Carbon stars and dust production as a function of metallicity

G.C. Sloan and many others

SOFIA Tele-Talk 2-26-2014

NGC 1978 in the LMC – observed by the HST

Conclusions

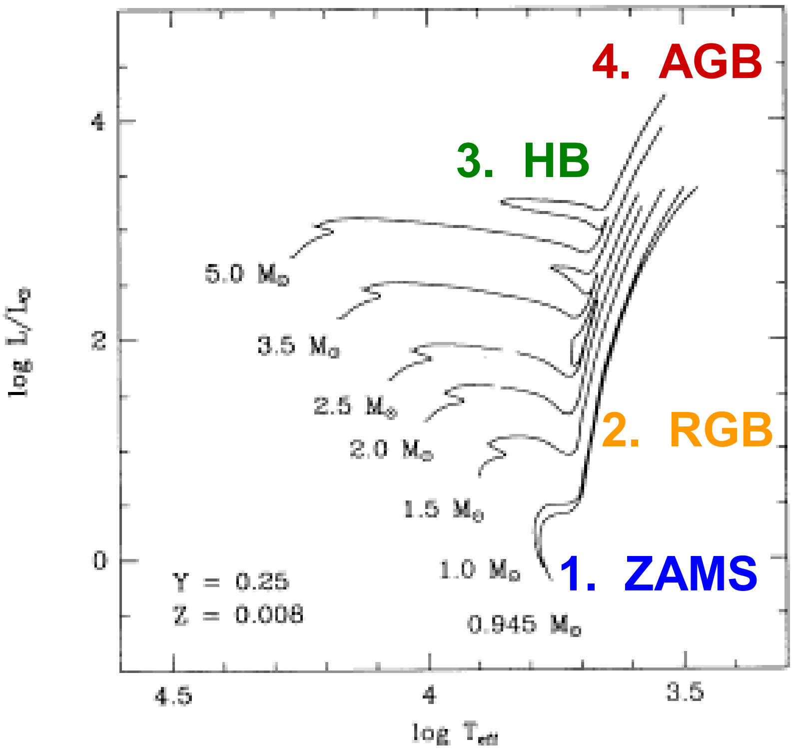
The amount of dust produced by carbon stars does *not* depend on metallicity (down to [Fe/H] ~ –1)

- Carbon stars should contribute dust at z > 6
- Exceeding a free carbon limit triggers a superwind and truncates AGB lifetimes
- Caution with dust budgets: Estimated dust production rates depend on assumed opacities

More conclusions

- Spectra and photometry support evidence for temporal variations in dust production
- SiC dust shows layering in grains, depending on Z
- We can measure the distances to Galactic carbon stars with a new J-K color-mag rel’n

Stellar evolution



Vassiliadis & Wood (1993)

Intermediate-mass stars

1. **Zero-Age Main Sequence**

   Core H burning

2. **Red Giant Branch**

   Shell H burning

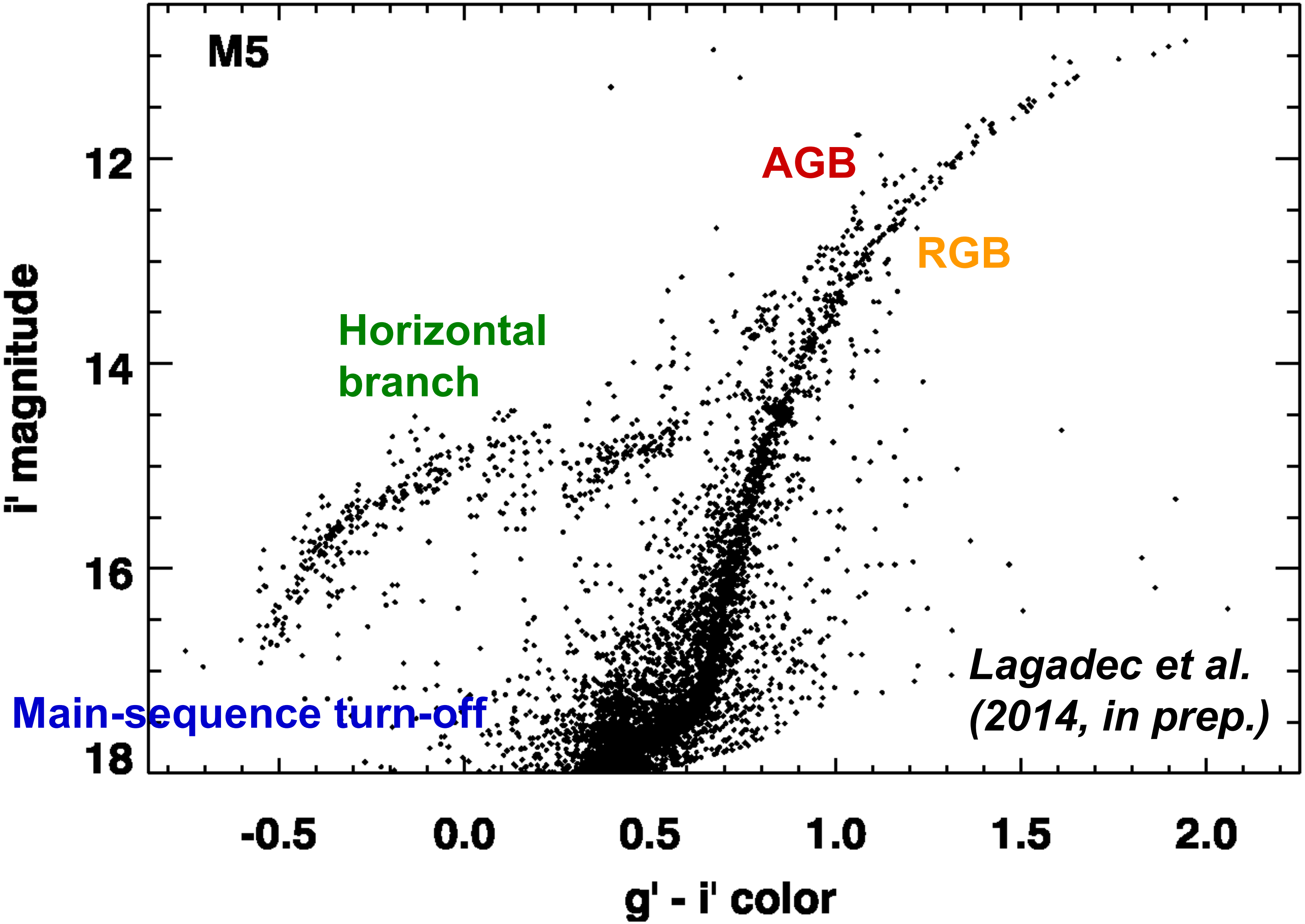
3. **Horizontal Branch**

   Core He burning

4. **Asymptotic Giant Branch**

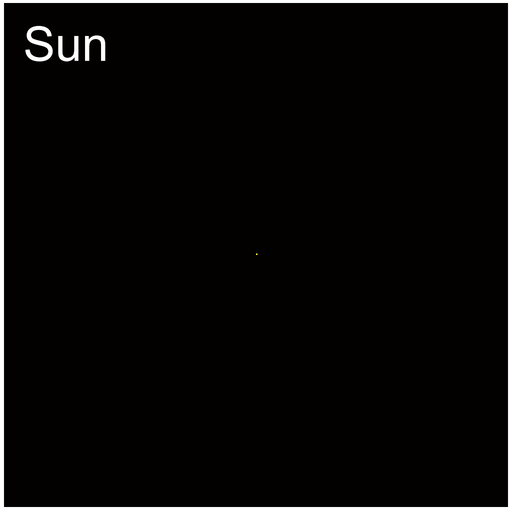
   Shell He/H burning

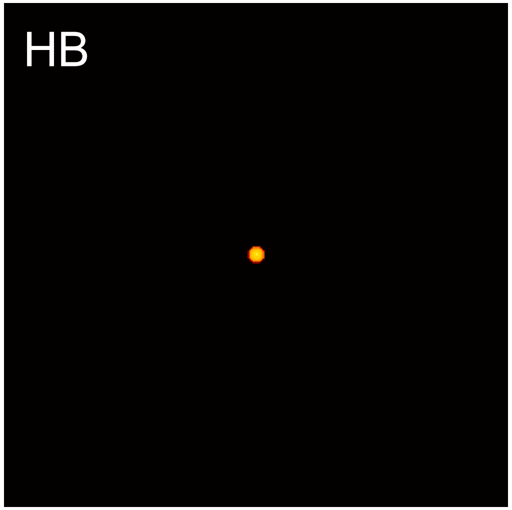
Evolved stars in M5



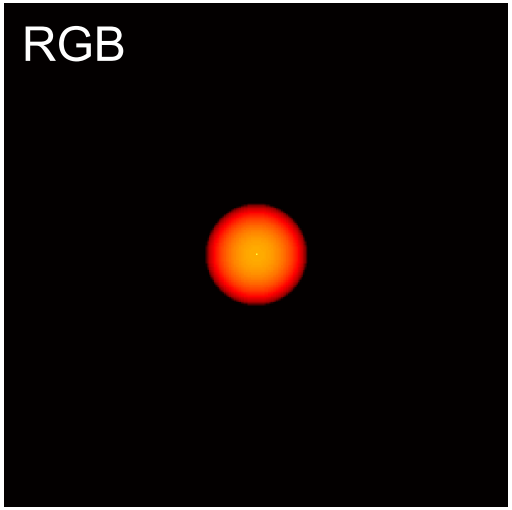
Lagadec et al. (2014, in prep.)

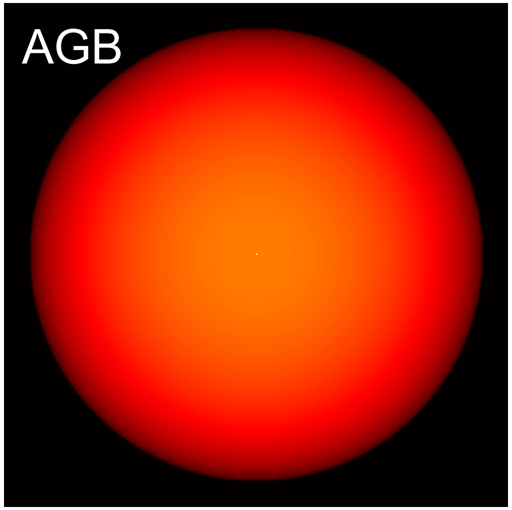
AGB stars are … big



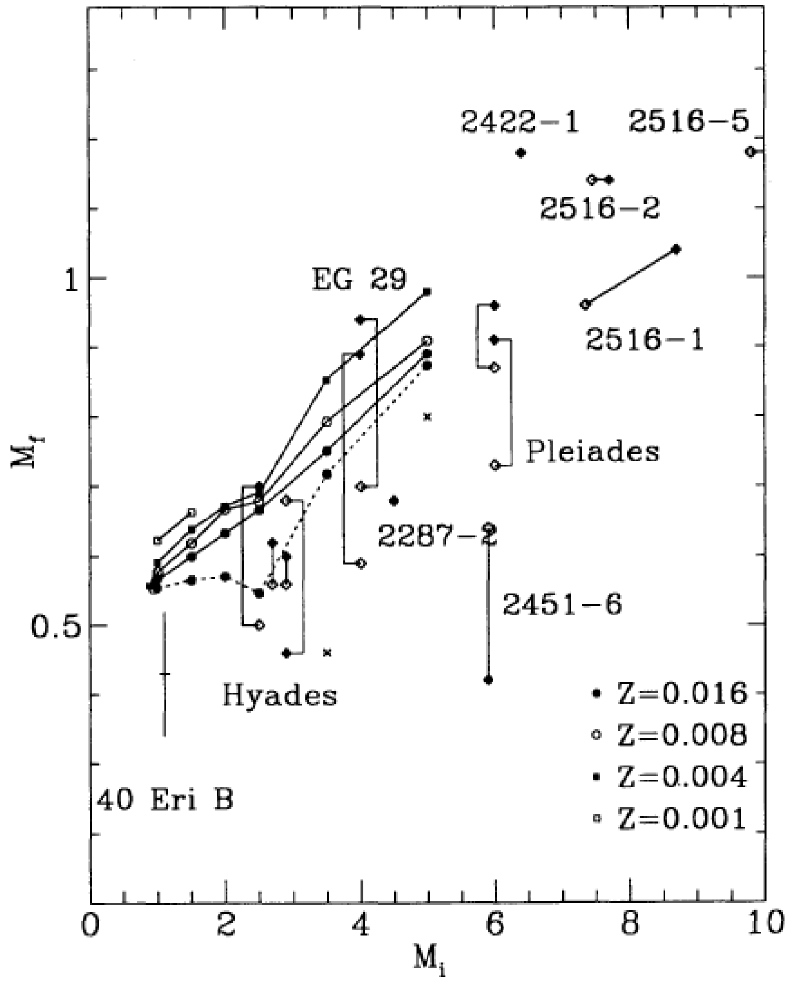


Scale:
Boxes are 2
AU on a side





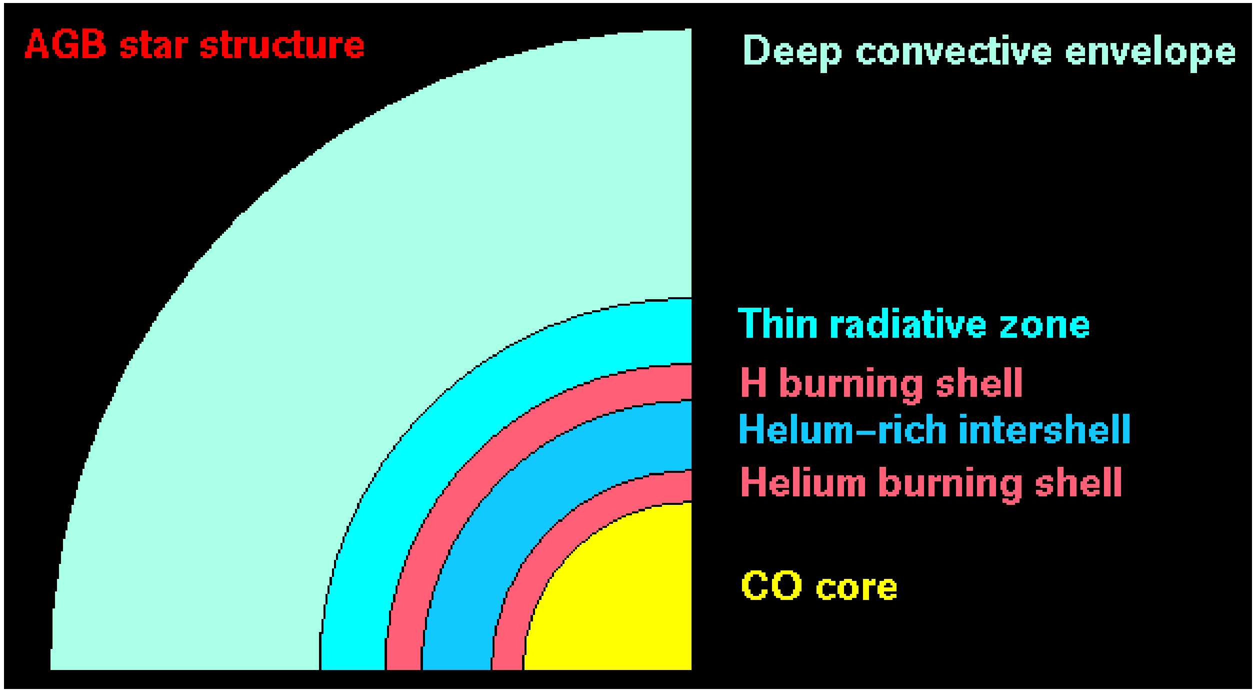
Final vs. initial mass



- Final mass = mass of white dwarf
- Sun-like stars
  lose ~1/2 their mass
- Massive AGB stars
  lose ~85% of their mass
- Most mass ejected on AGB

Vassiliadis & Wood (1993)

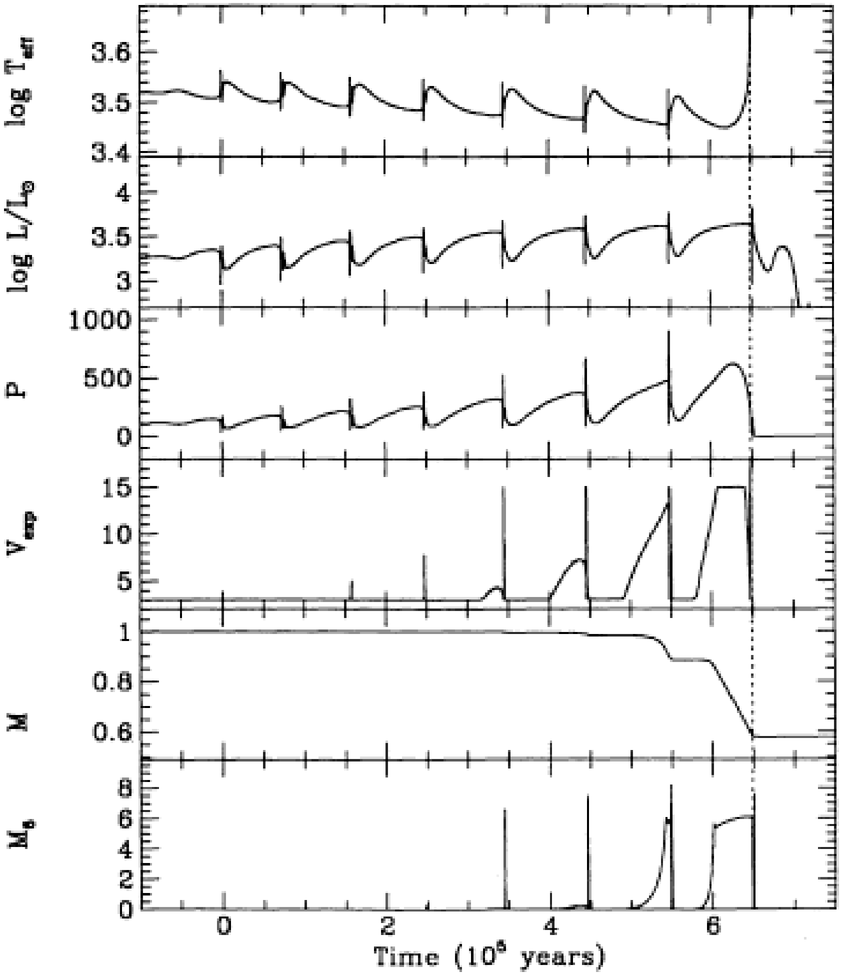
The AGB



From John Lattanzio's website

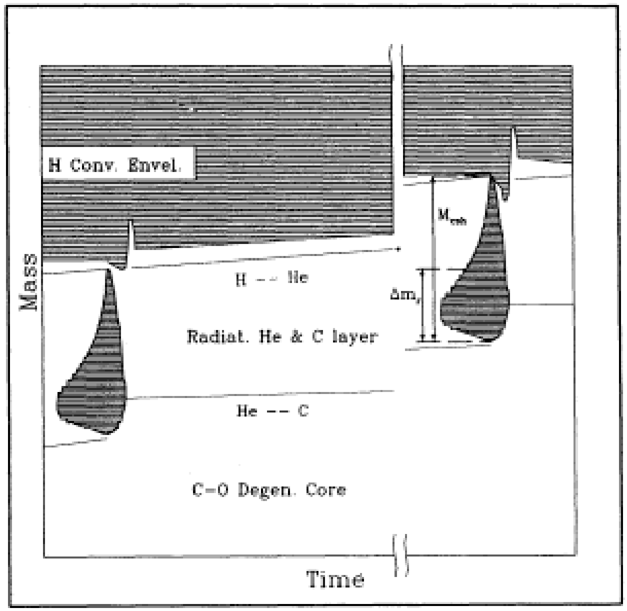
- Inner **He burning** shell
- **3-α sequence** (Salpeter 1952)
- He burns in **thermal pulses**, leads to dredge-ups

Thermal pulses & dredge-ups



Vassiliadis & Wood (1993)

- Convective envelope overlaps convection around He fusion zone
- C dredged up to surface



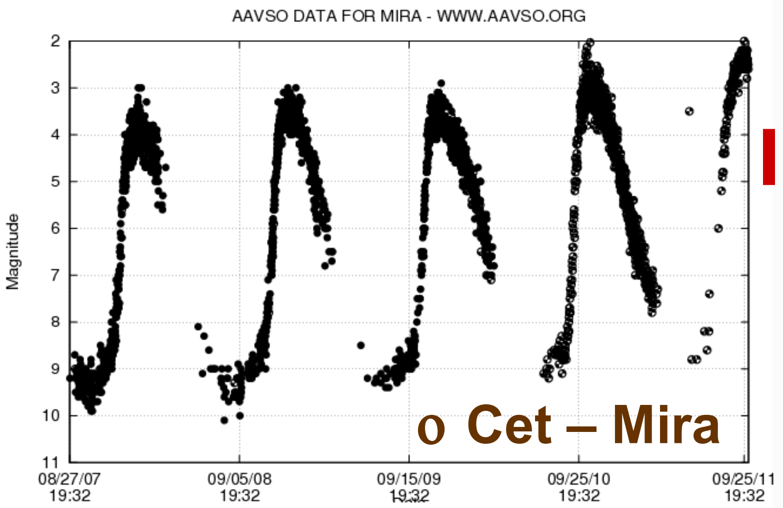
Busso et al. (1995)

Long-period variables

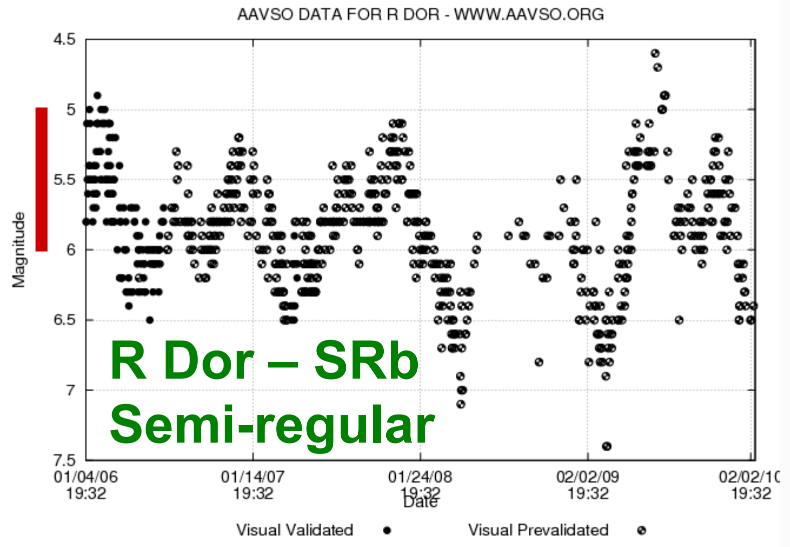
AGB envelopes pulsate

- **Mira – fundamental mode**
- **SRb – lower overtones**
- **Lb – higher overtones**

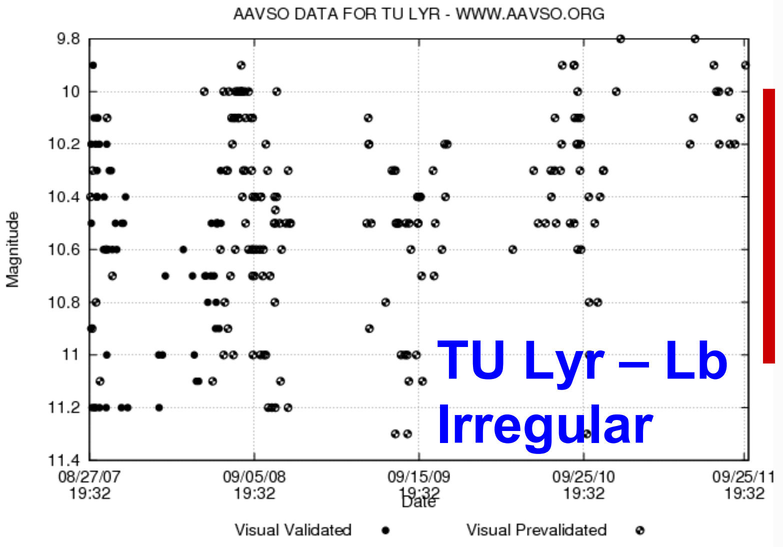
(Data from the AAVSO)


AAVSO DATA FOR MIRA - WWW.AAVSO.ORG

o Cet – Mira

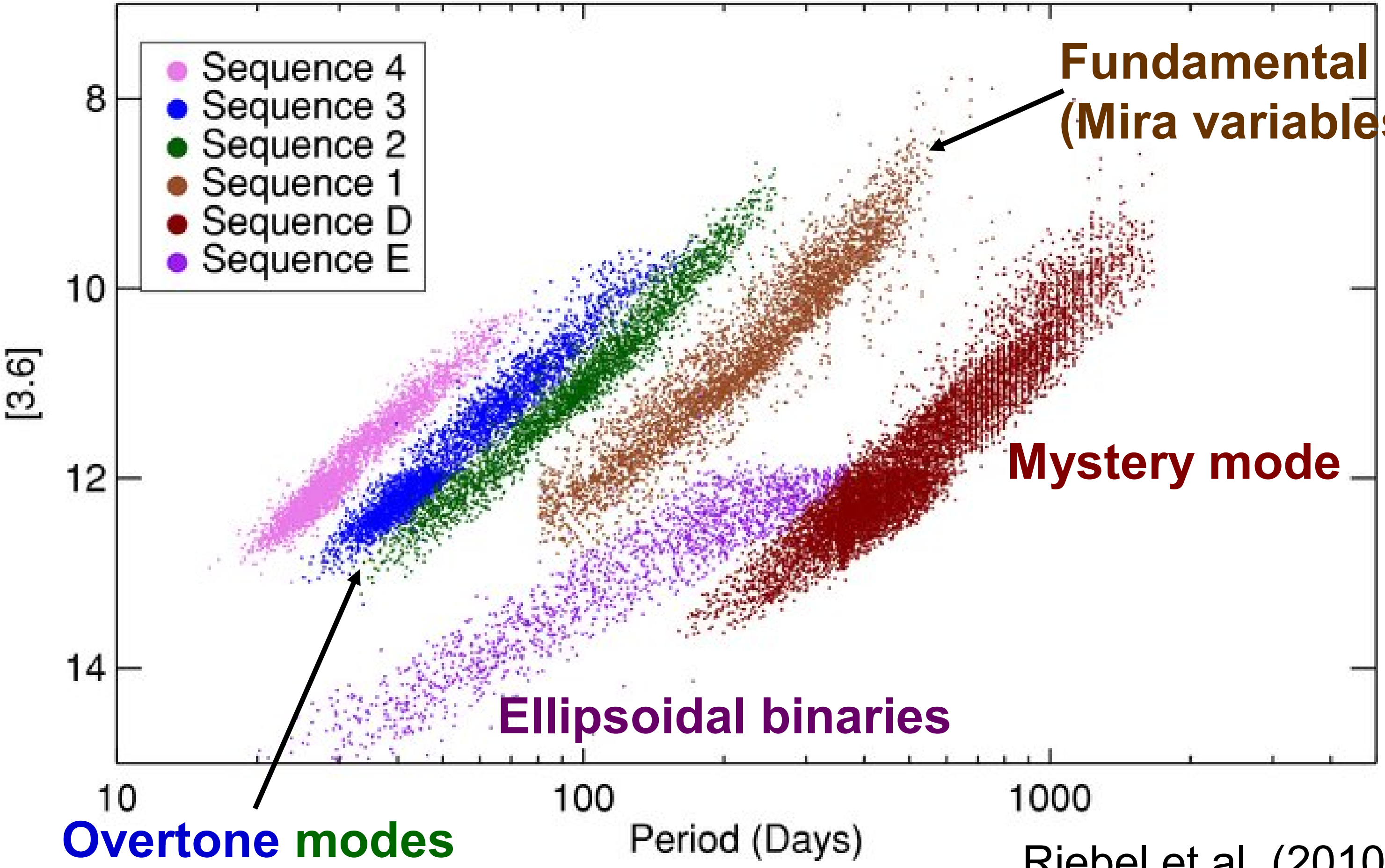

AAVSO DATA FOR R DOR - WWW.AAVSO.ORG

R Dor – SRb Semi-regular


AAVSO DATA FOR TU LYR - WWW.AAVSO.ORG

TU Lyr – Lb Irregular

The LPV P-L relation(s)



Fundamental mode (Mira variables)

Mystery mode

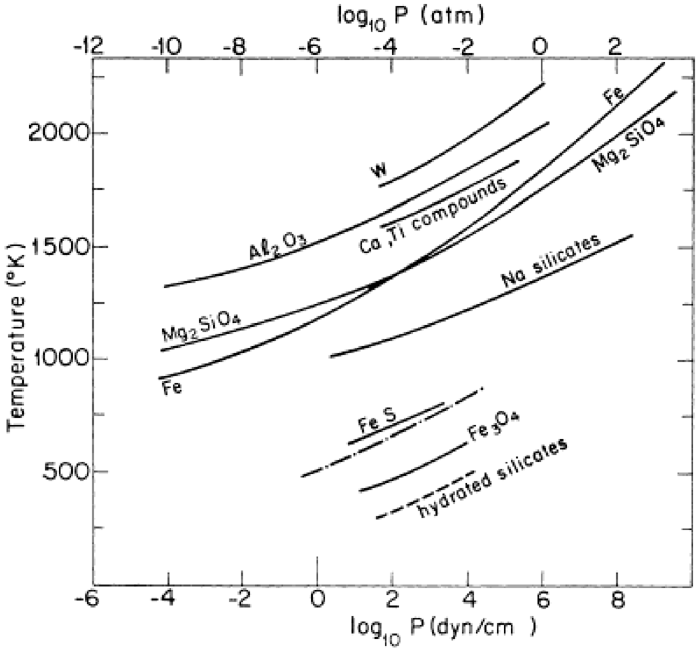
Ellipsoidal binaries

Overtone modes (Semi-regulars)

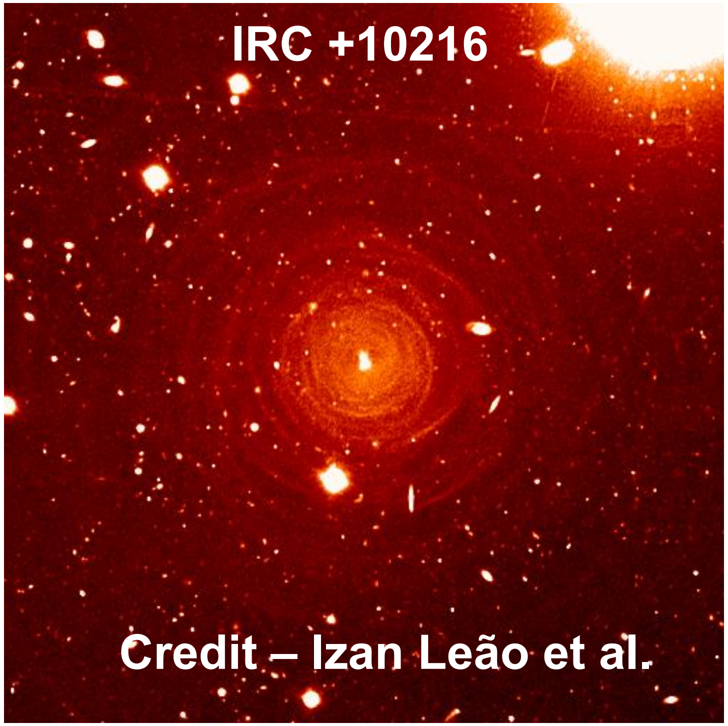
Riebel et al. (2010, Fig. 1)
(see also Wood & Sebo 1996)

Circumstellar dust chemistry

- **CO paradigm**
  - CO will form until C or O exhausted
- **C/O < 1 M giant**
  - OH, H_2O, MgO, SiO, other oxides
- **C/O > 1 Carbon star**
  - C_2H_2, HCN, hydrocarbons, carbides, sulfides



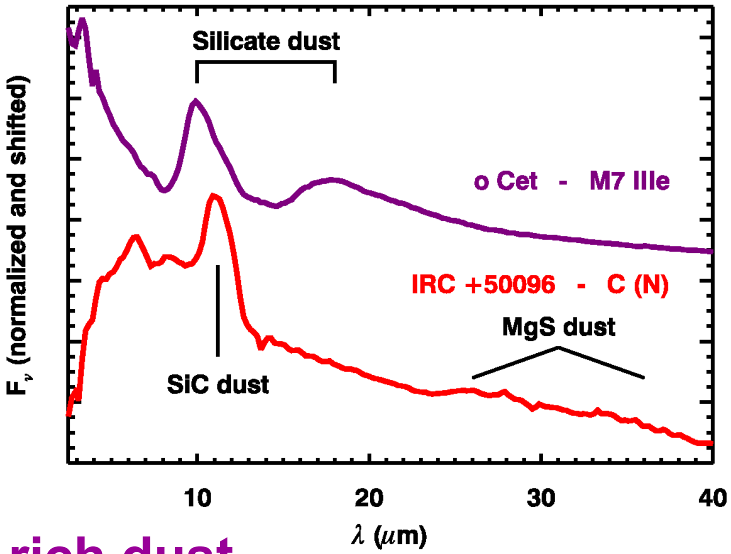
Salpeter (1977, Fig. 2)



IRC +10216

Credit – Izan Leão et al.

AGB dust composition



O-rich dust

Amorphous silicates

Alumina, crystalline tracers

C-rich dust

Amorphous carbon

SiC and MgS tracers

CO paradigm → dust dichotomy

C/O depends on dredge-ups

Low-mass AGB:

~0-2 $M_\odot$

Insufficient dredge-ups

O-rich dust

Intermediate-mass AGB:

~2-5 $M_\odot$

C-rich dust

High-mass AGB:

~5-8 $M_\odot$

Hot-bottom burning (CNO cycle)

O-rich dust

Supergiants:

> ~8 $M_\odot$

O-rich dust

Dust sources in the Galaxy

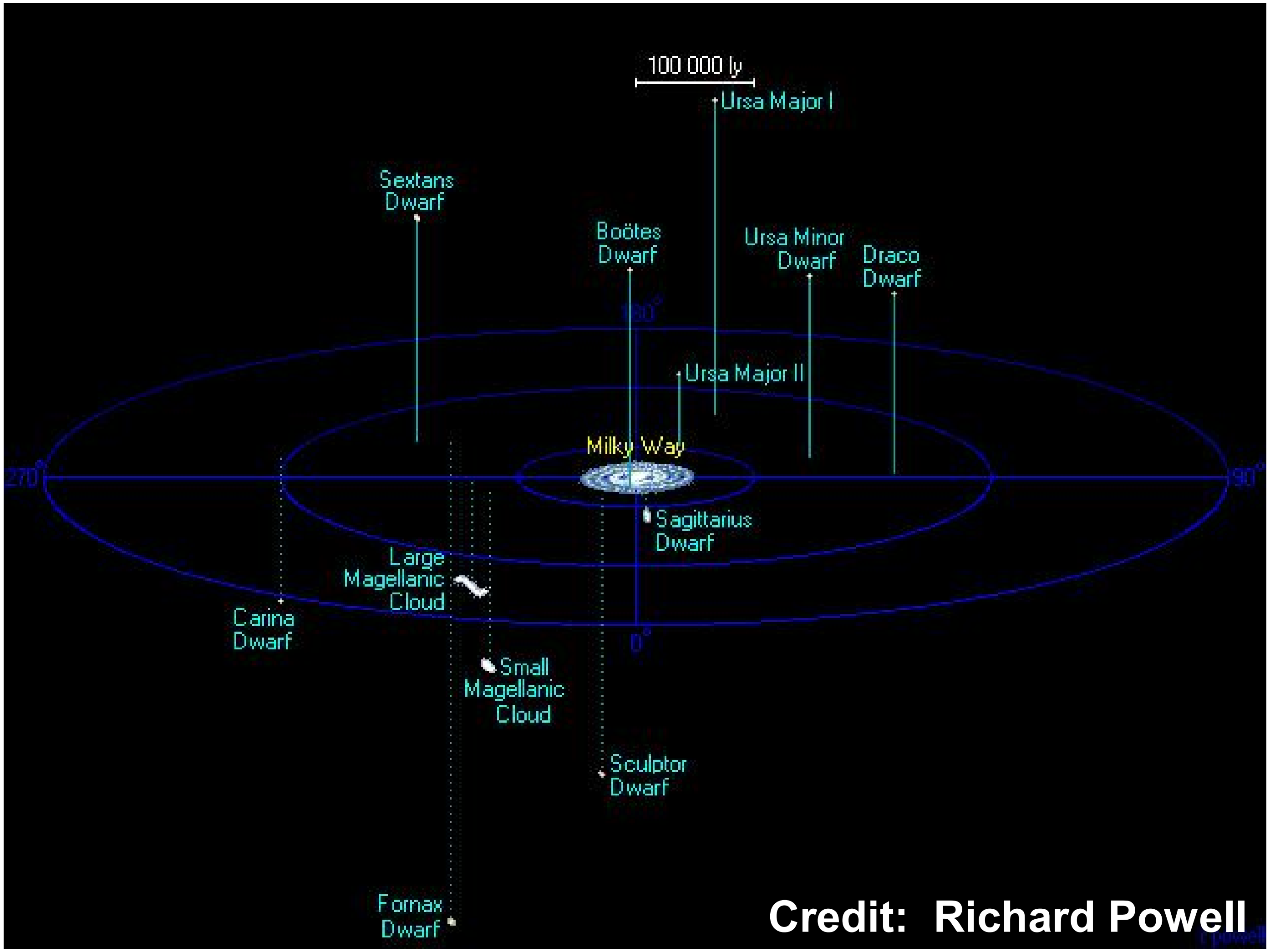
Dust traces the total input to the ISM

Source	% of dust
O-rich AGB	67
C-rich AGB	20
Red supergiants	8
Supernovae	4
Wolf-Rayet stars	0.5
Planetary nebulae	0.2
Novae	0.1

(Gehrz 1989, IAU Symp. 135, 445)

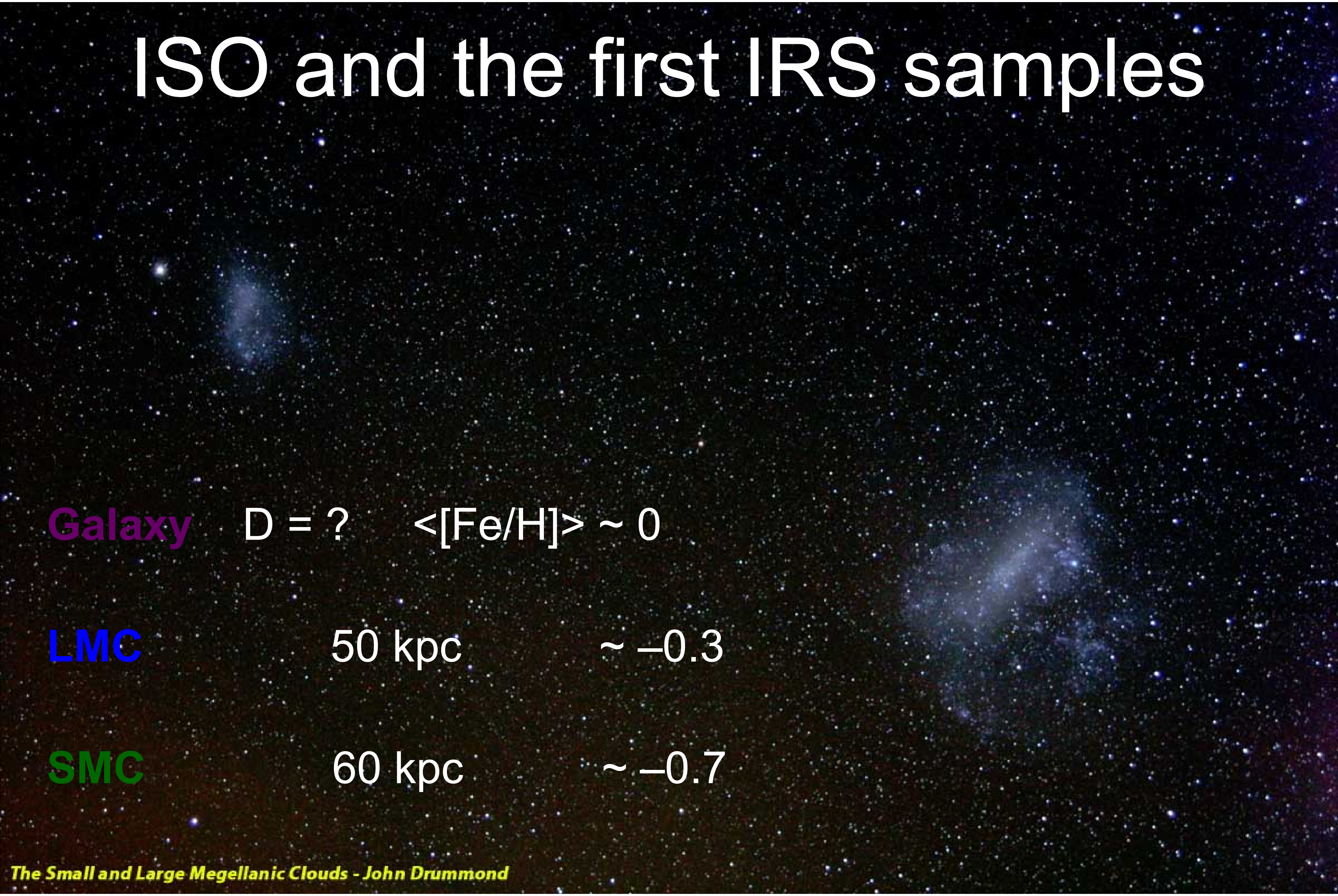
The AGB dominates dust production locally

The Milky Way System



Credit: Richard Powell

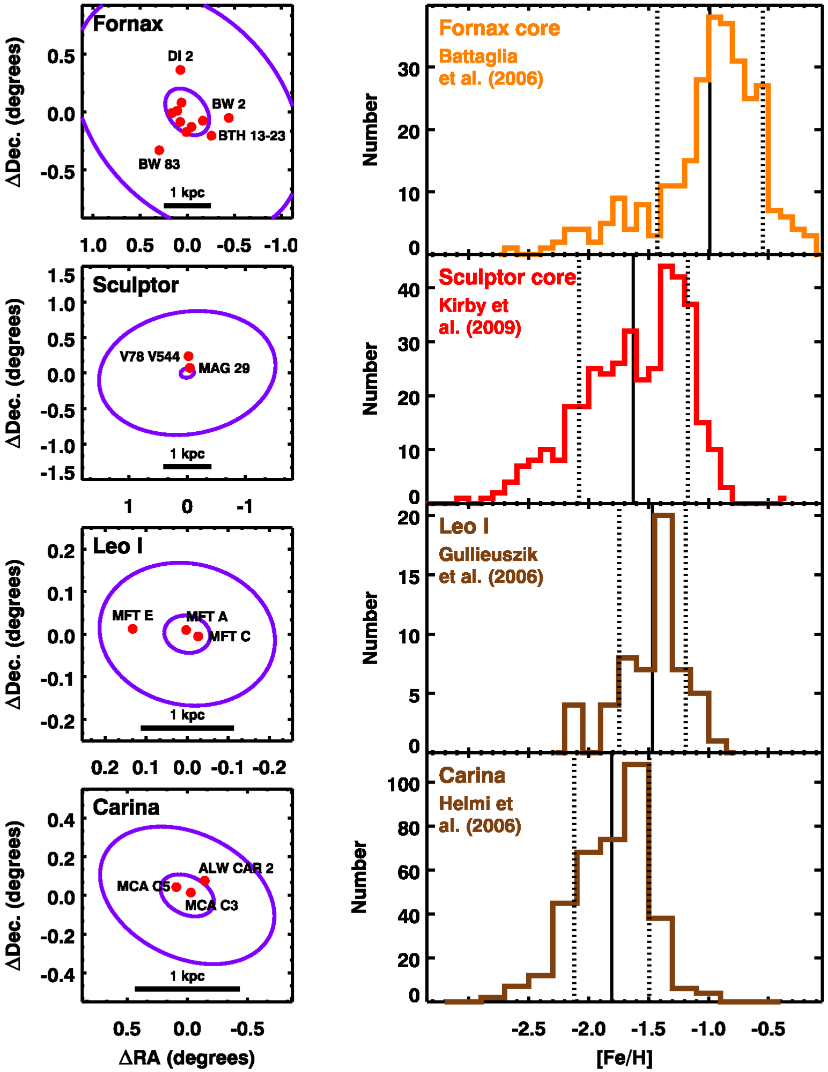
ISO and the first IRS samples



Galaxy	D = ?	<[Fe/H]> ~ 0
LMC	50 kpc	~ –0.3
SMC	60 kpc	~ –0.7

The Small and Large Megellanic Clouds - John Drummond

Samples and metallicities



Fornax dSph

<[Fe/H]> ~ **–0.3-0.8**   150 kpc

Sculptor dSph

~ **–1.0**   87 kpc

Leo I dSph

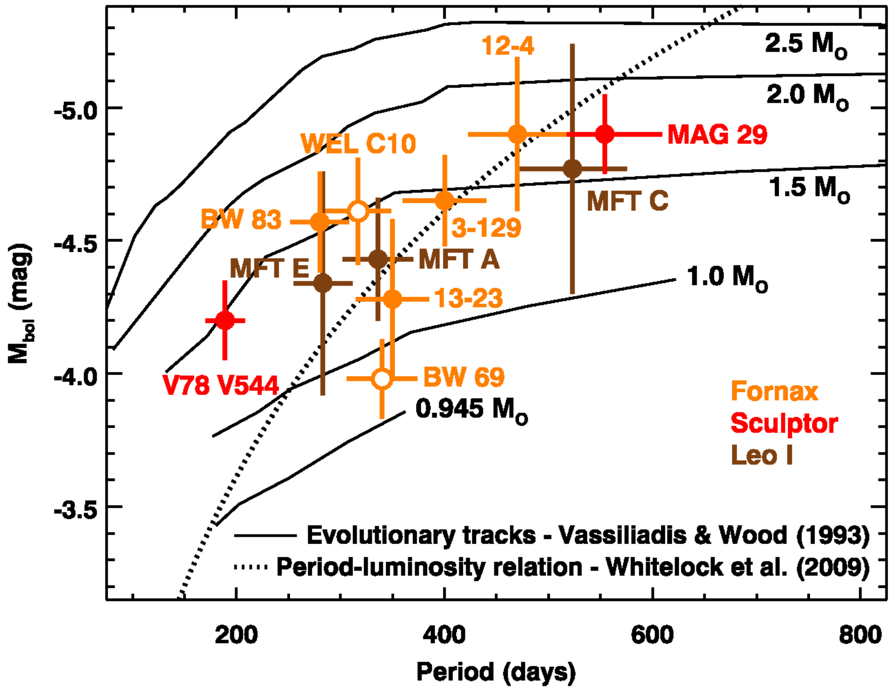
~ **–1.4**   280 kpc

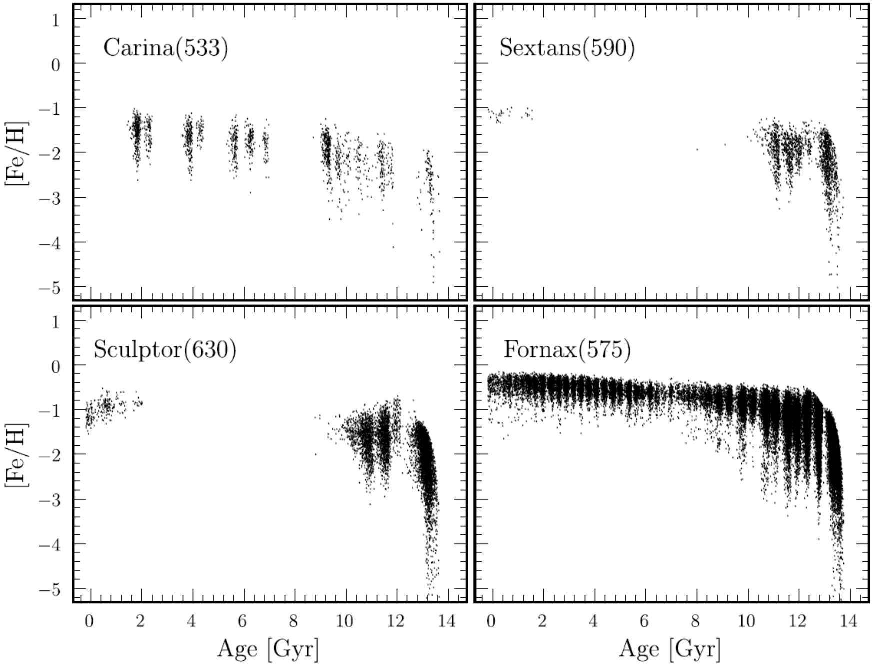
Carina dSph

~ **–1.7**   100 kpc

Sloan et al. (2012)

Estimating metallicity





M_{bol} → mass → age → [Fe/H]

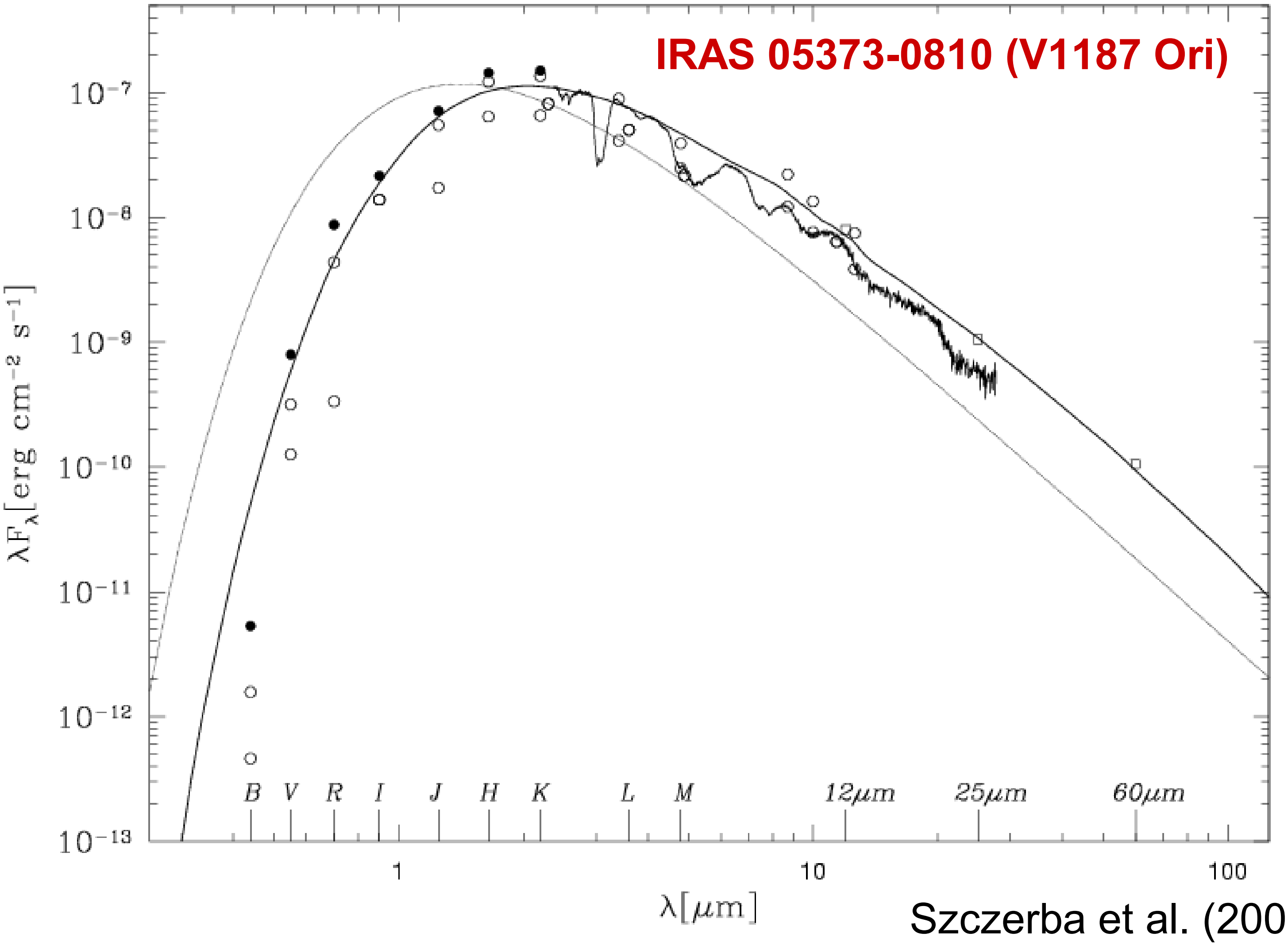
Evolutionary models by Revaz et al. (2009, Fig. 14)

Fornax – Most targets are younger than ~3 Gyr

- Metallicities most like SMC and LMC

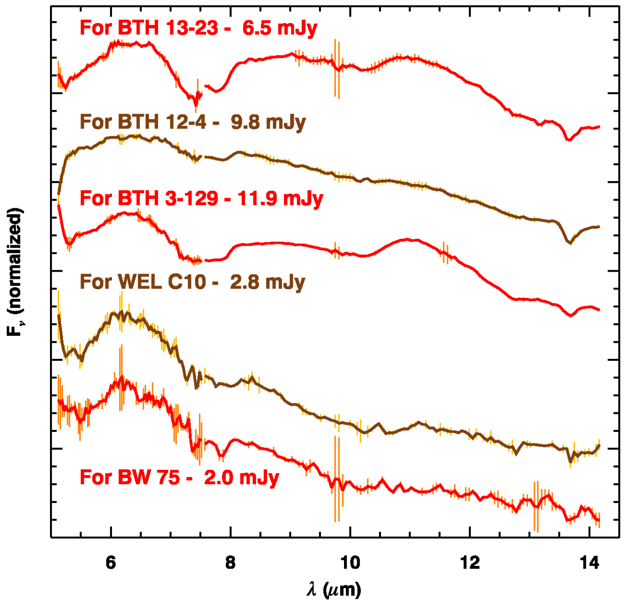
Sculptor – Both targets are < 2 Gyr old – [Fe/H] ~ –1.0

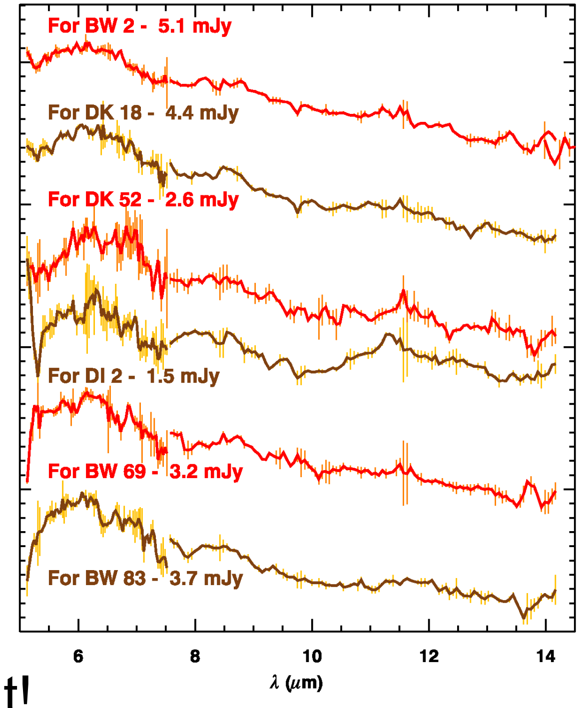
A carbon star

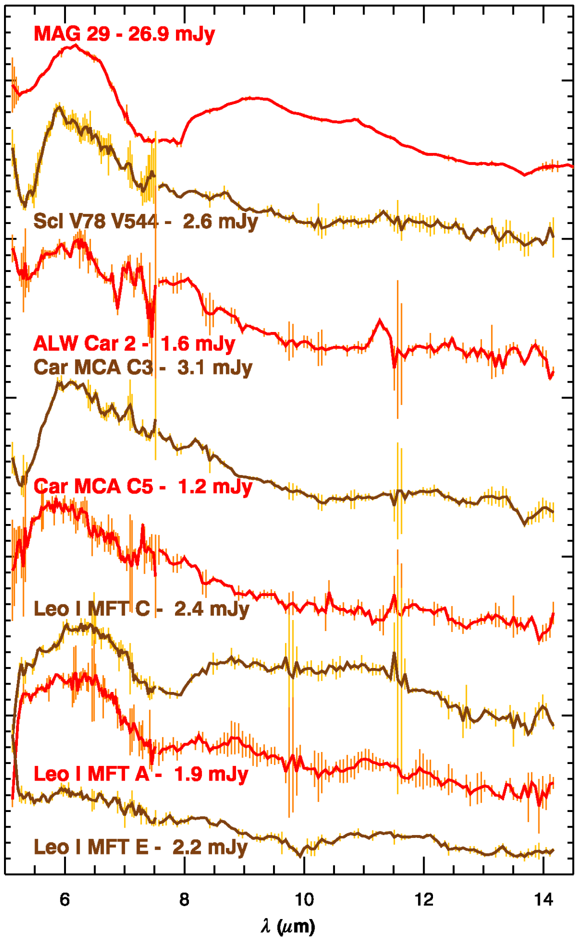


Szczerba et al. (2002)

Local Group spectra

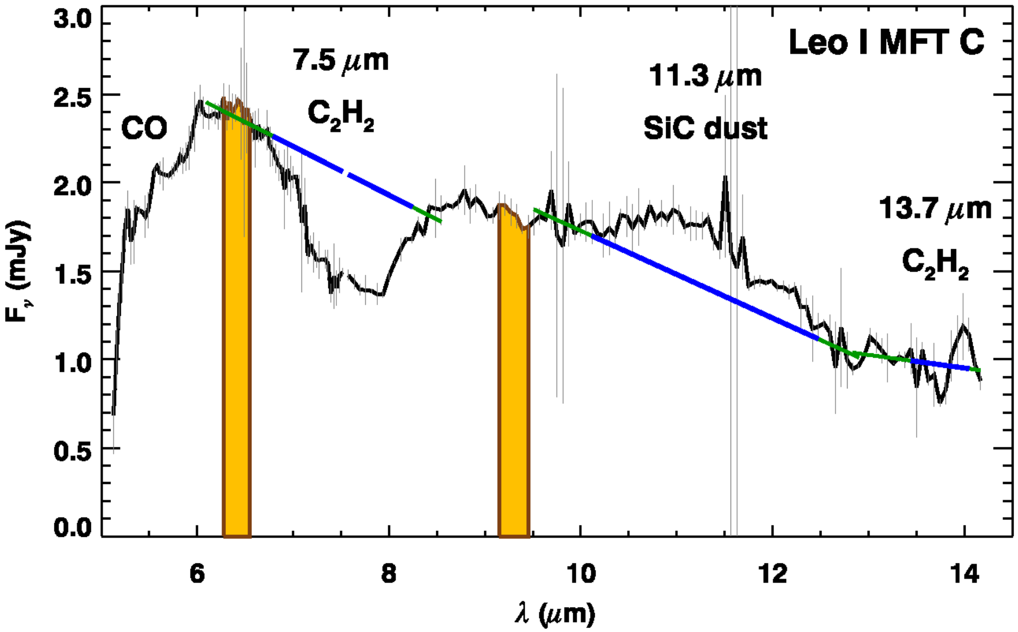






- These targets are faint!
- Need **Cornell's** optimal extraction algorithm (***Lebouteiller et al. 2010***)
- Extracted spectra publicly available: http://cassis.astro.cornell.edu

Manchester Method



Introduced by ***Sloan et al. (2006)*** and ***Zijlstra et al. (2006)***

Applied to large comparison samples from the Galaxy, LMC, and SMC

Total warm amorphous carbon content

- Measured by the **[6.4] – [9.3] color**
- Need outflow velocity, gas-to-dust ratio to get mass-loss rate
- Calibrated with radiative transfer models (***Groenewegen et al. 2007***)

Gaseous acetylene absorption strength at 7.5 μm

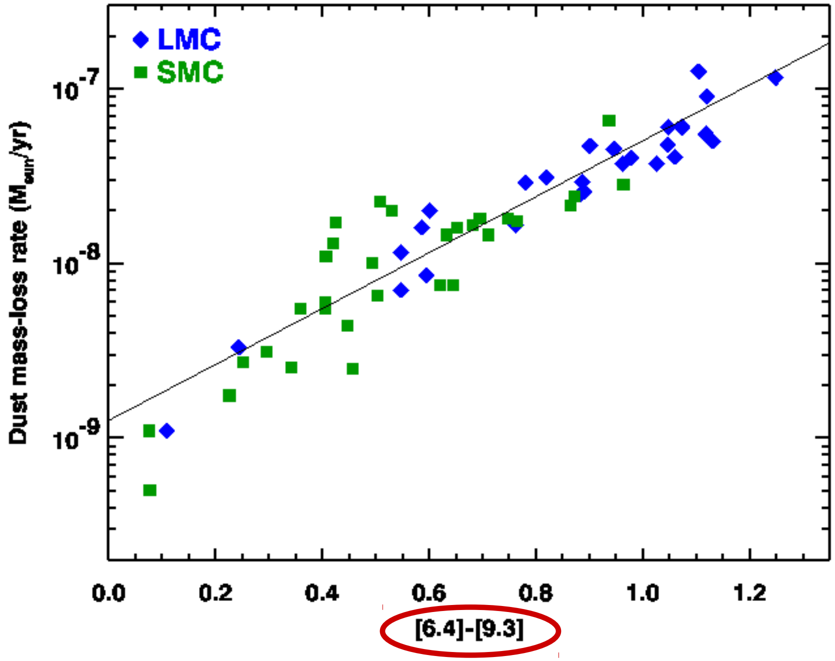
SiC dust emission strength at 11.3 μm

Total mass-loss rates

Models: ***Groenewegen et al. (2007)***

Data: ***Sloan et al. (2006), Zijlstra et al. (2006), Lagadec et al. (2007)***

[6.4]–[9.3] scales with dust emissivity (i.e. dust content)



In more detail:

$$\log \dot{M}\left(\frac{\mathrm{M}_\odot}{\mathrm{yr}}\right) = [-8.9+1.6([6.4]-[9.3])]\log\left(\psi\frac{v_\mathrm{out}}{10\,\mathrm{km/s}}\right)$$

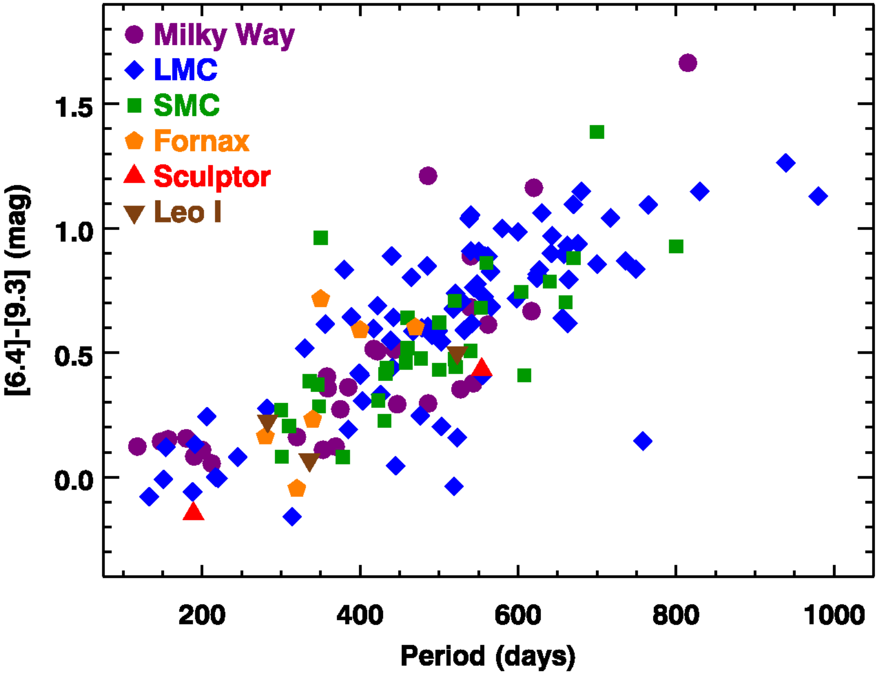
Multiply by outflow velocity of dust to get dust-production rate

Multiply by gas-to-dust ratio (ψ) to get total mass-loss rate

Carbon-rich dust content

Dust content increases with pulsation period

Metallicity has little *obvious* influence



Pulsation periods from the SAAO

Fornax: Whitelock et al. (2009)

Sculptor: Menzies et al. (2011)

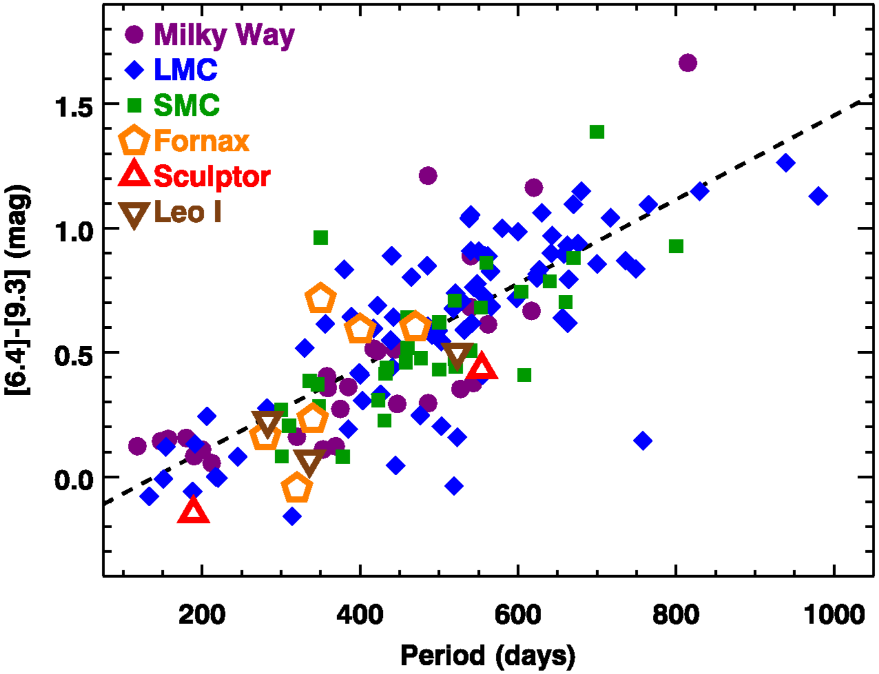
Leo I: Menzies et al. (2010)

Their work is the key to making these comparisons possible

A closer look

We may be seeing a decrease in dust content at the lowest metallicities

Sculptor and Leo I are below the fitted line, at a 3.6σ level



(The Fornax data are consistent with our assumed metallicity)

AGB dust vs. Z

- More carbon stars as metallicity drops

Z	0.02 (Solar)	0.008 (LMC)	0.004 (SMC)	0.0001
Lower limit (M_{O})	1.7-2.0	~1.5	1.2-1.4	~1.1
Upper limit (M_{O})	5	4	4	3

Voli & Renzini (1981, A&A, 94, 175)

Karakas & Lattanzio (2007, PASA, 24,103)

- Metal-poor galaxies → more carbon, less silicates

Dust sources in the Mag. Clouds

Galaxy	Total dust production rate ($M_\odot$/yr)
LMC	11×10^{-6}
SMC	9×10^{-7}

Class	LMC	SMC
x-AGB	61%	66%
C-AGB	6	13
O-AGB	7	8
RSG	2	3
other	24	10

Boyer et al. (2012)

- x-AGB = extreme AGB = (mostly) embedded carbon stars
- other = YSOs and other far-IR sources = no dust *production*

Carbon stars produce most of the dust in the LMC and SMC

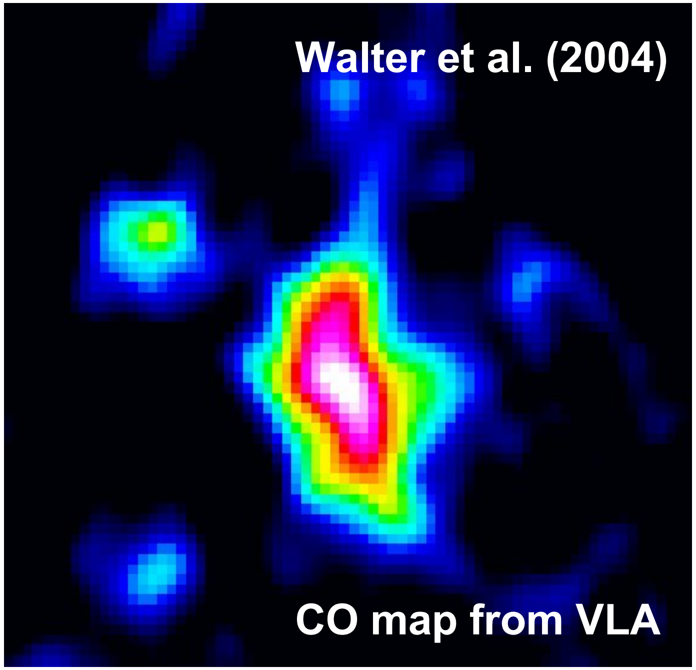
Timing

T (Myr)	z	Event
0	infinity	Big Bang
0.4	1050	Recombination & Dark Ages
480	10	Pop III & reionization (Greif et al. 2008)
870	6.42	J1148+5251

Vassiliadis and Wood (1993)

- Model lifetimes decrease as Z drops
- Time to thermally pulsing AGB at Z=0.004 (SMC)
  - 3 $M_\odot$ → ~ 390 Myr
  - 4 $M_\odot$ → ~ 180 Myr
- $Z=10^{-5}$, lifetimes even shorter

We have ~400 Myr to get from Pop III to J1148+5251



AGB making carbon-rich dust in J1148+5251

C/O and metallicity

$$\frac{C_{free}}{O} = \frac{C}{O} - 1$$

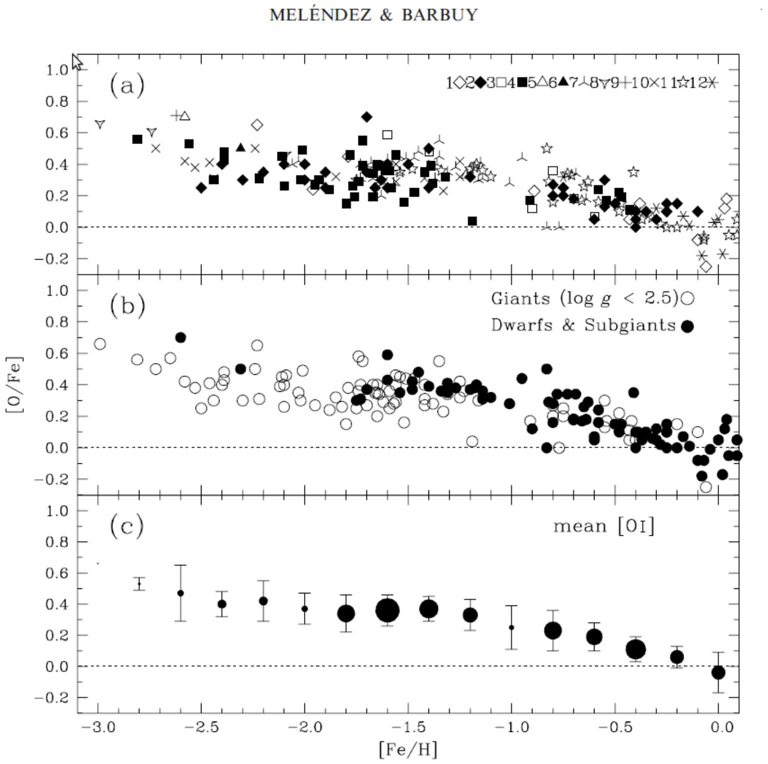
After formation of CO molecules

$$\frac{C}{O} = \frac{C_i + \delta C}{O}$$

- Assume C_i scales with Z
- Assume δC independent of Z
- $O = O_i$ ***does depend*** on Z

[O/Fe] = –0.25 [Fe/H]

for –1.5 < [Fe/H] < 0.0



Melendez & Barbuy (2002, Fig. 5)

Expected free carbon

$$\frac{C}{O} = \left(\frac{C}{O}\right)_{\odot} \left(10^{0.25\,[Fe/H]} + \delta C\, 10^{-0.75\,[Fe/H]}\right)$$

$$\frac{C_{free}}{C_{\odot}} = \left(\frac{C}{O} - 1\right) 1.85 \times 10^{0.75\,[Fe/H]}$$

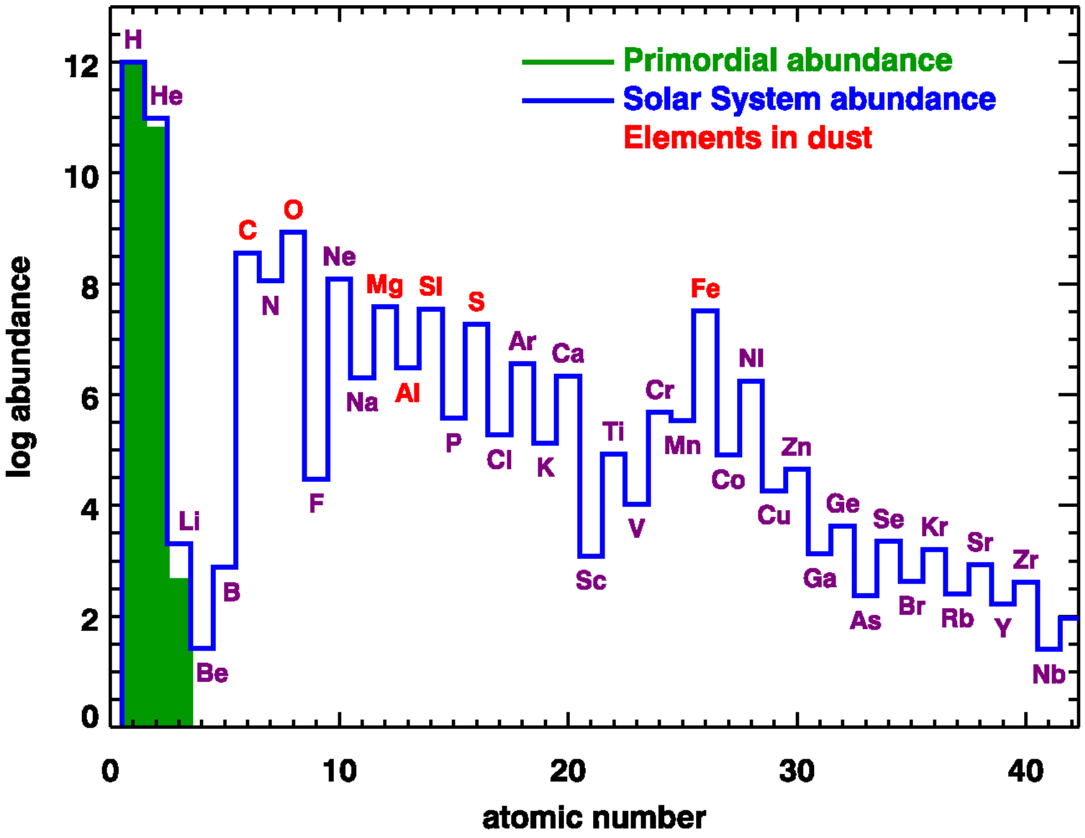
Take $(C/O)_{\odot} = 0.54$ and $\delta C = 0.56\ O_{\odot}$

Galaxy	[Fe/H]	C/O	$C_{free}/C_{\odot}$
Milky Way	0.0	1.1	0.19
LMC	–0.3	1.4	0.44
SMC	–0.7	2.2	0.68
Sculptor	–1.0	3.5	0.81

Four times more free carbon in Sculptor than the Milky Way?

It's not in the dust!
And it's not in the C_2H_2

Impact on enrichment



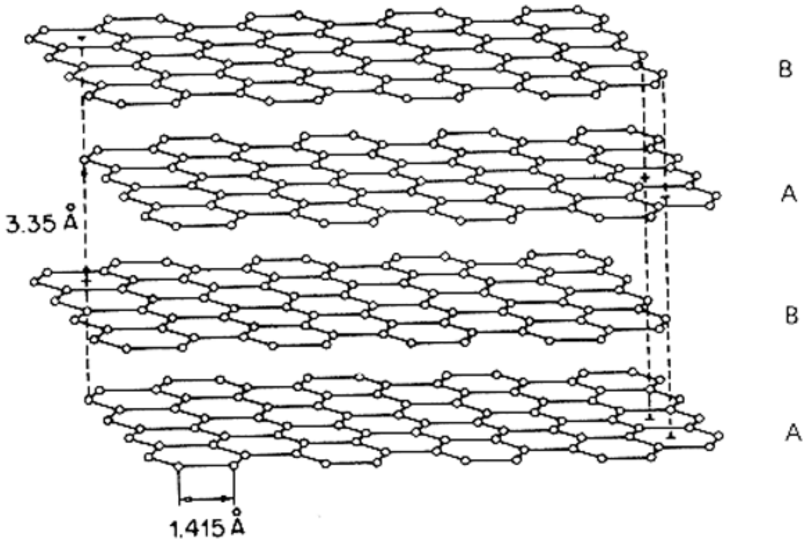
The mass-loss history and lifetime on the AGB will determine what a star can produce and inject back into the ISM

This will impact the enrichment history of a galaxy

Graphite vs. amorphous carbon

Draine & Lee (1984)

- The standard reference
- But how graphitic is circumstellar dust?

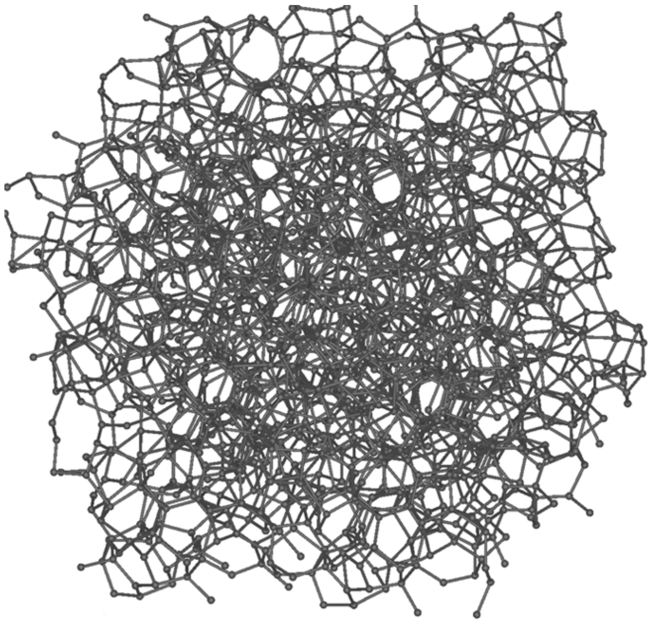


Rouleau & Martin (1991)

- Astronomical amorphous carbon

Zubko et al. (1996)

- ACAR – lab data
- We suspect it is more crystalline (graphitic)



Variations in opacity

- For a given amount of dust emission, higher opacity requires less dust
- ***Dust opacity increases*** for
  - ***More crystallinity*** (graphite vs. amorphous carbon)
  - ***Non-spherical grain shapes***
  - ***Aggregate grains***, which will be more porous
  - For graphite, ***larger*** grains

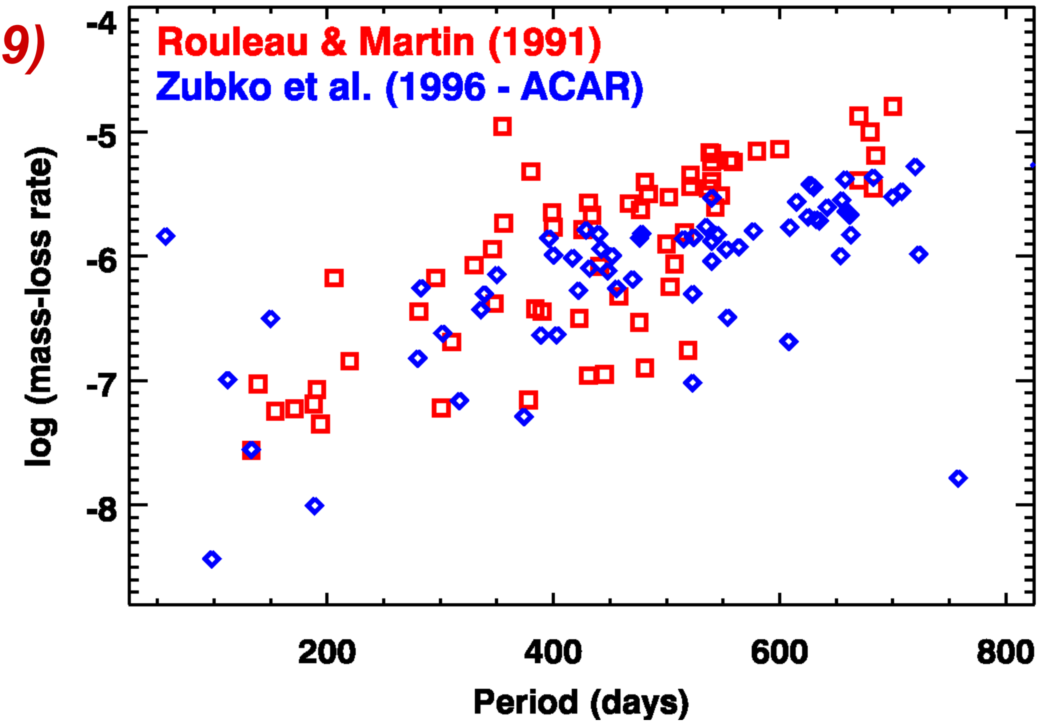
Testing the opacities

Groenewegen et al. (2007, 2009)

- Models use dust from Rouleau & Martin (1991)

Srinivasan et al. (2009, 2010)

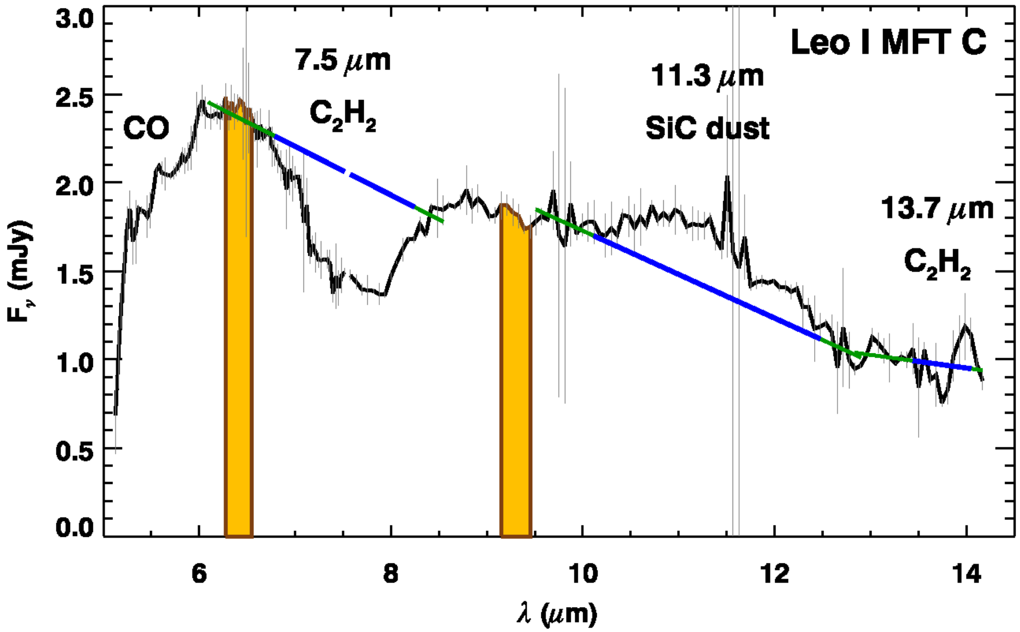
- GRAMS model grid
- These use ACAR dust (Zubko et al. 1996)



DPRs from GRAMS models will be smaller

Groenewegen & Sloan (2014, in prep.)
Assumed g-to-d ratio = 200, v_{out}=10 km/s

Manchester Method



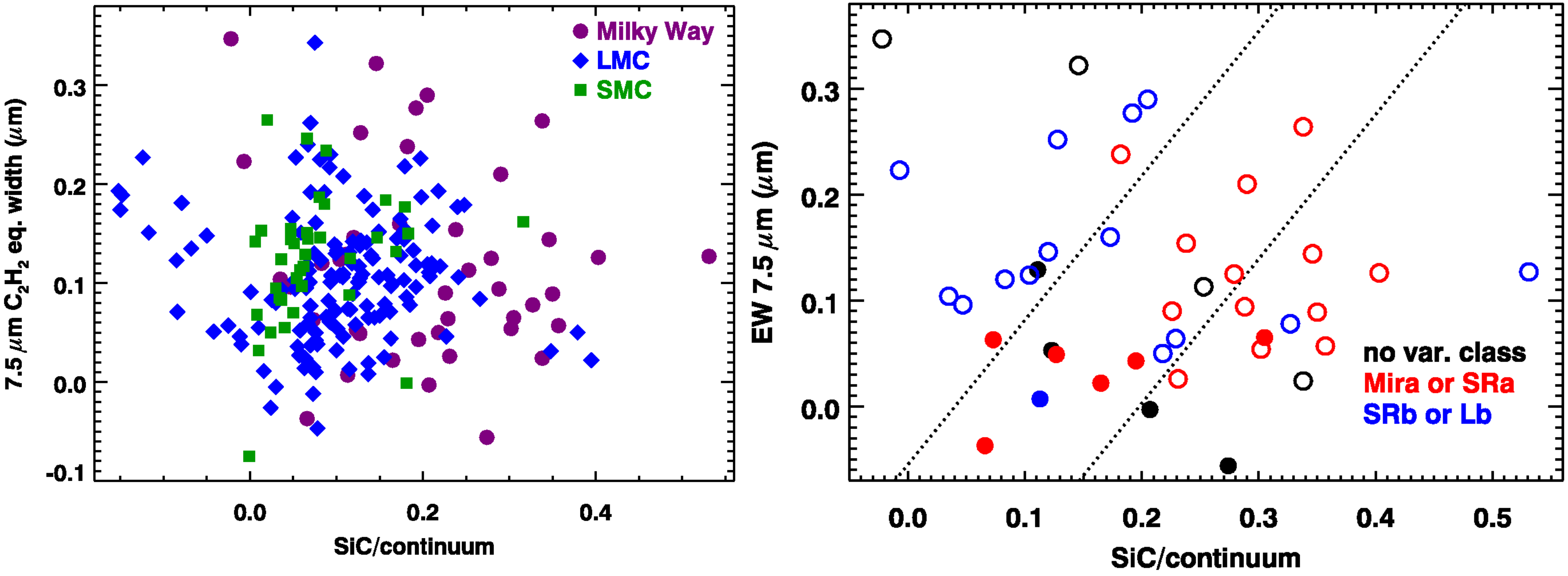
Total warm amorphous carbon content

- Measured by the **[6.4] – [9.3] color**
- Need outflow velocity, gas-to-dust ratio to get mass-loss rate
- Calibrated with models by ***Groenewegen et al. (2007***)

Gaseous acetylene absorption strength at 7.5 μm

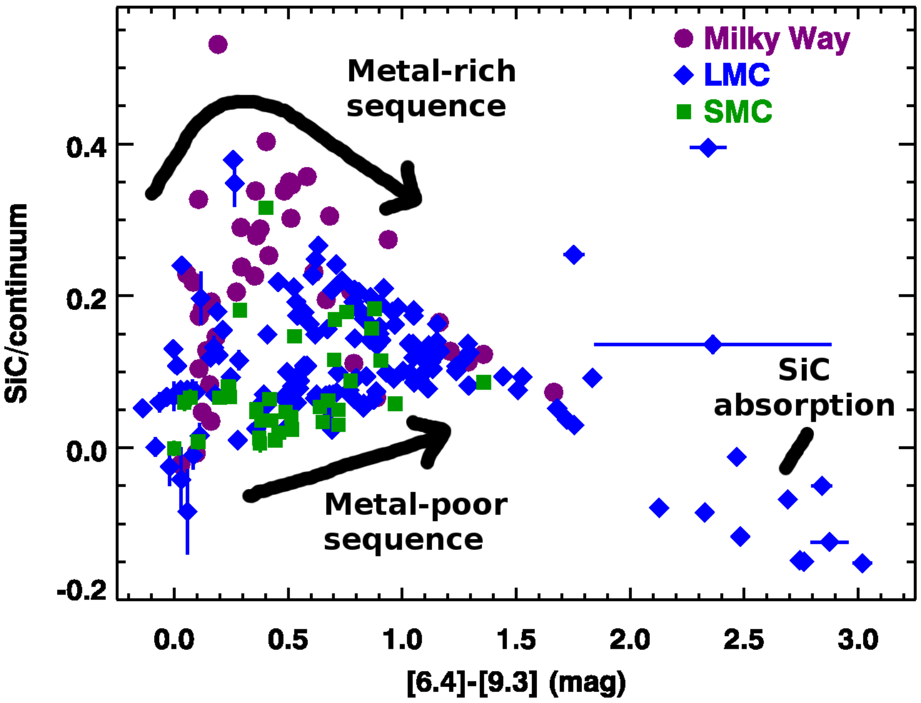
SiC dust emission strength at 11.3 μm

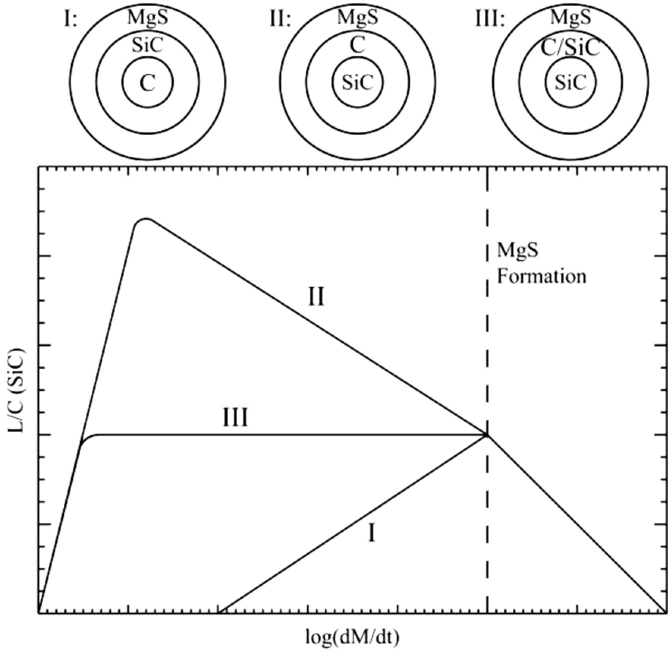
The “metallicity” plot



- Left: Comparing Milky Way, LMC, and SMC
  - shows regions populated by different metallicities
- Right: Just the Milky Way
  - shows regions populated by different variability types
- SRbs show the same mean galactic scale height as Miras

SiC in carbon stars



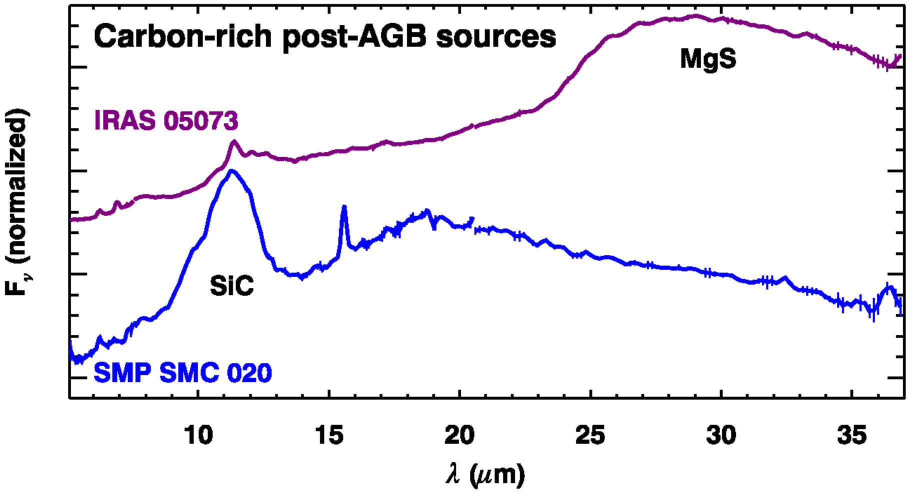


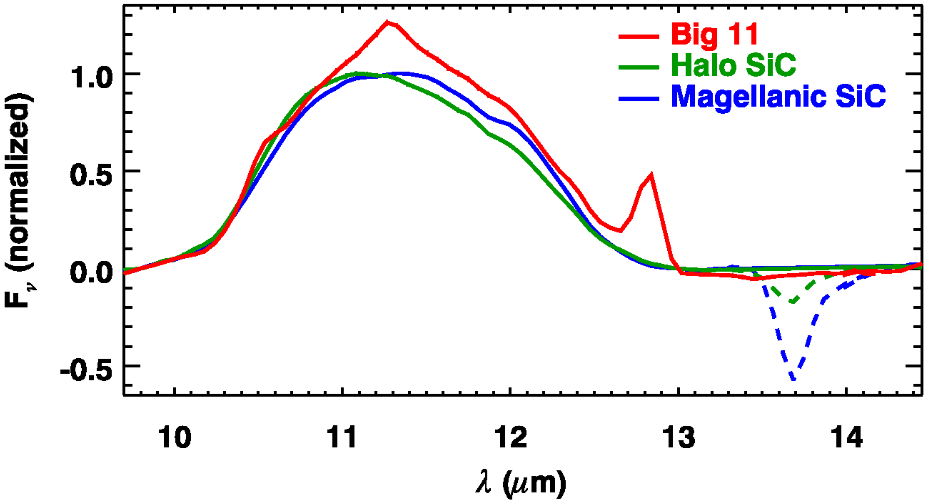
- Left: Two sequences observed ***(Sloan et al. 2014c, in prep.)***
- Right: May be tracks I and II from ***Leisenring et al. (2008)***

  I – metal-poor – amorphous carbon condenses first

  II – metal-rich – SiC condenses first
- Coating by am C and MgS reduces strength of SiC – maybe

Coatings, SiC, and MgS





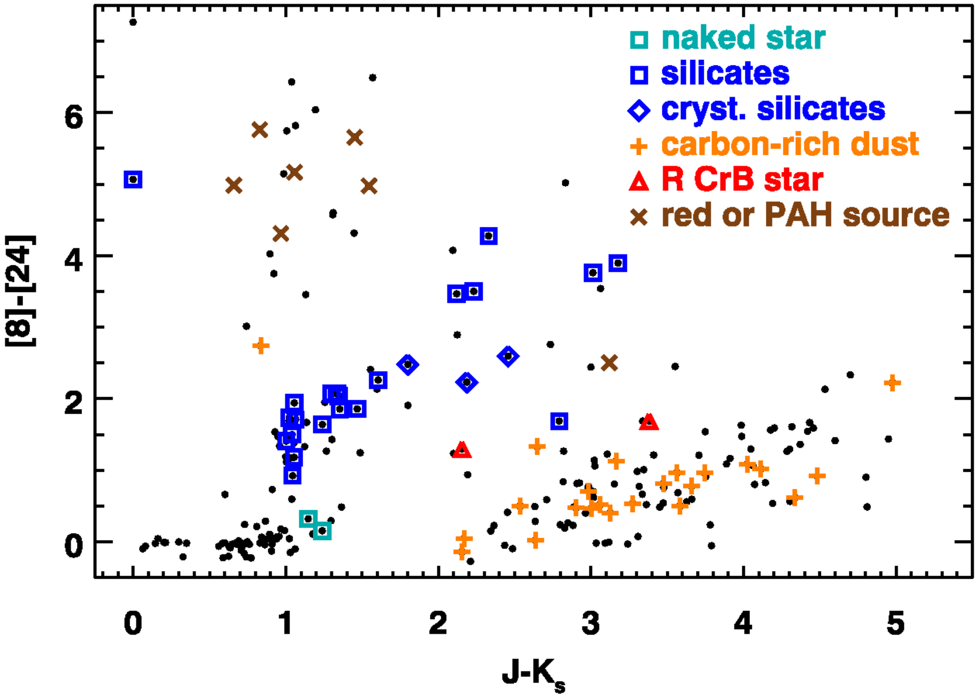
26-30 μm feature from MgS (Goebel & Moseley 1985; Hony et al. 2001)

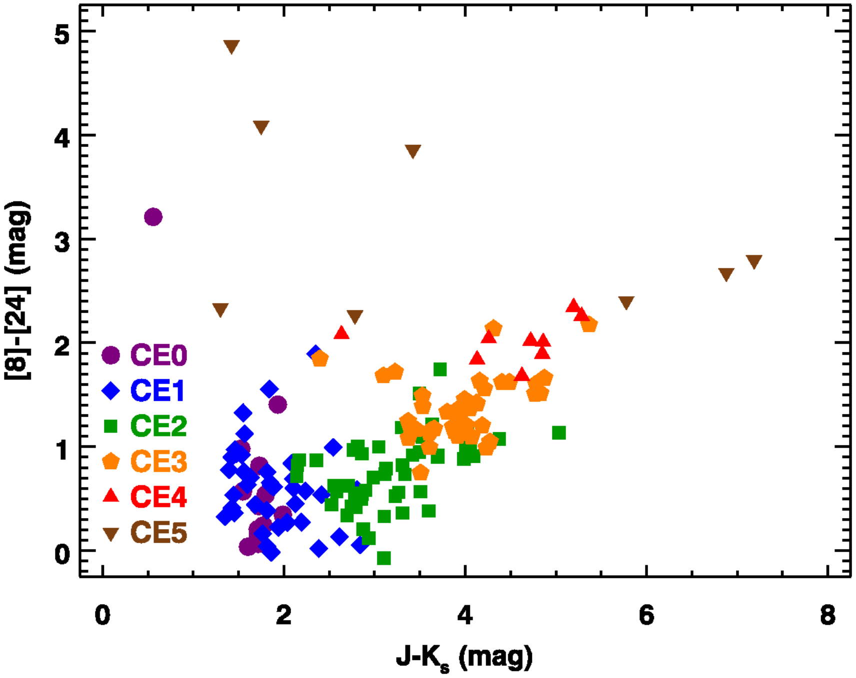
- Strength of feature in some post-AGB objects and PNe violates abundance limits (Zhang et al. 2009)
- Lombaert et al. (2012) – MgS coatings solve the problem

Magellanic PNe can show strong SiC-like emission (*Bernard-Salas 2006*)

- The “Big 11 feature” is indeed SiC ***(Sloan et al. 2014a, submitted)***
- SiC coatings solve the abundance difficulties for metal-poor stars

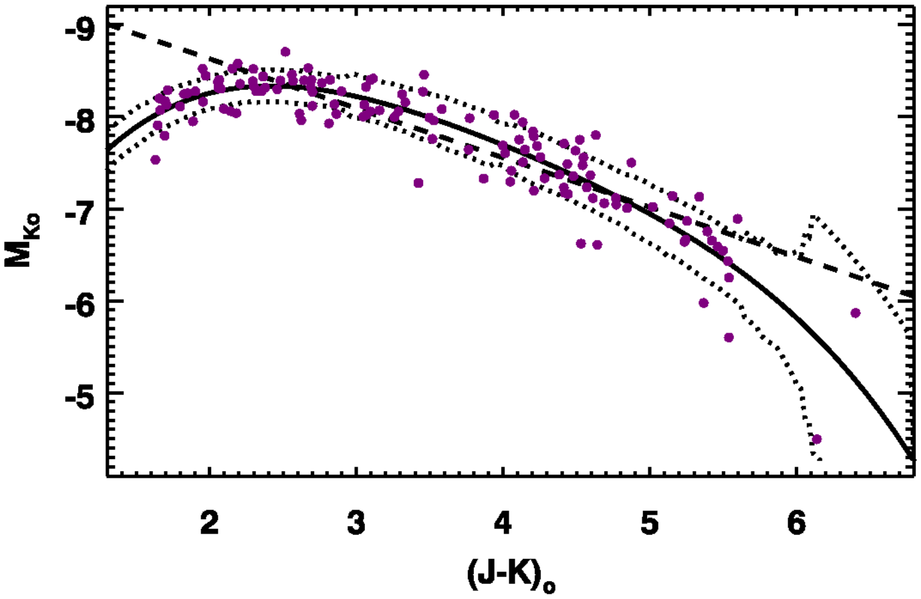
Infrared color-color space

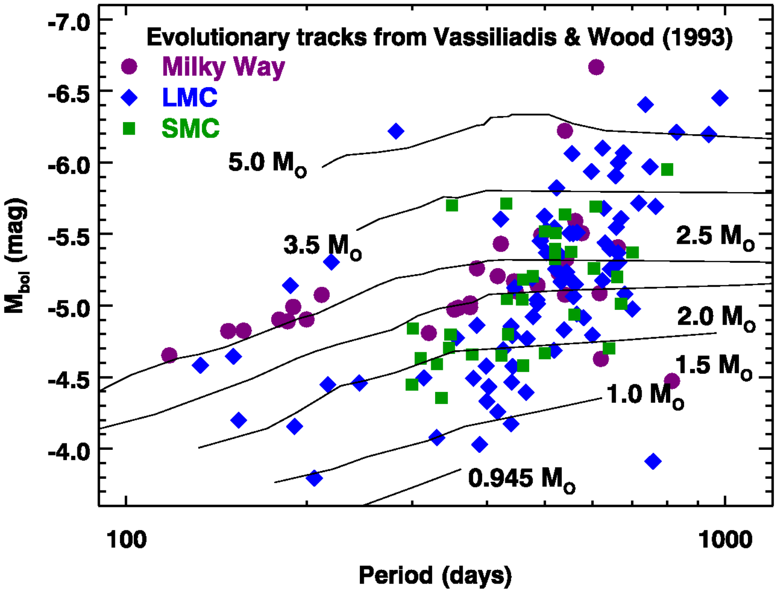




- Left: MSX SMC sample, with IRS sources color-coded
- Right: Galactic sample, color-coded by [6.4]–[9.3] color
- J–K and [8]–[24] measure dust at different temperatures

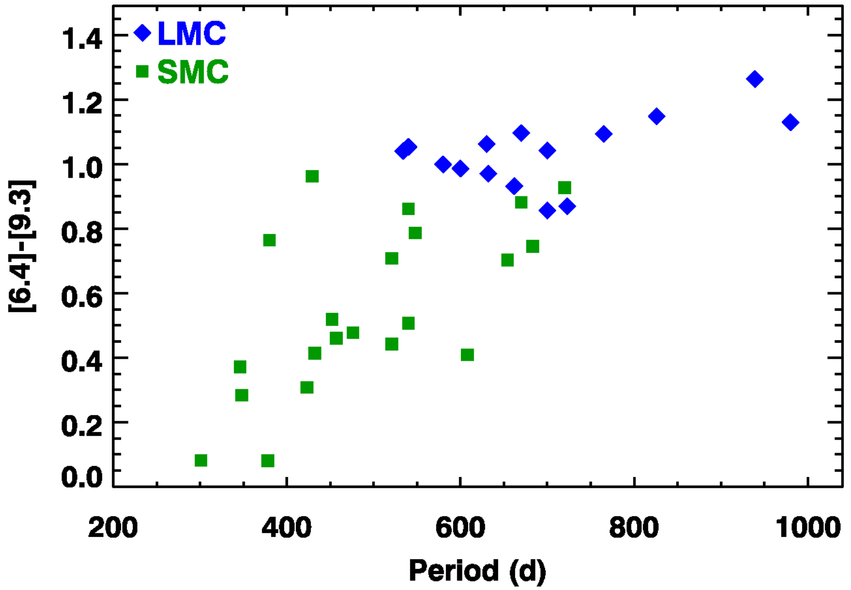
Distances for the SWS sample





- Carbon stars have a well-defined color-mag relation at J–K
  - Calibrated for Galaxy using SAAO mean magnitudes (Whitelock et al. 2006; Menzies et al. 2006)
  - and the SAAO P-L relation and bolometric correction
- J–K distances allow us to compare the P-L relation among galaxies

Spectral samples and bias



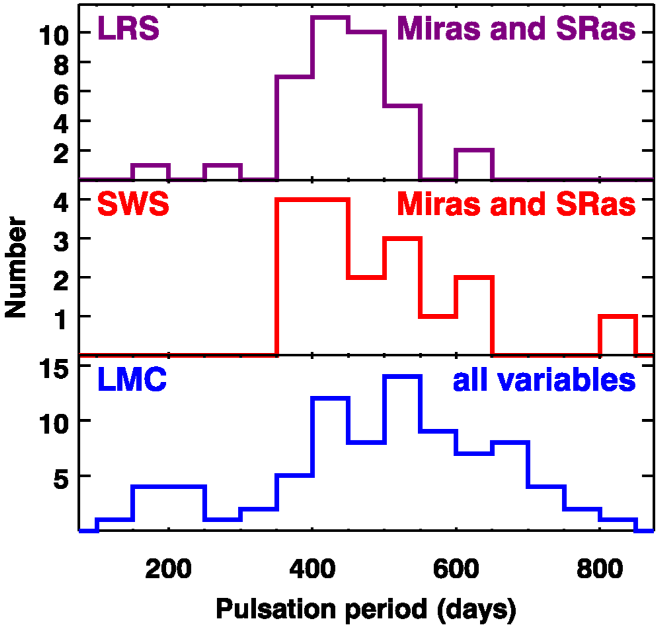
van Loon et al. (2008)

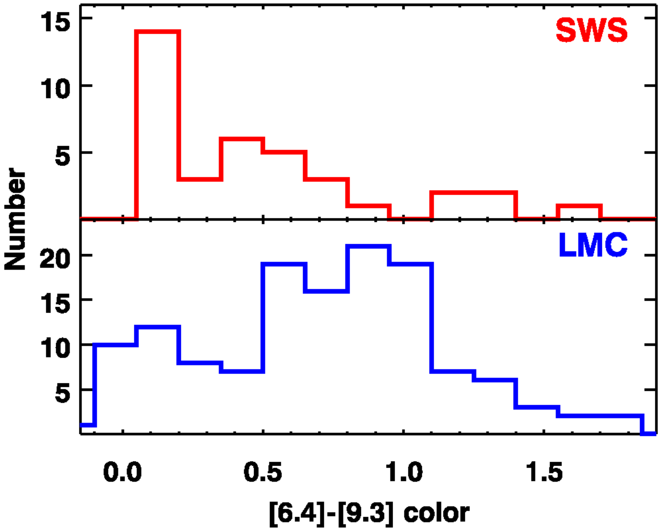
- 3-µm spectra of Magellanic carbon stars
- In their sample, SMC showed less dust than LMC

But comparing periods shows why ***(Sloan et al. 2014c, in prep.)***

- ***Unbiased spectroscopic samples are rare***
- Our *Spitzer* samples also suffer from this

Biases in the Galactic sample





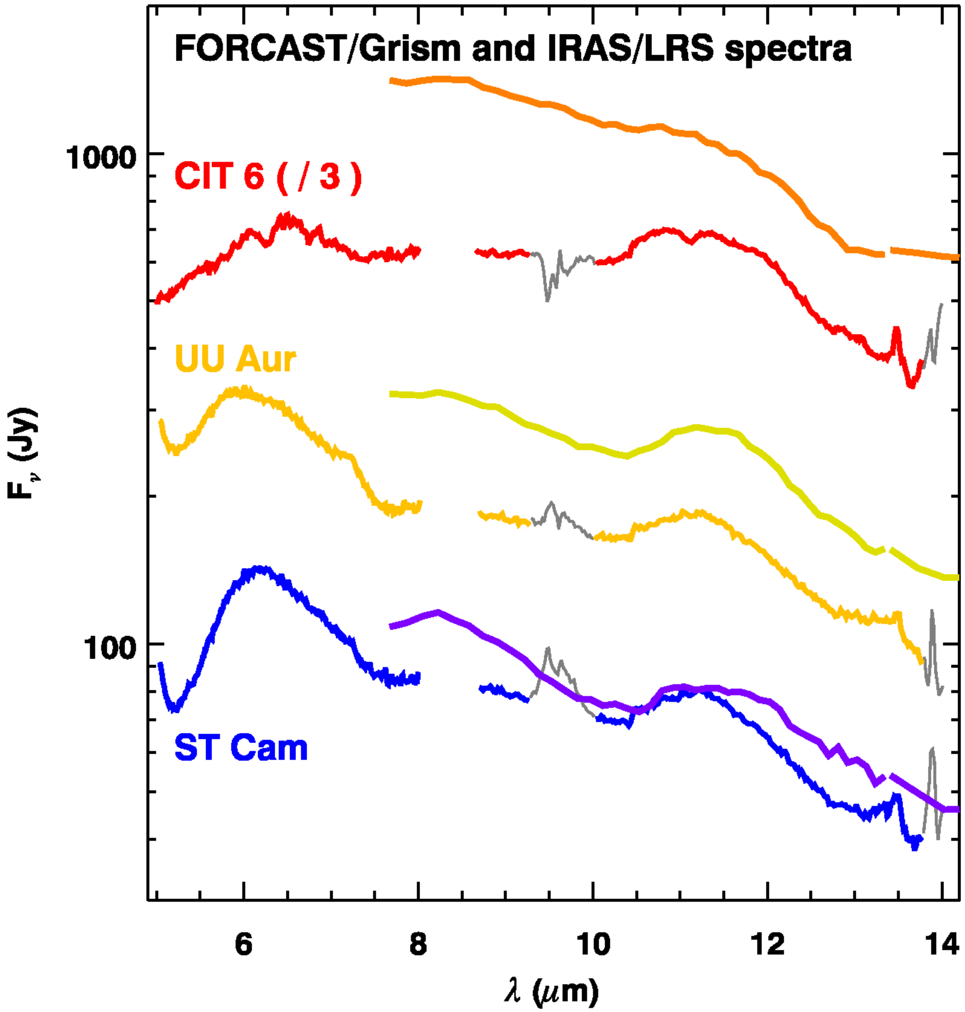
Galactic metal-rich control sample:

- **IRAS/LRS** – 538 spectra classed 4n (LRS Atlas 1986)
  - matched ***96*** matched with GCVS ***(Sloan et al. 1998)***
- **ISO/SWS** – **42** in control sample ***(Leisenring et al. 2008; Sloan et al. 2014b, in prep.)***

- Compared to LMC, the Galactic sample selects against
  - Long pulsation periods
  - Dust-embedded sources
  - Overtone pulsators
- Our Cycle 1 SOFIA/FORCAST grism program was designed to rectify this

Between canceled flights and the shutdown, we only got 3 of 40 objects – with no carryover to Cycle 2

FORCAST/Grism spectra



- These data are preliminary, especially G3
- Ozone is always a challenge
- With a better calibration, we can
  - Measure [6.4] – [9.3]
  - Model and estimate the acetylene absorption at 7.5 µm
  - Measure the SiC strength and profile
- We just need a sample!