Dust production in low-mass stars

Sundar Srinivasan (孫達鑫)

ASIAA, Taipei, Taiwan & IRyA/UNAM, Morelia, Mexico

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Outline

- Review: Sources of dust and AGB stars.
- The dust budget in nearby galaxies
  - GRAMS: A grid of RSG and AGB ModelS.
  - Computing the dust budget.
  - Results for nearby galaxies.
- The dust budget in our galaxy
  - The Nearby Evolved Stars Survey.
Review: why study dust?

- Catalyst for $\text{H}_2$ formation.

- Efficient cooling of collapsing cores at higher densities (Evans 1999).

- “Dust remembers, gas forgets”
  Dust retains information in mineralogy and physical structure (e.g. crystallisation) for $\sim0.1$ Gyr
  $\rightarrow$ constraints on astrophysical processes.

- Star/planet formation, grain processing in ISM $\rightarrow$ Galactic chemical evolution.
Review: sources of dust

- Stellar winds and explosions (This session and tomorrow).
- Growth in the ISM (Dwek 1988, Draine 2009; morning session).
- Tori of AGN (Elvis 2002, Elitzur & Shlosman 2006; Wednesday).
How much from evolved stars? (Dust budget)
AGB Refresher

- Inert C/O
- H/He burning & S-process
- Convective Envelope
- Pulsating Atmosphere

Dust Condensation
- Dusty Wind
- To ISM

T (K) = 10^8, 10^13, 3000
R (cm) = 10^8, 10^14, 10^16

Martha Boyer, GSFC

Sundar Srinivasan 2018-06-11
Inert C/O C/O < 1

M-type

C/O < 1

H/He burning & S-process

Convective Envelope

Pulsating Atmosphere

Molecule Formation

CO, H_2

Dust Condensation

Silicates Mg/Al-oxides

VO, H_2O, CO_2, TiO, SiO

C/O < 1

Dusty Wind

To ISM

Circumstellar Envelope

H_2O / OH masers

Martha Boyer, GSFC
C/O > 1

Martha Boyer, GSFC

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2018-06-11
Composition, mineralogy, etc.: Most obvious dust signatures lie in the 5-30 \( \mu \text{m} \) range.

Martha Boyer, GSFC

C/O $> 1$

Inert C/O

H/He burning & S-process

Convective Envelope

C-type

Amorphous carbon

SiC

CN, \( \text{C}_2 \), HCN, \( \text{C}_2 \text{H}_2 \)

C/O type

C0 type

Martha Boyer, GSFC
The dust budget in nearby galaxies

Requires us to know the dust-production rate (DPR, dust mass-loss rate) from each AGB/RSG star...
Computing the dust budget

- Use MIR color as proxy for DPR
- Use IR excess as proxy for DPR
- Fit SEDs with radiative transfer models

Mid-IR colors affected by dust, so should correlate with DPR.

Computing the dust budget

- Use MIR color as proxy for DPR
- Use IR excess as proxy for DPR
- Fit SEDs with radiative transfer models

Dust contributes to mid-IR flux, so excess should correlate with DPR.

Srinivasan+ 2009, Boyer, Srinivasan+ 2012
Computing the dust budget

- Use MIR color as proxy for DPR
- Use IR excess as proxy for DPR
- Fit SEDs with radiative transfer models

Detailed RT model fit to SED, get best fit parameters including chemical type.

van Loon+ 1999, Groenewegen+ 2009, Sargent, Srinivasan+ 2010, Srinivasan+ 2010, and many others
Computing the dust budget

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van Loon+ 1999, Groenewegen+ 2009, Sargent, Srinivasan+ 2010, Srinivasan+ 2010, and many others

Sample best-fit to SMC carbon star (red) vs O-rich fit (blue)

Most accurate method, but also very time-consuming for tens of thousands of sources!

ANYTHING FASTER?
GRAMS: A Grid of RSG and AGB Models
Sargent, Srinivasan & Meixner 2011 (O-rich), Srinivasan, Sargent & Meixner 2011 (C-rich)

Srinivasan 2016
GRAMS: A Grid of RSG and AGB Models

Sargent, Srinivasan & Meixner 2011 (O-rich), Srinivasan, Sargent & Meixner 2011 (C-rich)

Detailed modelling takes time!

OGLE LMC LPV 28579
(Srinivasan+ 2010)

Srinivasan+ 2016
GRAMS: A Grid of RSG and AGB Models
Sargent, Srinivasan & Meixner 2011 (O-rich), Srinivasan, Sargent & Meixner 2011 (C-rich)

Model grid over range of expected parameter values.

Srinivasan+ 2011, C–rich dust grid.

Detailed modelling takes time!

Srinivasan+ 2016

- Photosphere model
  - \( L, L_{\odot} \)
  - \( T_{\text{eff}} \) (K)
  - \( \log g \) [cm s\(^{-1}\)]
  - \( M \) (M\(_{\odot}\))
  - C/O
- Dust shell properties
  - \( R_{\text{in}} \) (R\(_{\odot}\))
  - \( R_{\text{out}} \) (R\(_{\text{in}}\))
- Density profile
  - \( \rho(r) \) = \( r^{-2} \)
- Velocity of dust grains
  - \( V_{\text{ex}} \) (km s\(^{-1}\))
- Dust grain properties
  - Species
  - SIC fraction
  - \( r(11 \mu m) \)
- Size distribution
  - \( a_{\text{min}}(\mu m) = 0.01 \)
  - \( a_0(\mu m) = 1 \)
  - \( \gamma = 3.5 \)
- Mass-loss rate and dust temperature
  - \( M_{\text{dust}} \) (M\(_{\odot}\) yr\(^{-1}\))
  - \( M_{\text{dust}} \) (M\(_{\odot}\) yr\(^{-1}\))
  - \( T_{\text{in}} \) (K)

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Method similar to Robitaille+ 2007 YSO grid.

Sample best-fit to SMC carbon star (red).

ORMS: A Grid of RSG and AGB ModelS
Sargent, Srinivasan & Meixner 2011 (O-rich), Srinivasan, Sargent & Meixner 2011 (C-rich)

Detailed modelling takes time!

Model grid over range of expected parameter values.

Srinivasan+ 2011, C-rich dust grid.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosphere model</td>
<td>~1100 to ~26 000</td>
</tr>
<tr>
<td>$L_*$ ($L_\odot$)</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>2500 to 4000 (100)</td>
</tr>
<tr>
<td>$\log g$ [cm s$^{-1}$]</td>
<td>-1.0 to 0.0 (0.1)</td>
</tr>
<tr>
<td>$M$ ($M_\odot$)</td>
<td>1.4, 2.0 and 5</td>
</tr>
<tr>
<td>C/O</td>
<td></td>
</tr>
<tr>
<td>Dust shell properties</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{in}}$ (R$_*$)</td>
<td>1.5, 3, 4.5, 7, 12</td>
</tr>
<tr>
<td>$R_{\text{out}}$ (R$_*$)</td>
<td>1000</td>
</tr>
<tr>
<td>density profile</td>
<td>$\rho(r) = r^2$</td>
</tr>
<tr>
<td>$v_{\text{exc}}$ (km s$^{-1}$)</td>
<td>10</td>
</tr>
<tr>
<td>Dust grain properties</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>AmC$^d$ + SiC$^e$</td>
</tr>
<tr>
<td>SIC fraction</td>
<td>10%</td>
</tr>
<tr>
<td>$r(11 \mu m)$</td>
<td>$10^{-3}$ to $10^{-1}$ (5 per dex), 0.1 to 1 (0.1) and 1.5 to 4 (0.5)</td>
</tr>
<tr>
<td>Size distribution</td>
<td>$K_{\min}f^f$</td>
</tr>
<tr>
<td>$a_{\min}(\mu m)$</td>
<td>0.01</td>
</tr>
<tr>
<td>$a_0(\mu m)$</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>3.5</td>
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<tr>
<td>Mass-loss rate and dust temperature</td>
<td></td>
</tr>
<tr>
<td>$\dot{M}<em>{\text{dust}}$ ($M</em>\odot$ yr$^{-1}$)</td>
<td>$1.5 \times 10^{-12}$ to $2.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\dot{M}<em>{\text{dust}}$ ($M</em>\odot$ yr$^{-1}$)</td>
<td>$3.0 \times 10^{-10}$ to $4.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$T_{\text{in}}$ (K)</td>
<td>710 to 1800$^h$</td>
</tr>
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GRAMS: A Grid of RSG and AGB ModelS
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Detailed modelling takes time!

Model grid over range of expected parameter values.

Srinivasan+ 2011, C-rich dust grid.

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<th>$T_{\text{eff}}$ (K)</th>
<th>$\log\rho$ [cm s$^{-2}$]</th>
</tr>
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<tr>
<td></td>
<td>$\sim 1100$ to $\sim 26,000$</td>
<td>$2500$ to $4000$ (100)$^b$</td>
<td>$-1.0$ to $0.0$ (0.1)$^c$</td>
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</tbody>
</table>

- $L_\star, (L_\odot)$
- $T_{\text{eff}}$ (K)
- $\log\rho$ [cm s$^{-2}$]

- $1.5, 3, 4.5, 7, 12$
- $1000$
- $\rho(r) = r^2$

<table>
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<th>Mass-loss rate and dust temperature</th>
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<tr>
<td>$\dot{M}<em>{\text{Dust}}$ ($M</em>\odot$ yr$^{-1}$)</td>
</tr>
<tr>
<td>$\dot{M}<em>{\text{Gas}}$ ($M</em>\odot$ yr$^{-1}$)$^g$</td>
</tr>
<tr>
<td>$T_{\text{in}}$ (K)</td>
</tr>
</tbody>
</table>

Many assumptions...
- Grain shape and size distribution
- Constant wind speed
- Spherical symmetry
- Single star
- Dust optical constants (2-4x)
- Wind speed (2x)
- C vs. M dust (10x)

YSO grid.
Sample best-fit to SMC carbon star (red).
The dust budget in nearby galaxies

- CMD selection of AGB/RSG candidates.
- GRAMS model fits to each SED.
- Best 100 fits for each source used to determine chemical type, luminosity, DPR, and associated uncertainties.
- Results: luminosity function, DPR as a function of chemical type, population, etc.
The dust budget in the LMC/SMC

Spitzer data from the SAGE (Meixner+ 2006) and SAGE-SMC (Gordon+ 2010) programs.
The dust budget in the LMC/SMC
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LMC evolved star sample (e.g., Boyer+ 2011).
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2MASS CMD for optically thin sources.

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Spitzer CMDs for very dusty objects.

(Boyer, Srinivasan+ 2011)
The dust budget in the LMC/SMC

Breakdown by dust mass contribution
The dust budget in the LMC/SMC

Breakdown by dust mass contribution

- x-AGB: 81%
- C-AGB: 13%
- RSG: 2%
- O-AGB: 9%

- x-AGB: 76%
- C-AGB: 13%
- RSG: 5%
- O-AGB: 5%
The dust budget in the LMC/SMC

Breakdown by dust mass contribution

LMC
Total: \((2-6) \times 10^{-5} \, M_{\text{Sun}} \, \text{yr}^{-1}\)
(Riebel, Srinivasan+ 2012)
The dust budget in the LMC/SMC

Breakdown by dust mass contribution

**LMC**
Total: \((2-6) \times 10^{-5} \, M_{\text{sun}} \, \text{yr}^{-1}\)
(Riebel, Srinivasan+ 2012)

**SMC**
Total: \((0.1-1.3) \times 10^{-5} \, M_{\text{sun}} \, \text{yr}^{-1}\)
(Srinivasan+ 2016)
The dust budget in the LMC/SMC

Breakdown by number
The dust budget in the LMC/SMC

**Breakdown by number**

- Dominant contribution from a very small population of very dusty sources (extreme AGB stars).
The dust budget in the LMC/SMC

Breakdown by number

- Dominant contribution from a very small population of very dusty sources (extreme AGB stars).

Breakdown by chemistry

- O-AGB: 60%
- C-AGB: 21%
- RSG: 15%
- x-AGB: 4%
The dust budget in the LMC/SMC

Breakdown by number

- Dominant contribution from a very small population of very dusty sources (extreme AGB stars).

Breakdown by chemistry

The dust budget in nearby galaxies: 
the story so far
The dust budget in nearby galaxies: the story so far
The dust budget in nearby galaxies: 
the story so far

Papers in prep for:

- MW (Lower L*)
- LMC
- SMC
- M33 (Lower L*)
- DustINGS galaxies
- NGC 6822 (Lower L*)
The dust budget in nearby galaxies: the story so far

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- M33 (Srinivasan+).
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- NGC 6822 (Srinivasan+).
The dust budget in nearby galaxies: 
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Papers in prep for:

- M33 (Srinivasan+).
- NGC 6822 (Srinivasan+).
- Solar Neighbourhood (Trejo, Srinivasan+ 2015, also in prep – see poster by Ciska Kemper).
Balancing the dust budget in the LMC/SMC
Balancing the dust budget in the LMC/SMC

- AGB/RSG dust input to the SMC: \((0.1 - 1.3) \times 10^{-5} \text{ M}_{\text{sun}} \text{ yr}^{-1}\) (Srinivasan+ 2016)

- SNe dust input (w/o destruction): \((0.1 - 51) \times 10^{-5} \text{ M}_{\text{sun}} \text{ yr}^{-1}\) (Temim+ 2015)

- ISM dust mass: \((8.3 \pm 2.1) \times 10^{4} \text{ M}_{\text{sun}}\) (Gordon+ 2014)
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==> A significant fraction of ISM dust originates from stellar sources.
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\[ \Rightarrow \text{Replenishment timescale} > 0.4 \, \text{Gyr (w/o dust destruction)} \]
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Similar result in the LMC.
Balancing the dust budget in the LMC/SMC

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2018-06-11
Sub-mm dust opacities may be overestimated by up to 20x!
(Fanciullo et al. in prep, see Lapo’s talk)
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- Lab opacities compared with those derived from observations.
Sub-mm dust opacities may be overestimated by up to 20x! (Fanciullo et al. in prep, see Lapo’s talk)

- Lab opacities compared with those derived from observations.

![Graph showing dust opacity vs. wavelength with data points and lines for different models.]

- Gordon+ 2014
- Omont+ 2001 from Hildebrand+ 1983
- Zavala+ 2015 from Dunne+ 2003
- Rowlands+ 2014 from Dunne+ 2003
- Beelen+ 2006 from Alton+ 2004

Legend:
- Compact spheres
- Hollow spheres
- Ellipsoids
- Typical values used in literature by observers
Sub-mm dust opacities may be overestimated by up to 20x! (Fanciullo et al. in prep, see Lapo’s talk)

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- Lower lab opacities ==> lower dust masses.

![Graph showing sub-mm dust opacities comparison with observations]
Sub-mm dust opacities may be overestimated by up to 20x! (Fanciullo et al. in prep, see Lapo’s talk)

- Lab opacities compared with those derived from observations.
- Lower lab opacities ==> lower dust masses.
- Could resolve the high-z “dust budget crisis”! Less burden on ISM.
AGB studies in
AGB studies in “...this galaxy, MW...”
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- Foreground extinction!
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- Last dust budget study was 30 years ago (Gehrz 1989).
- See Ciska Kemper’s poster on Alfonso’s work.
AGB studies in the Milky Way:
The Nearby Evolved Stars Survey (NESS)

http://evolvedstars.space
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Volume-limited survey of mass-losing AGB stars in the Solar Neighbourhood.

http://evolvedstars.space
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- Sub-mm data (dust continuum and CO line emission) combined with other data to produce what will be the authoritative dataset for Galactic evolved-star studies in the next decade.

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NESS will be fully reproducible!
In the interest of open science, the NESS program aims to be fully reproducible. All raw, processed and auxiliary data, scripts, and outputs will be made available to the scientific community.

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AGB studies in the Milky Way: The Nearby Evolved Stars Survey (NESS)
AGB studies in the Milky Way:  
The Nearby Evolved Stars Survey (NESS)

- JCMT Large Program (~500h, ~300 sources, PI: P. Scicluna) already 43% complete.

- APEX (~80h) and NRO (~80h) time also acquired.

- SMA and ALMA proposals in prep (PI: Srinivasan).

- Team of > 70 scientists across Asia, Europe, the UK, and North America.

- And you? (Talk to me, Peter, or Ciska)
AGB studies in the Milky Way: 
The Nearby Evolved Stars Survey (NESS)

Mass-loss history
AGB studies in the Milky Way:
The Nearby Evolved Stars Survey (NESS)

Mass-loss history

- Dharmawardena et al. 2018
AGB studies in the Milky Way: The Nearby Evolved Stars Survey (NESS)

Mass-loss history

- Dharmawardena et al. 2018
- Sub-mm dust continuum map of IRC+0216, W Aql, and U Ant.
AGB studies in the Milky Way: The Nearby Evolved Stars Survey (NESS)

Mass-loss history

- Dharmawardena et al. 2018
- Sub-mm dust continuum map of IRC+0216, W Aql, and U Ant.
- Extensions up to 16–80″ (0.01 – 16 pc).
AGB studies in the Milky Way: The Nearby Evolved Stars Survey (NESS)

Mass-loss history

- Dharmawardena et al. 2018
  - Sub-mm dust continuum map of IRC+0216, W Aql, and U Ant.
  - Extensions up to 16–80" (0.01 – 16 pc).
  - Up to 40% of total flux is in the extended component.
AGB studies in the Milky Way:
The Nearby Evolved Stars Survey (NESS)
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- **U Ant**
  (Dharmawardena et al. in prep)
AGB studies in the Milky Way: The Nearby Evolved Stars Survey (NESS)

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  - Detect detached shell for the first time in the sub-mm!
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- Simultaneous fits to the SED and intensity profile... first step towards fully self-consistent modelling.
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- See poster P102 on Wednesday.
Summary

• We have a tested method to derive the global dust budget in resolved evolved-star populations, and to provide statistical results on their dust production.

• The AGB contribution in nearby galaxies is well determined [systematic model uncertainties dominate].
  
  • Reddest sources contribute most of the dust.
  
  • Relative contributions from O-/C-rich stars can be estimated.
  
  • 12 orders of magnitude in DPR over 6 orders of magnitude in stellar mass!

• We have an ongoing massive collaboration, NESS, that will investigate the entire mass-losing population within 2 kpc. This will result in more robust results for evolved stars.
Thanks to the organisers!

This presentation has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]