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

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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

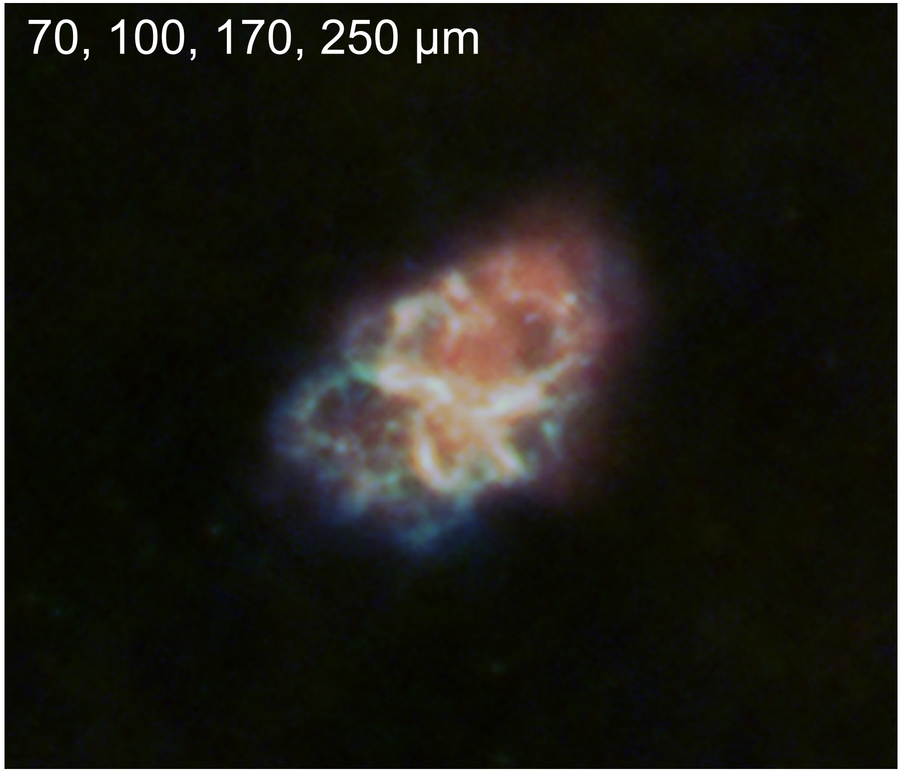
[1] Morgan and Edmunds 2003 MNRAS [2] Dwek et al 2007 ApJ

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 [3] and 0.4 $M_\odot$ in SN1987A [4] supernovae
- This is enough dust for supernovae to account for the observed mass of dust at high redshifts

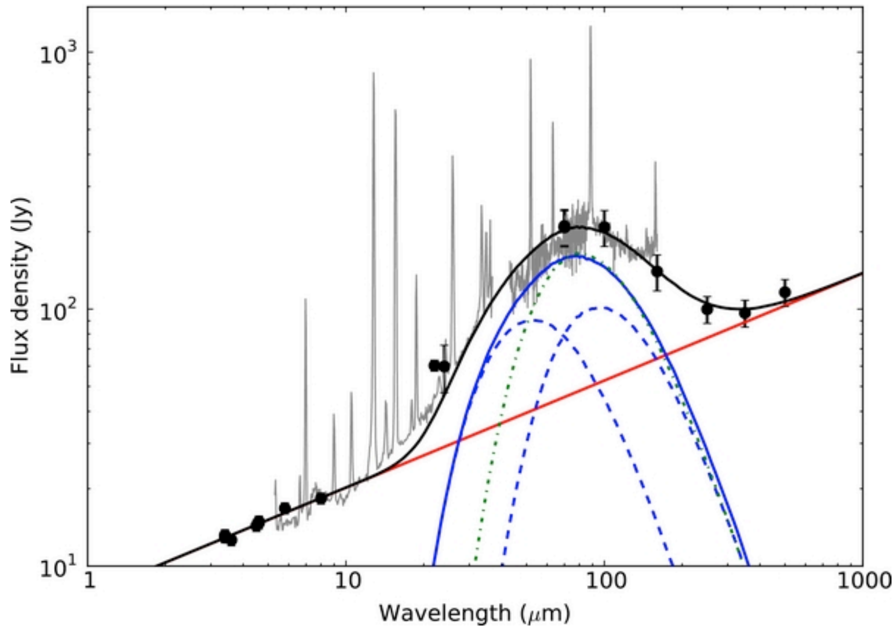
[3] Barlow et al 2010 A&A
[4] Matsuura et al 2011 Science and ESTEC2013 talk

ESA *Herschel* and *Planck* Observations of the Crab Nebula



Estimating the Dust Mass in the Crab

- Amorphous Carbon $0.11 \pm 0.01\ M_{\odot}$ [5]
- Silicates $0.24 \pm^{0.32}_{0.08}\ M_{\odot}$ [5]
- Previous estimates from Spitzer $2.4 \times 10^{-3}\ M_{\odot}$ of warm dust [6]

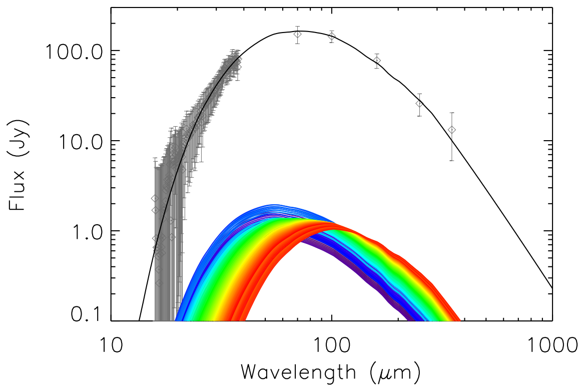


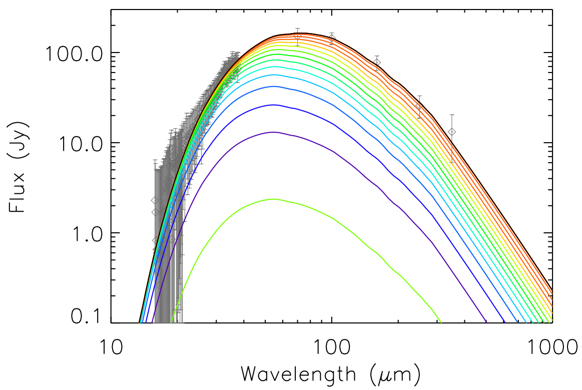
[5] Gomez et al 2012 ApJ [6] Temim et al 2012 ApJ

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 μm

Building a radiative transfer model to estimate the dust mass using MOCASSIN[7]

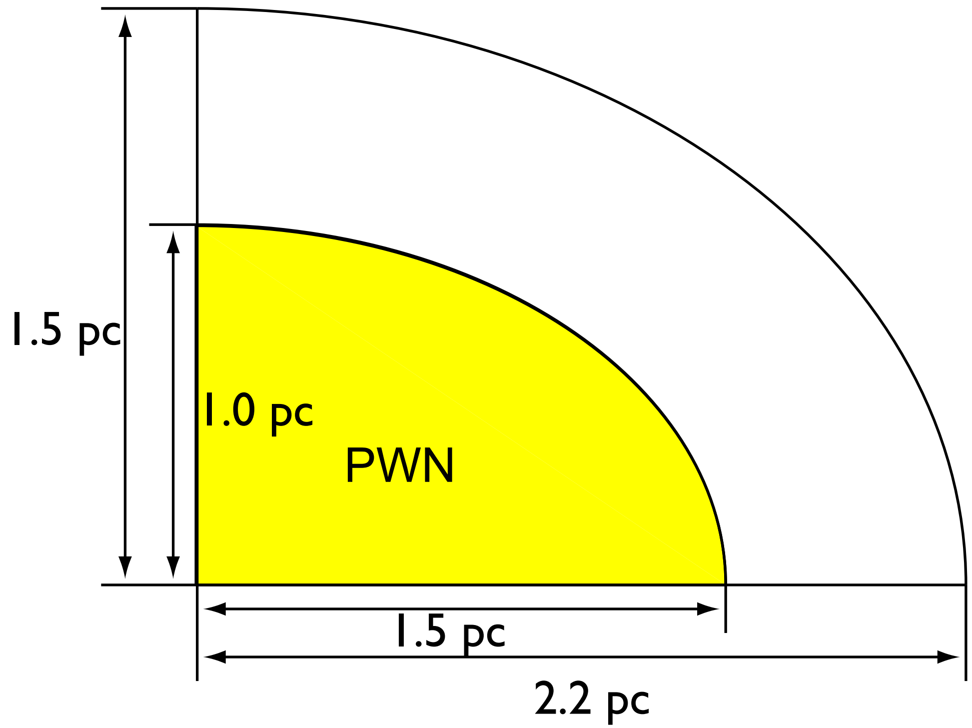
- Heats the dust radiatively
- Allows different grain size distributions
- Can use different sets of optical constants
- Provides a diffuse photon source
- Can model smooth, shell and clumpy density distributions

[7] Ercolano et al 2003, 2005, 2008

Ionisation in the Crab Nebula

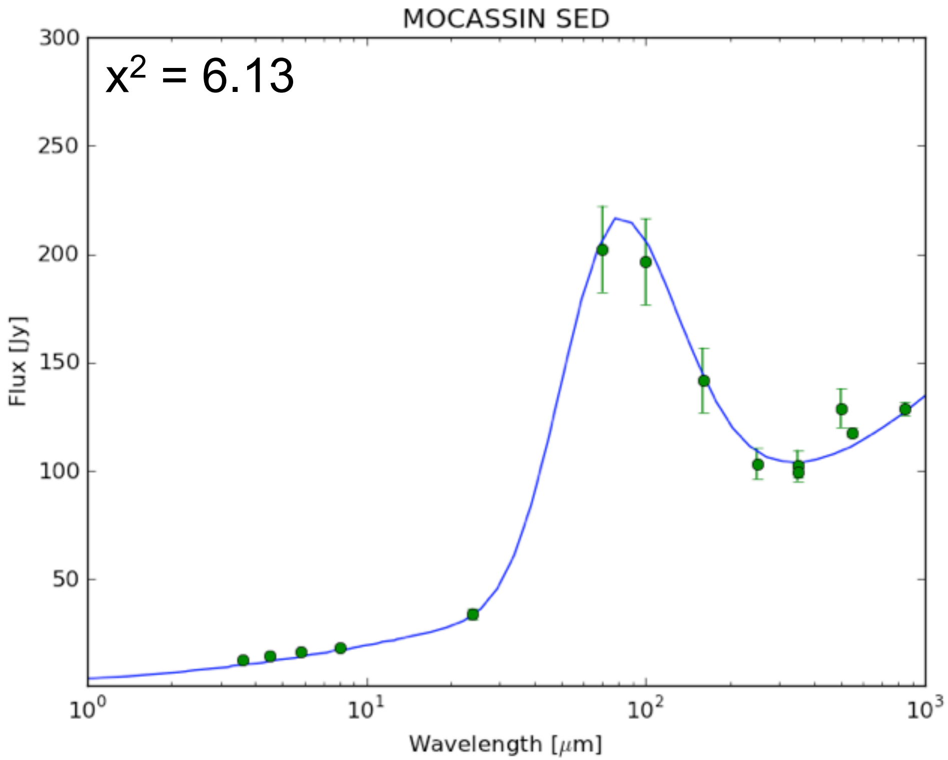
- The Crab contains an inner pulsar wind nebula
- Photoionised rather than shock-ionised
- Diffuse photon source through the central 2/3 of the nebula
- Synchrotron spectrum from Hester 2006, modified to take in to account *Planck* sub-mm and mm observations

Geometry of the smooth model



[8] Hester 2006 ARAA 46

Best fits for dust mass with a smooth model



a_{min} = 0.07 μm

a_{max} = 1.0 μm

α = 2.9

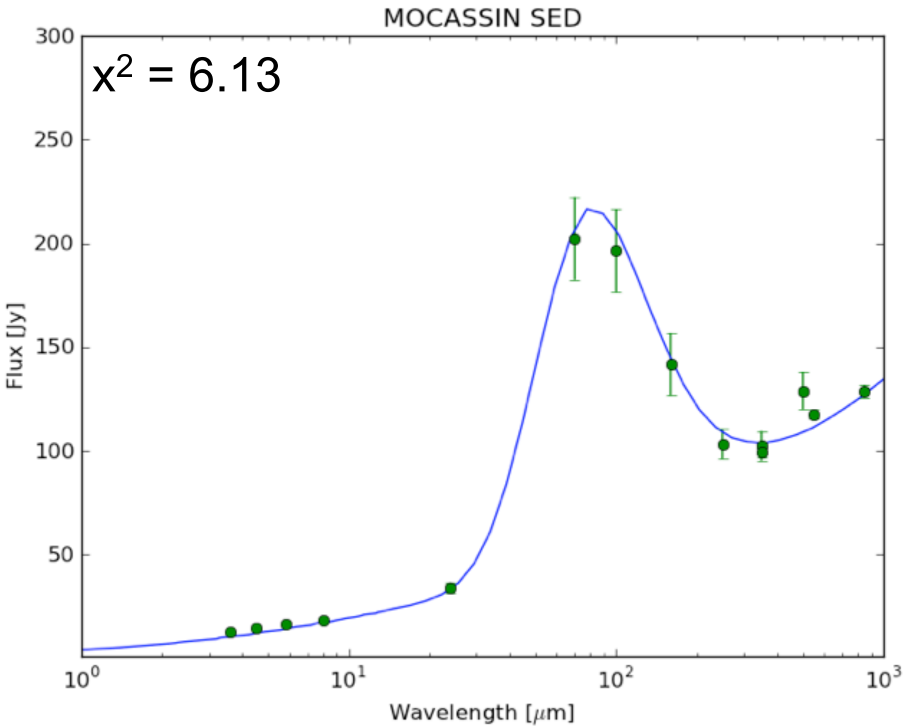
0.31 $M_\odot$ of dust

Zubko AC[9] Optical constants

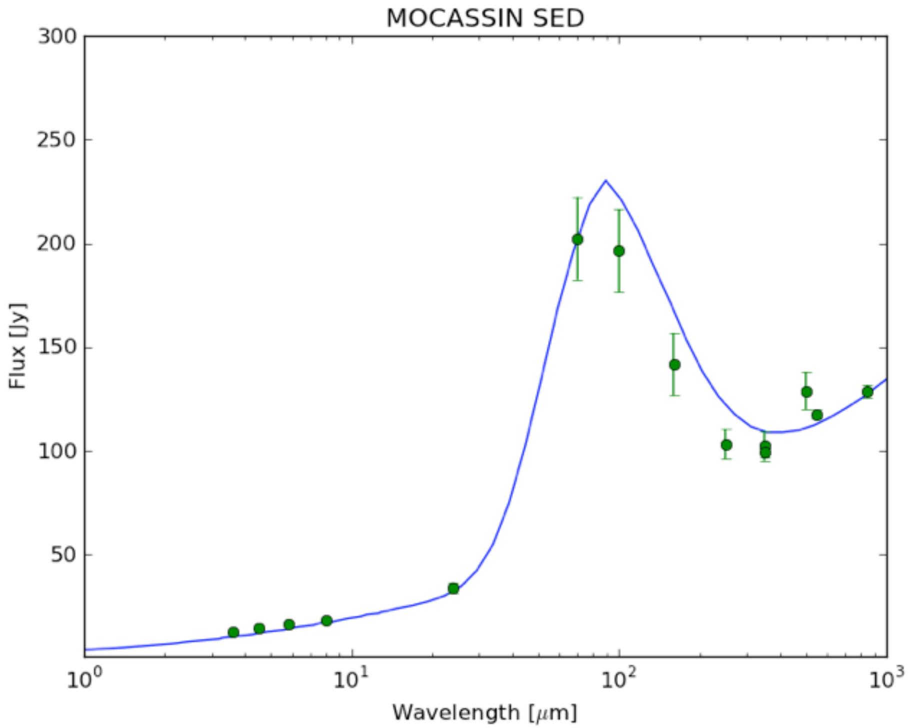
[9] Zubko et al 1996 ApJ

Different Amorphous Carbon Optical Constants

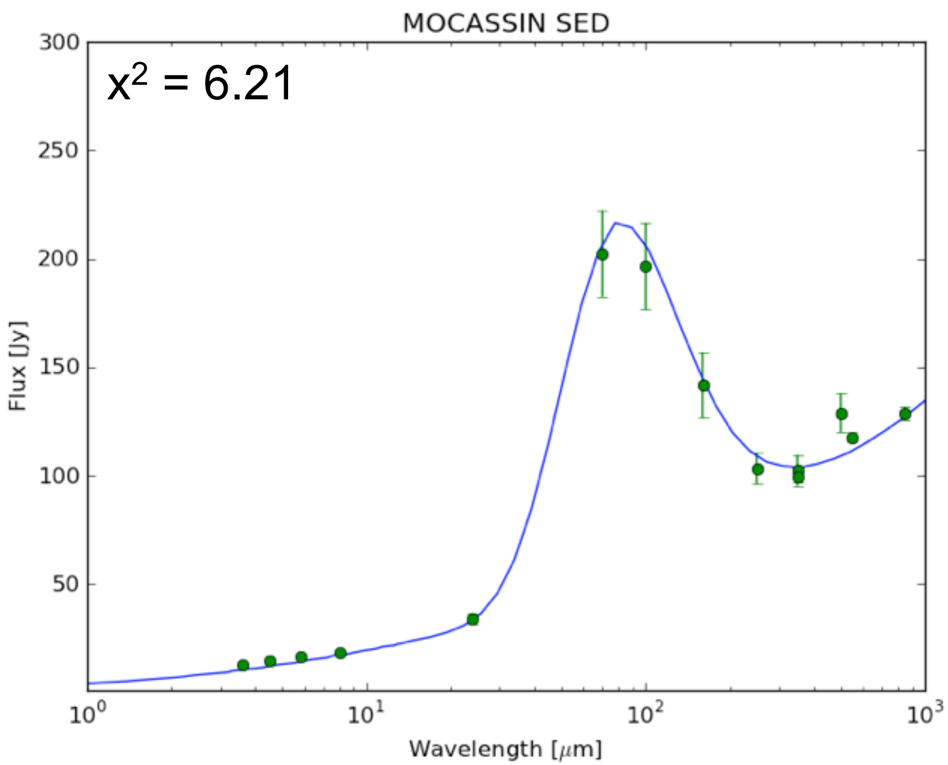
a) Zubko AC Best Fit



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



Fitting with Amorphous Carbon with Zubko BE optical constants



a_{min} = 0.07 μm

a_{max} = 0.2 μm

α = 2.9

0.16 $M_\odot$ of dust

Zubko BE Optical constants

Smooth Model Best Fit Results

	Amorphous Carbon				Silicate [12]	Graphite [12]
	Zb AC	Zb BE	Hanner[1	R&M[11]		
a_{min}	0.07 μm	0.07 μm	0.07 μm	0.07 μm	0.07 μm	0.001μm
a_{max}	1.0 μm	0.2 μm	1.0 μm	1.0 μm	1.0 μm	0.25 μm
α	2.9±0.1	2.9±0.1	2.9±0.1	3.0±0.1	3.5±0.1	3.0±0.1
dust mass	0.31 $M_\odot$ x^2 =6.13	0.16 $M_\odot$ x^2 =6.21	0.30 $M_\odot$ x^2 =7.01	0.08 $M_\odot$ x^2 =10.0	0.46 $M_\odot$ x^2 =9.48	0.09 $M_\odot$ x^2 =7.16

Different optical properties give very different dust masses

[10] Hanner 1998 [11] Rouleau and Martin 1991 ApJ [12] Draine and Lee 1984 ApJ

Line Fluxes

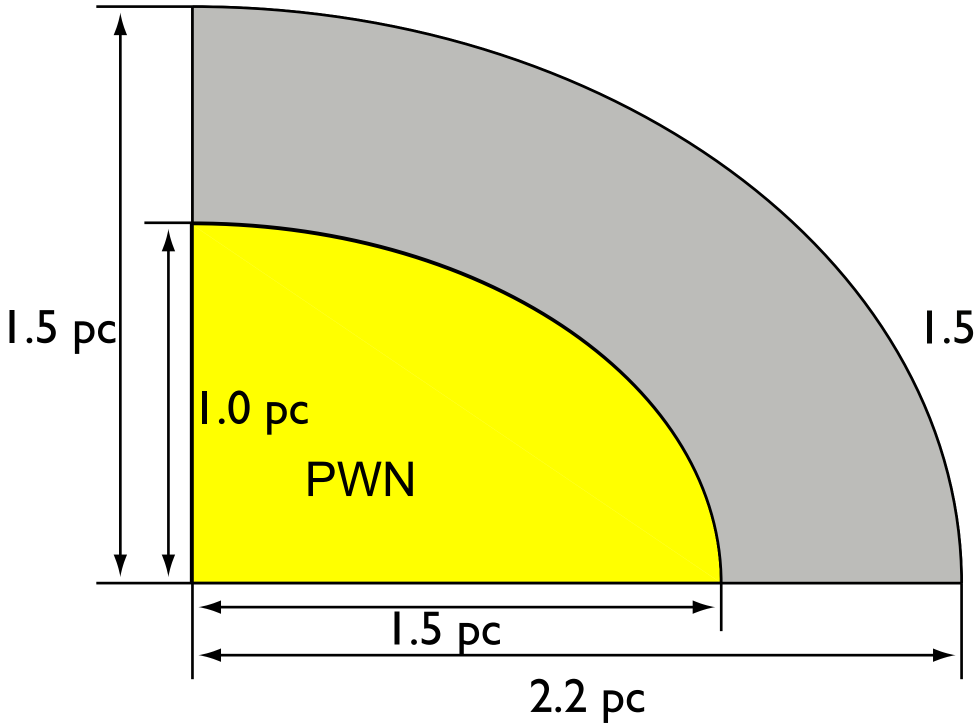
- As well as fitting the SED, the model needs to fit the optical and IR emission line fluxes
- The smooth model (with N_e = 450 cm^{-3}) fits dereddened H_β flux
- Optical line fluxes[13] are fitted by varying the elemental abundances

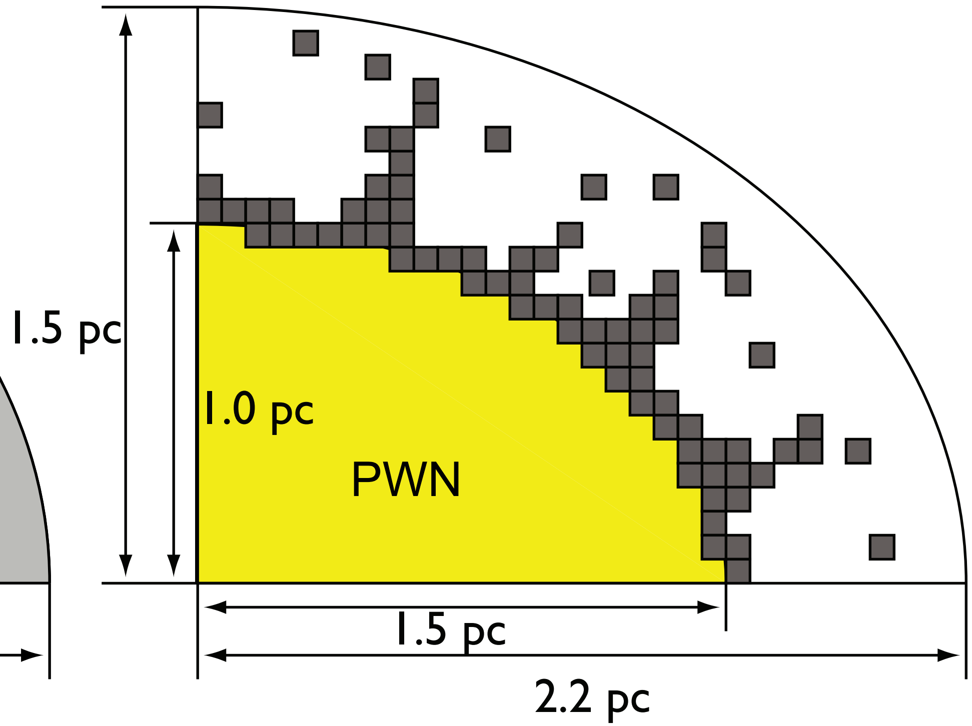
[13] Smith 2003 MNRAS

Line Fluxes

	Wavelength	Observed	Modelled	Ratio
H_β	4861	1.78×10^{-11}	1.80×10^{-11}	0.99
[O II]	3726+3729	18.11	19.9	0.91
[Ne III]	3869	4.65	3.90	1.19
[S II]	4069	0.37	0.32	1.16
[O III] + Hγ	4363	0.57	0.50	1.14
He I	4471	0.37	0.36	1.04
He II	4686	0.78	0.87	0.90
[O III]	5007	11.92	12.4	0.96
Hα	6563	2.85	2.92	0.98
[N II]	6548+6584	6.87	4.67	1.11
[S II]	6717+6731	4.31	4.80	0.90

Shells: Smooth or Clumpy





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

Mass in clumps of radius 0.1 pc
Filling factor of 0.1
Decreasing with r
N_e = 750 cm^{-3}

Results of Shell and Clumpy Models

	Amorphous Carbon				Silicate	Graphite
	Zb AC	Zb BE	Hanner	R&M		
Smooth	0.31 $M_\odot$ $x^2 = 6.13$	0.16 $M_\odot$ $x^2 = 6.21$	0.30 $M_\odot$ $x^2 = 7.01$	0.08 $M_\odot$ $x^2 = 10.0$	0.46 $M_\odot$ $x^2 = 9.48$	0.09 $M_\odot$ $x^2 = 7.16$
Shell	0.27 $M_\odot$ $x^2 = 9.9$	0.11 $M_\odot$ $x^2 = 9.7$	0.27 $M_\odot$ $x^2 = 10.6$	0.08 $M_\odot$ $x^2 = 12.1$	0.40 $M_\odot$ $x^2 = 11.3$	0.08 $M_\odot$ $x^2 = 11.0$
Clumpy	0.64 $M_\odot$ $x^2 = 11.3$	0.48 $M_\odot$ $x^2 = 11.5$	0.60 $M_\odot$ $x^2 = 13.1$	0.38 $M_\odot$ $x^2 = 14.3$	1.5 $M_\odot$ $x^2 = 14.4$	0.4 $M_\odot$ $x^2 = 13.2$
Clumpy ICM	0.68 $M_\odot$ $x^2 = 11.2$	0.50 $M_\odot$ $x^2 = 10.9$	0.63 $M_\odot$ $x^2 = 13.9$	0.44 $M_\odot$ $x^2 = 13.7$	2.0 $M_\odot$ $x^2 = 12.1$	0.47 $M_\odot$ $x^2 = 12.2$

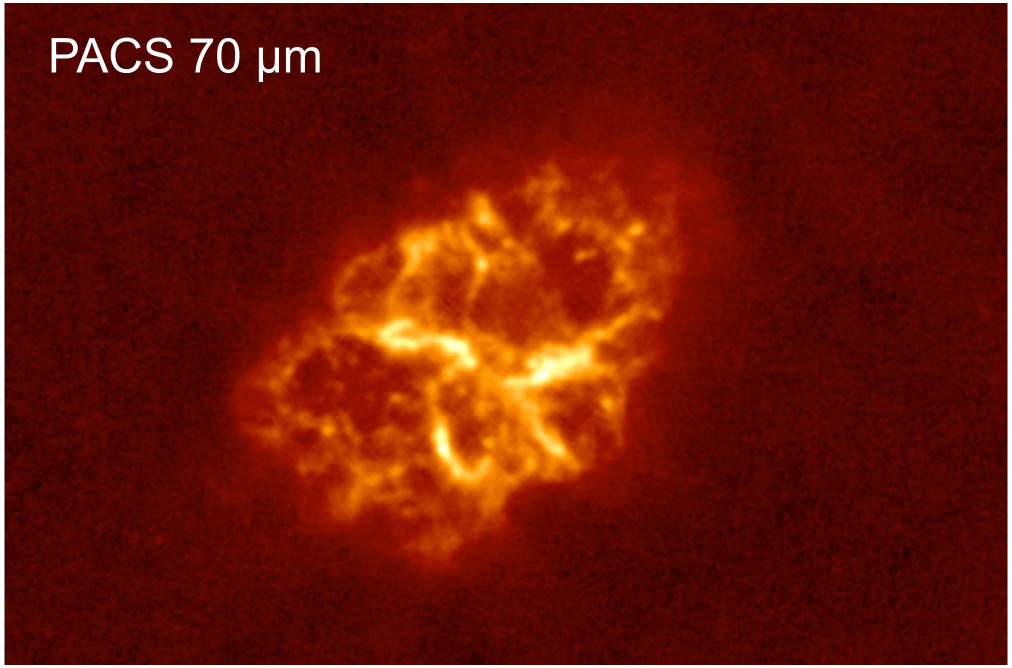
Different density distributions give very different dust masses

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]

[14] MacAlpine et al 2008 AJ [15] Smith 2013 MNRAS

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