amorphous carbon dust

Clumpy models
0.4-0.6 $M_\odot$ of amorphous carbon dust
Conclusions

- Determining the dust mass using RT modelling gives higher dust masses than simple SED fits
- Different dust properties give very different dust masses
- Clumped dust density distributions give 2-3 times higher dust masses compared to smooth dust density distributions
- There is a large mass of dust in the Crab
Thank You