The Mass-loss of Red Supergiants

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Speaker: Yuanhao (Harry) Zhang
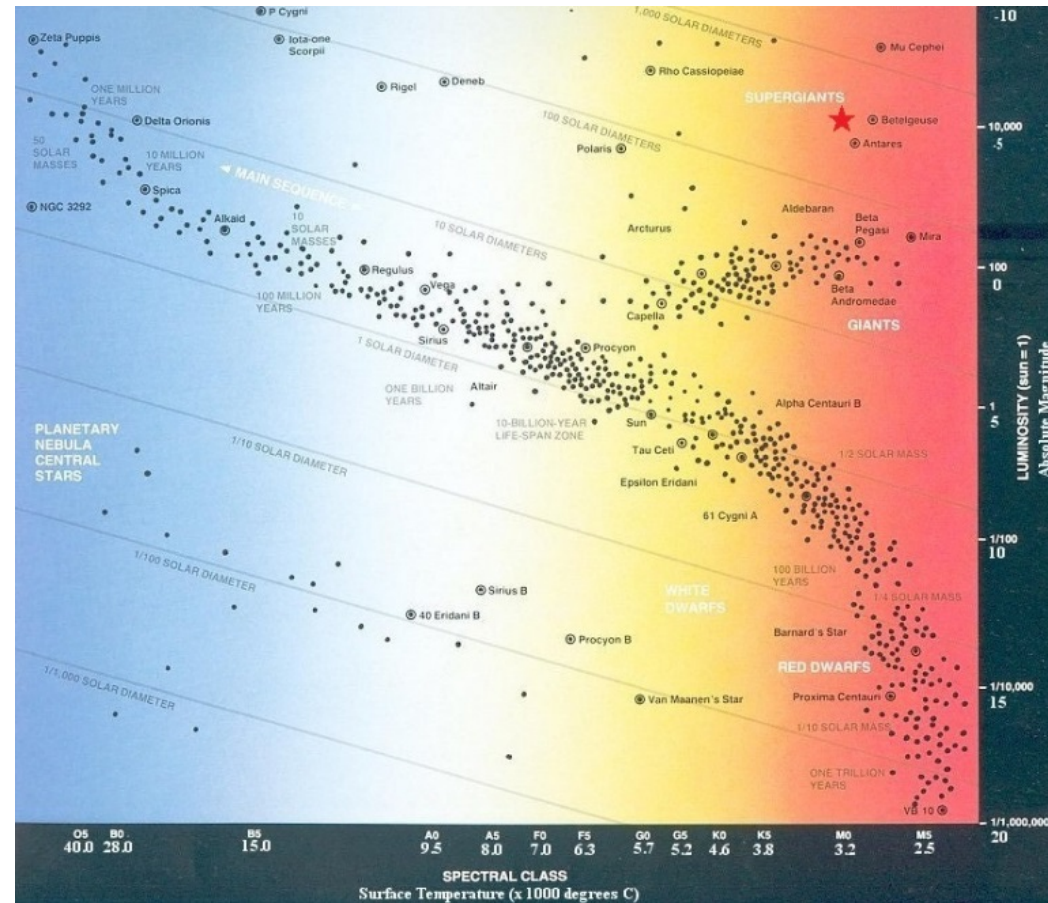
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Outline

- Introduction
- Motivation
- Objects
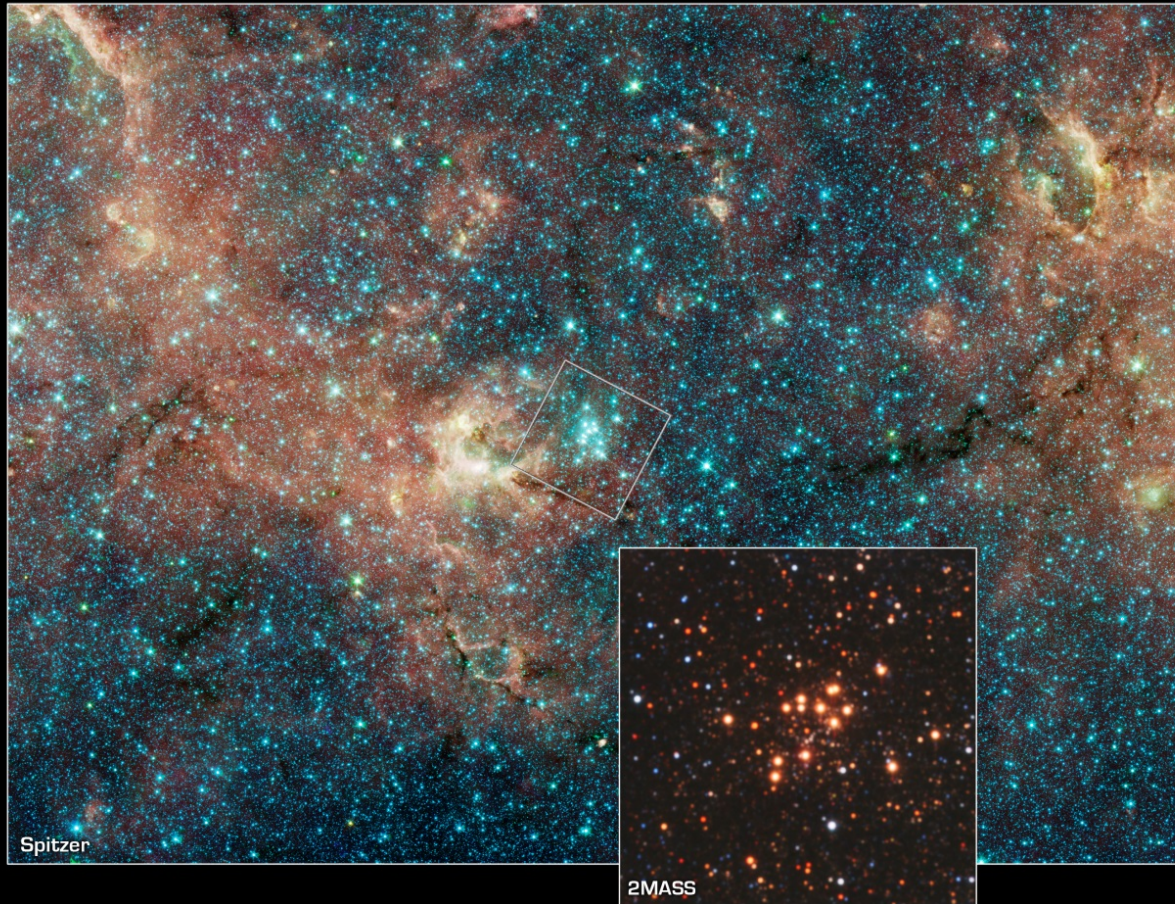- Method
- Need for SOFIA/FORCAST data
- Reduction

Red Supergiant (RSG)

- Luminosity class I
- K or M stars
- Enormous radius
- Likely to be supernova progenitor
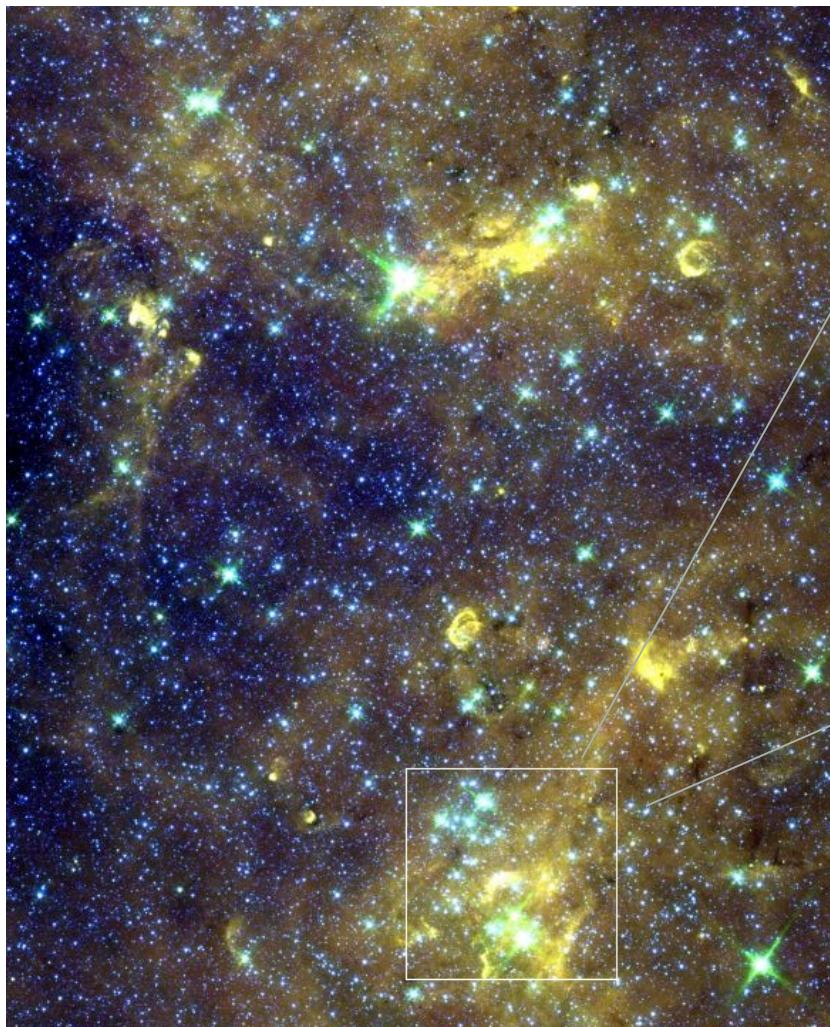- Cool surface Temperature (3500-4500 K)
- Extremely bright in near-IR

Object 1: RSGC1

14 RSGs

Located at the base of the Scutum-Crux Galactic arm

Figer et al. 2006
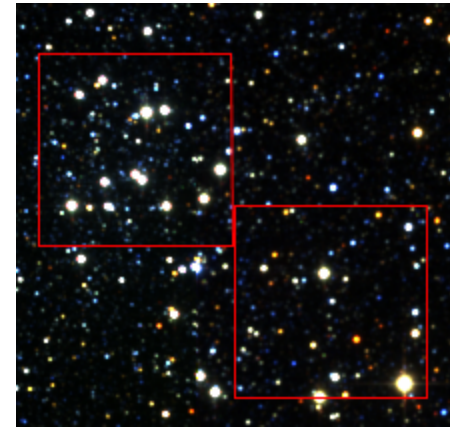
Object 2: RSGC 2 (Stephenson 2(1990))

26 RSGs

(RGB composite using 2MASS
J (Blue) H (Green) K (Red)
3 bands)

Red rectangles: SOFIA FOV

Davies et al. 2007

(Spitzer/GLIMPSE data)

Properties of RSGC 1&2

Cluster (1)	M_{init} (evol) ($\times 10^4 \, M_\odot$) (2)	M_{dyn} ($\times 10^4 \, M_\odot$) (3)	Age (Myr) (4)	d (pc) (5)	$D_\odot$ (kpc) (6)	D_{GC} (kpc) (7)	M_{init}(RSGs) ($M_\odot$) (8)
RSGC1........................	3 ± 1	5 ± 1	12 ± 2	1.5 ± 0.3	6.60 ± 0.89	3.2	18^{+4}_{-2}
RSGC2........................	4 ± 1	6 ± 4	17 ± 3	$3.2^{+1.2}_{-0.7}$	$5.83^{+1.91}_{-0.76}$	3.5	14 ± 2

NOTES.—Col. (1), cluster name; col. (2), total initial cluster mass derived from evolutionary models; col. (3), cluster mass derived from stellar velocity dispersion; col. (4), cluster age; col. (5), cluster diameter; col. (6), cluster distance; col. (7), distance from cluster to the Galactic center; col. (8), initial mass range of the RSGs within the clusters. RSGC2 values come from DFK07.
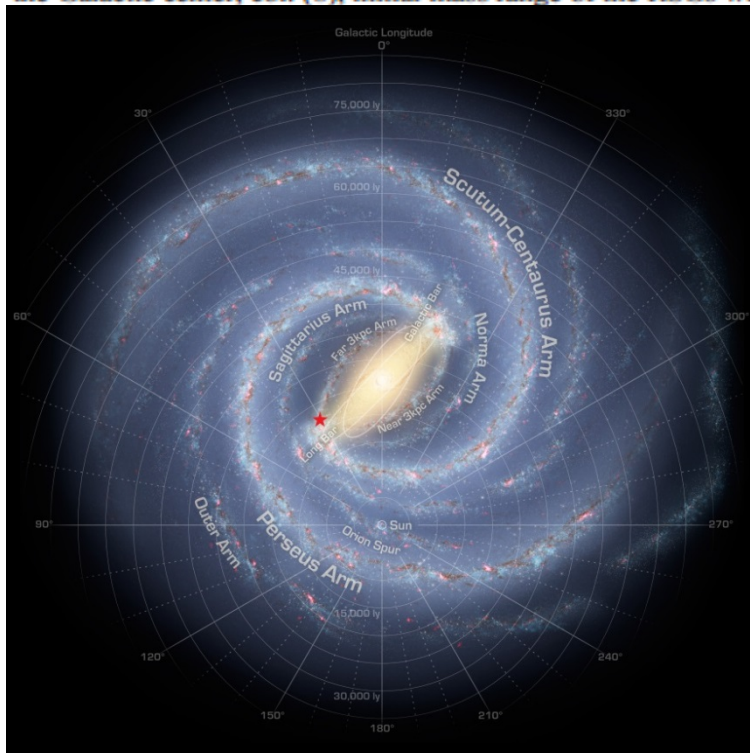
Approximated location of RSGC 1&2

★At the end of the MW long bar

Motivation

- The mass-loss rate is the key ingredient to understand the end stages of massive stars.

- The final stages of massive star evolution can enrich our knowledge about a multitude of astrophysical processes.

  1. which stars produce neutron stars and black holes
  2. how galaxies are seeded with heavy elements

- Late-stage massive star evolution remains poorly understood.
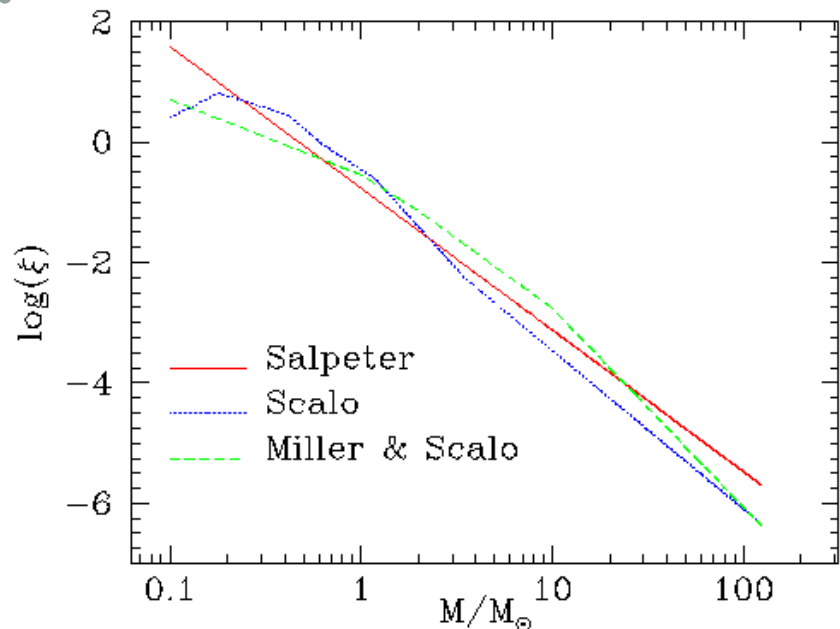
Question

- What is the mass-loss rate of RSGs as a function of **age** and **initial mass**?

- How much mass is lost in the RSG phase?

Difficulty in Observation

- The steepness of the initial mass function and short lifetimes make massive stars rare.

- There are only ~200 RSGs were known in the Galaxy, and no more than 5 in any one cluster (Caron et al. 2003).

-

IMF

Figure: The three IMFs used in the spectral evolutionary models of Bruzual & Charlot (1993).

Red Supergiant Cluster 1&2

(RGB composite using SPITZER 3.6(B), 5.8(G), and 8(R) um data)

- RSGC1 & RSGC 2 host to 20% of all known RSGs in the Galaxy.
- Infrared surveys revealed stars which are heavily reddened by circumstellar dust.

Mass-loss Behavior in Post-MS Phases

- Strong stellar wind
- Mass-loss is driven by radiation pressure on circumstellar dust-grains (T of RSGs in these two clusters ~3500 K, the temperature is cool so the dust will not vaporize)
- Replenish the interstellar medium (ISM) with chemically processed material
- High mass-loss rates were estimated for these stars, ~10^{-6} to 10^{-4} M$_\odot$ yr^{-1} (Olnon et al. 1984)
- Subsequent core collapse supernovae (SNe) inject the ISM with heavy elements and drive shocks into the surrounding material
- Trigger new bursts of star formation

The Mass-loss Rate of RSGs

- The last stages of massive stellar evolution depend strongly on the initial mass and the mass lost over its lifetime.

- The majority of mass-loss of RSGs occurs in the post-MS phases, where the mass-loss rates of RSGs are thought to reach ~ 10^{-4} $M_\odot$ yr^{-1} (van Loon et al. 2005).

- The inferred ages of the clusters are different, ~12 Myr for RSGC1 (Figer et al. 2006), ~17 Myr for RSGC2 (Davies et al. 2007).

Dependence on Initial Mass

- The average initial mass of RSGs in RSGC 1 & RSGC 2 are ~18 $M_\odot$ and ~14 $M_\odot$.

- The total mass lost in the RSG phase will be studied as a function of initial mass.

- These two clusters are perfect samples to study the RSG mass-loss at two distinct ranges of initial masses.

Dependence on Metallicity

- The mass-loss rate depends on metallicity, due to the interplay between the radiation pressure and the circumstellar dust (van Loon 2006).

- In order to test the predictions of RSG pre-SN evolution, we must observe the mass-loss behavior of large samples of RSGs with a range of initial masses at fixed metallicities.

- The observations will provide us with two statistically-complete samples of RSGs at Galactic (~>solar) metallicities, and will provide a dataset comparable to the studies of the low-metallicity LMC.

The Advantages of RSGC 1&2

- These two extraordinary clusters contain a large number (>40) of RSGs.

- They are powerful natural laboratories for studying the pre-SN evolution of RSGs.

- The corresponding initial masses of the red supergiants in the clusters span a very narrow range (~1 $M_{\odot}$).

- We are effectively seeing the **same** star at **different** stages of RSG evolution!

Determining the Mass-loss of RSGs

- The mass-loss is driven by radiation pressure on circumstellar dust-grains, the mass-loss rate depends on luminosity, temperature and the amount of dust in the outer envelope.

- None of these variables is constant over the whole RSG phase

- To calculate the total pre-SN mass-loss, and hence the terminal mass of the star, we must integrate $\dot{M}$ over the **whole RSG phase.**

- We are able to add-up the mass-loss rates of the different stages of RSG evolution, and hence directly measure the total mass lost over the whole RSG phase for stars with almost the same initial mass.

Derive Mass-loss Rate from Observable

$$\tau \propto \frac{\psi \dot{M}}{v_{\text{exp}}\sqrt{L}}, \qquad (1)$$

where we notice that although the optical depth, τ, is proportional to the (gas+dust) mass-loss rate, $\dot{M}$, it also depends on the dust:gas mass ratio, ψ, the expansion velocity of the wind, v_{exp}, as well as the luminosity, L.

$$\psi \propto Z.$$

(Ivezic & Elitzur 1995, Van Loon 2007)

Preliminary Work and Future Work

- We have already established the metallicities of the clusters, using our NIRSPEC/KECK high-resolution near-IR spectroscopy and the cool stellar atmosphere models (Davies et al. 2009).

- We will complement these data with measurements of **outflow velocities** from the separation of OH maser features, using future ALMA observations.

- For stars without masers, we will use the relation between velocity and luminosity in (Marshall et al. 2004). This will then enable us to determine the mass-loss rates of the cluster stars.
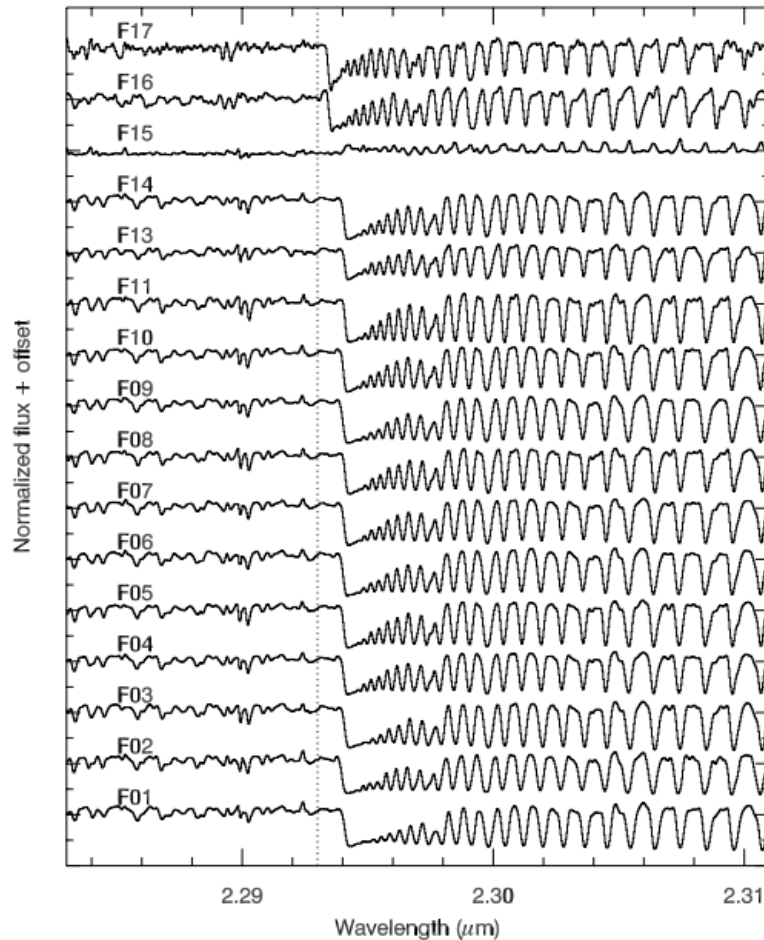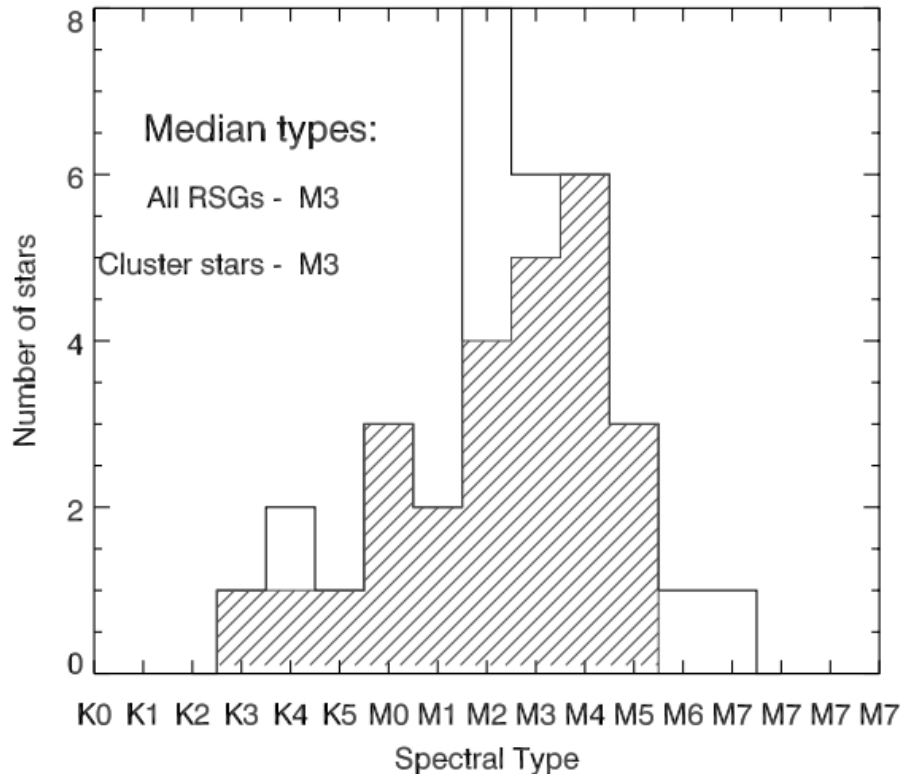
CO Bandhead

Fig. 3.— High-resolution spectra of all stars observed in the region of the CO band-head feature. The dotted line indicates the zero velocity of the blue edge of the CO band head. [*See the electronic edition of the Journal for a color version of this figure.*]

- Identify candidates RSGs in the cluster
- Determine spectral type

Figer et al. 2006

Spectral Type

•The spectral types of RSGs in the cluster show different stages of RSG stars

FIG. 6.—Histogram of the spectral types of the stars identified as supergiants, and the subsample determined to be "cluster members" (*cross-hatched region*). The median type of both subsamples (M3) is consistent with the nearby RSG cluster RSGC1 (M3; FMR06) and the rest of the Galaxy (M2; Elias et al. 1985). [*See the electronic edition of the Journal for a color version of this figure.*]

Need for SOFIA Data

- Investigation of RSG mass-loss requires study of the mid-IR excess emission of the dusty circumstellar ejecta.

- The data cannot be obtained by ground-based observatories.

- Existing Spitzer and MSX data do not have the required spatial resolution or photometric accuracy.

- The MSX photometry is different from that implied by the Spitzer data by a factor of two to five.
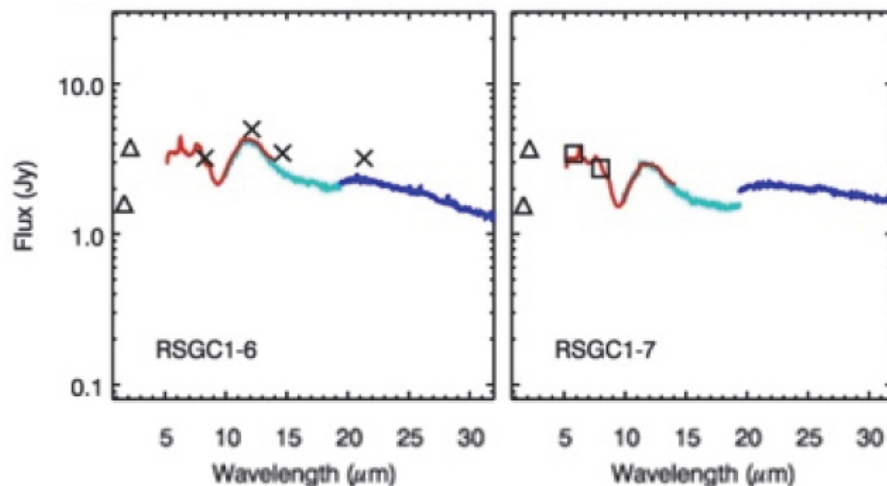
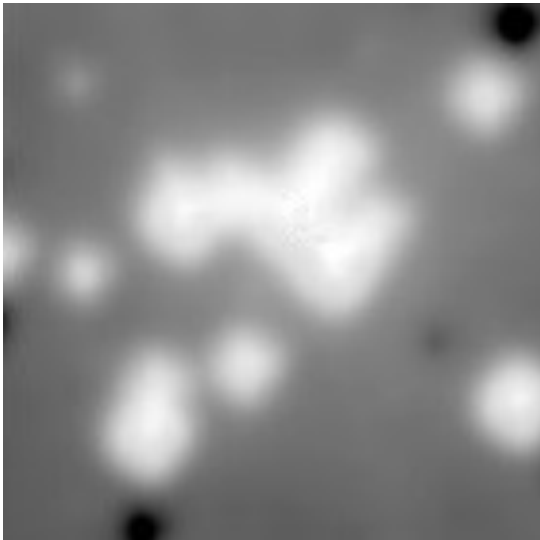Spitzer spectra and MSX photometry

Instrument & Wavelength Range

- The observations will use:
  - FORCAST in the dual channel configuration and the nod-match-chop sequence
  - filter combinations of: 6.6+31.5 µm, 11.1+34.8 µm, and 24.2+37.1 µm
- The stars in the two clusters produce fluxes of ~0.1-10 Jy over these wavebands.

Simulated Observation Result
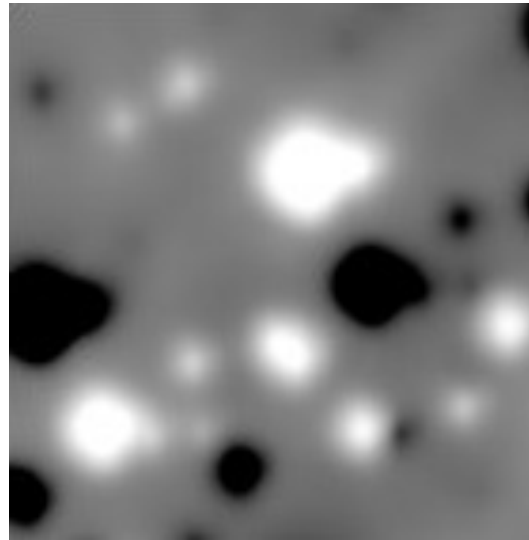
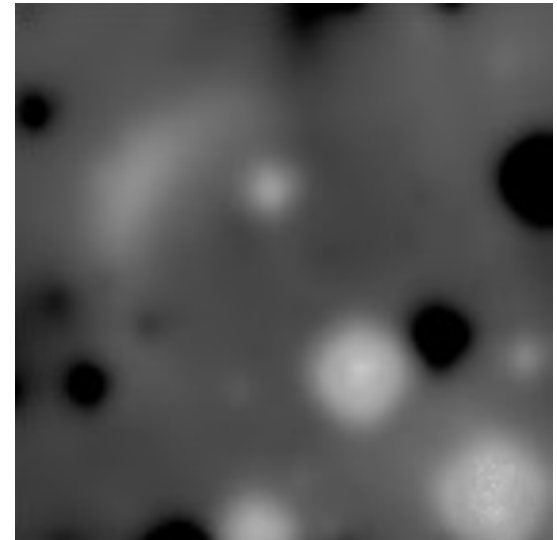RSGC 1   RSGC 2-1   RSGC 2-2

WISE 12 μm data

Reduction

- We will model the mid-IR spectral energy distributions (SEDs) with the radiative transfer (RT) code DUSTY.

- The SEDs are produced by computing simultaneously the radiation transfer through the dust envelope, and the thermal balance between the grain heating through irradiation and cooling through reradiation.

- The optical depth of the dust envelope can be derived from the observed SED by comparison with synthetic SEDs.

- We can derive the radiation pressure applied on dust from the SEDs (Van Loon 2007, Ivezic et al. 1995).

- Combined with some variables we already known as luminosity, metallicity, we will be able to derive the mass loss rate of red supergiants (Davies et al. 2009).

DUSTY

- DUSTY code is a classic code to model radiation from some source viewed after processing by a dusty region.

- DUSTY has built in optical properties for the most common types of astronomical dust ('warm' and 'cold' silicates, silicates and graphite grains, amorphous carbon, SiC).

- It supports various analytical forms for the density distribution, and can perform a full dynamical calculation for radiatively driven winds around AGB stars and RSGs.

- The spectral energy distribution of the source can be specified analytically as either Planckian or broken power-law.

- The DUSTY code is described in Ivezic, Nenkova & Elitzur, 1999.

# SED Samples by DUSTY with Different Optical Depth

230   van Loon
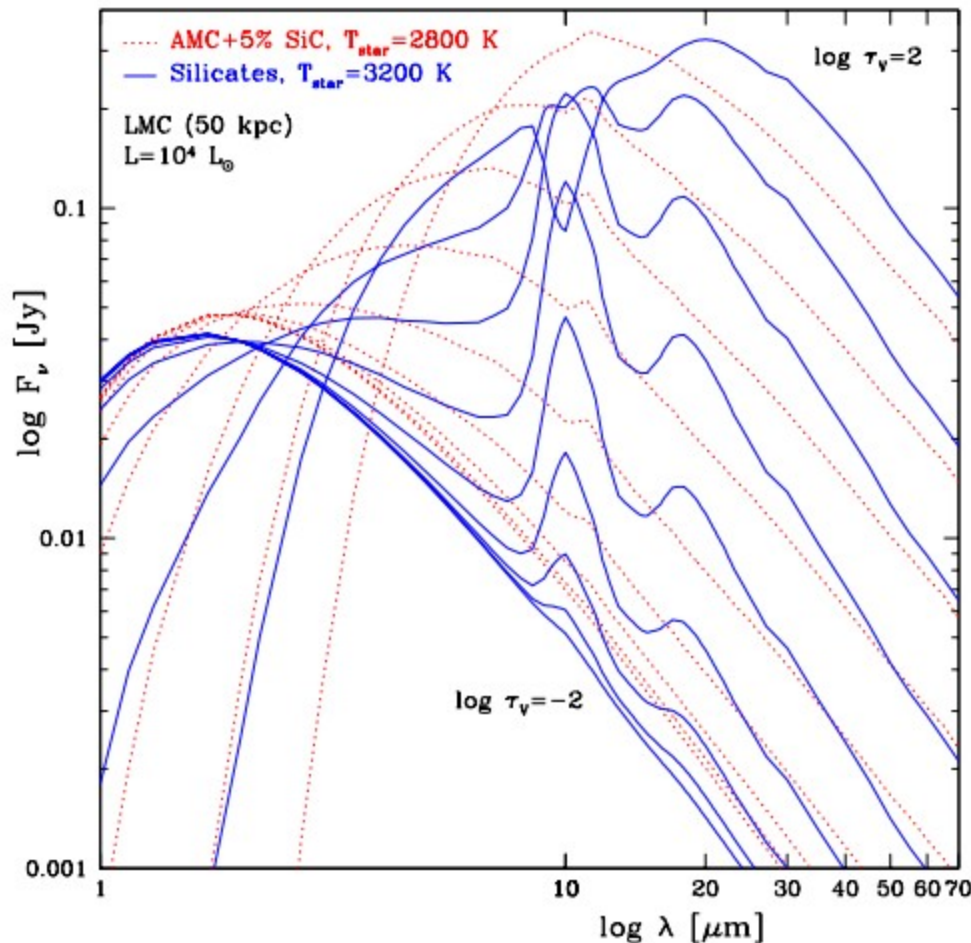
τ = 0.01 to 100, for an oxygen-rich red giant and a carbon star. Corresponding mass-loss rates are~5×10^{-8} to 4×10^{-5} $M_{\odot}$ yr^{-1} for a typical Asymptotic Giant Branch (AGB) star at solar metallicity, and from the interstellar contribution to the extinction. The absorbed photons are more energetic than the reradiated photons, small optical depths readily give rise to detectable amounts of excess emission at longer wavelengths. (Van Loon 2007)
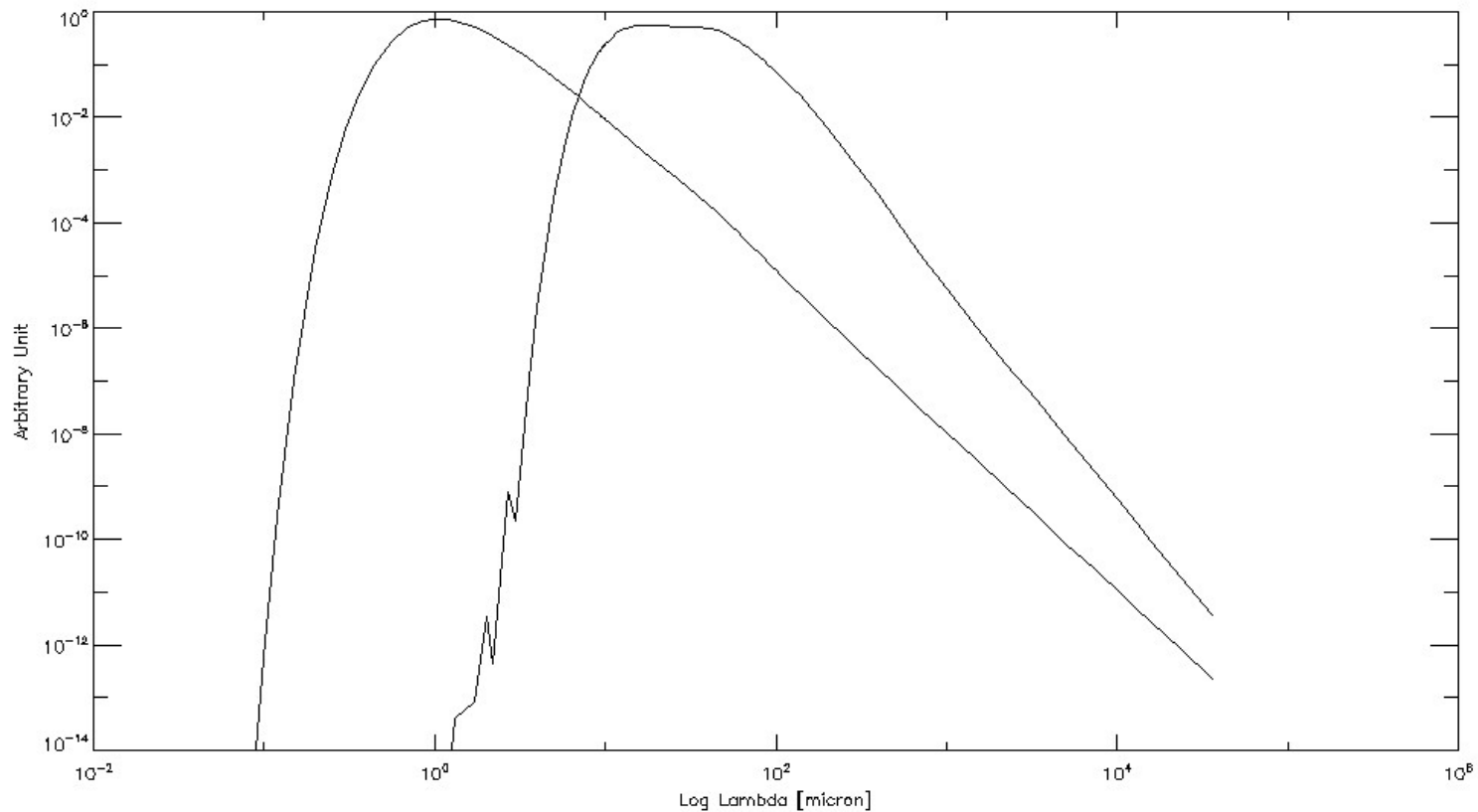
Warm Silicate
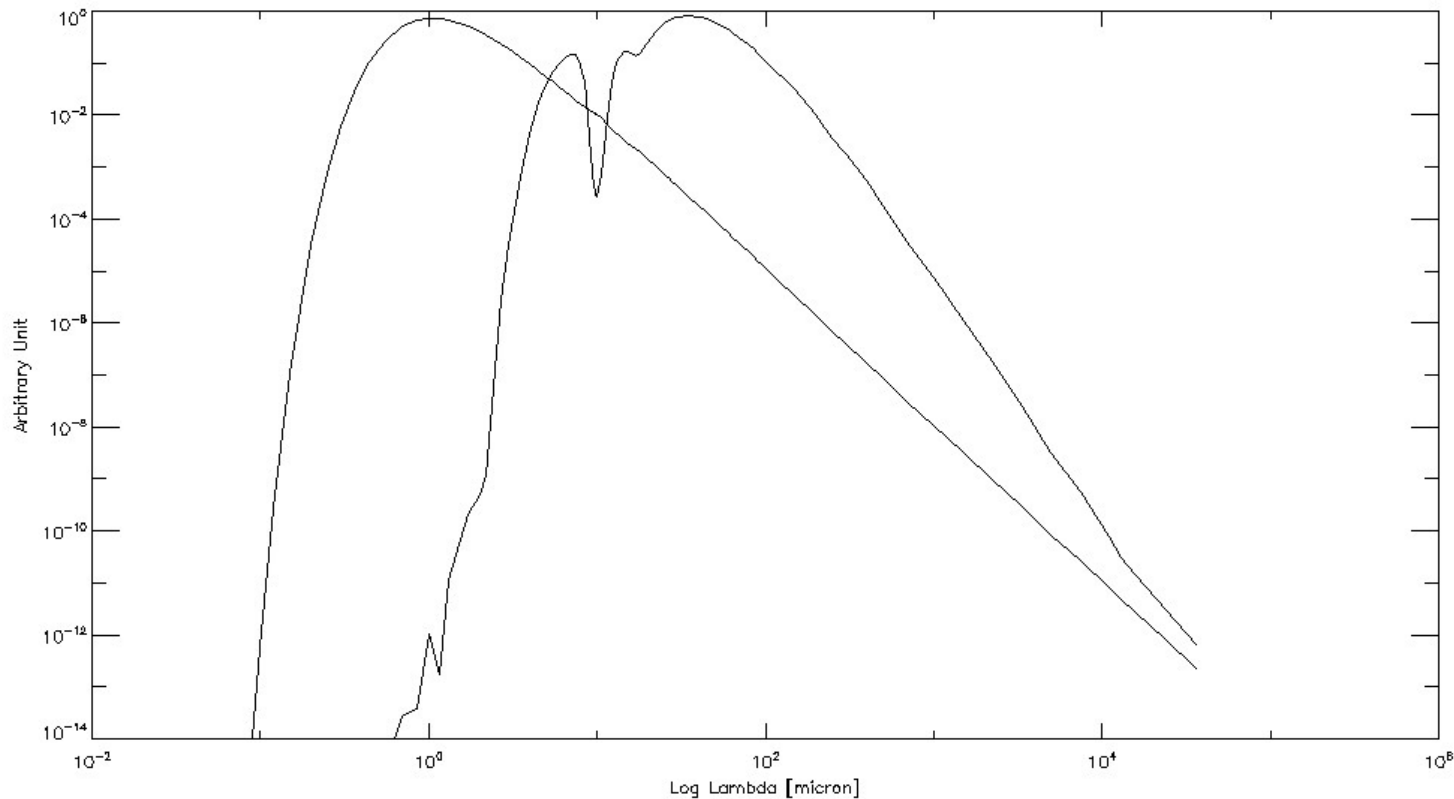
SEDs of optical length=0.01 and 1000

- The shape of the observed spectral energy distribution (SED) depends on the optical properties of the grains and the optical depth of the envelope.

Graphite Grains

SEDs of optical length=0.01 and 1000

Other Variables

- The dust:gas ratio:
-      Inferred from CO line emission
- Luminosity (Figer et al. 2006)
- Outflow velocity:
-      Can be inferred from the maser feature and derive from the relation between luminosity and velocity

Future Work

- For the dusty region around RSG stars is likely to be anisotropic (Schuster, Humphreys et al. 2006)
- 3D model Monte Carlo code will be used

Thanks