

The image is a composite of two astronomical observations of a star's surface. The top-left portion shows a solar flare, characterized by a bright, turbulent, and filamentary structure. The bottom-right portion shows a sunspot, which is a dark, circular region with a central umbra and a surrounding penumbra. The background is a textured, greyish-blue surface representing the star's photosphere.

How stars make dust

AAVSO Annual Meeting
Nantucket MA
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Mira Variables are Dust Factories for the galaxy

- They have IR excesses at 10-13 μ
- They have high-momentum winds possible only with dust

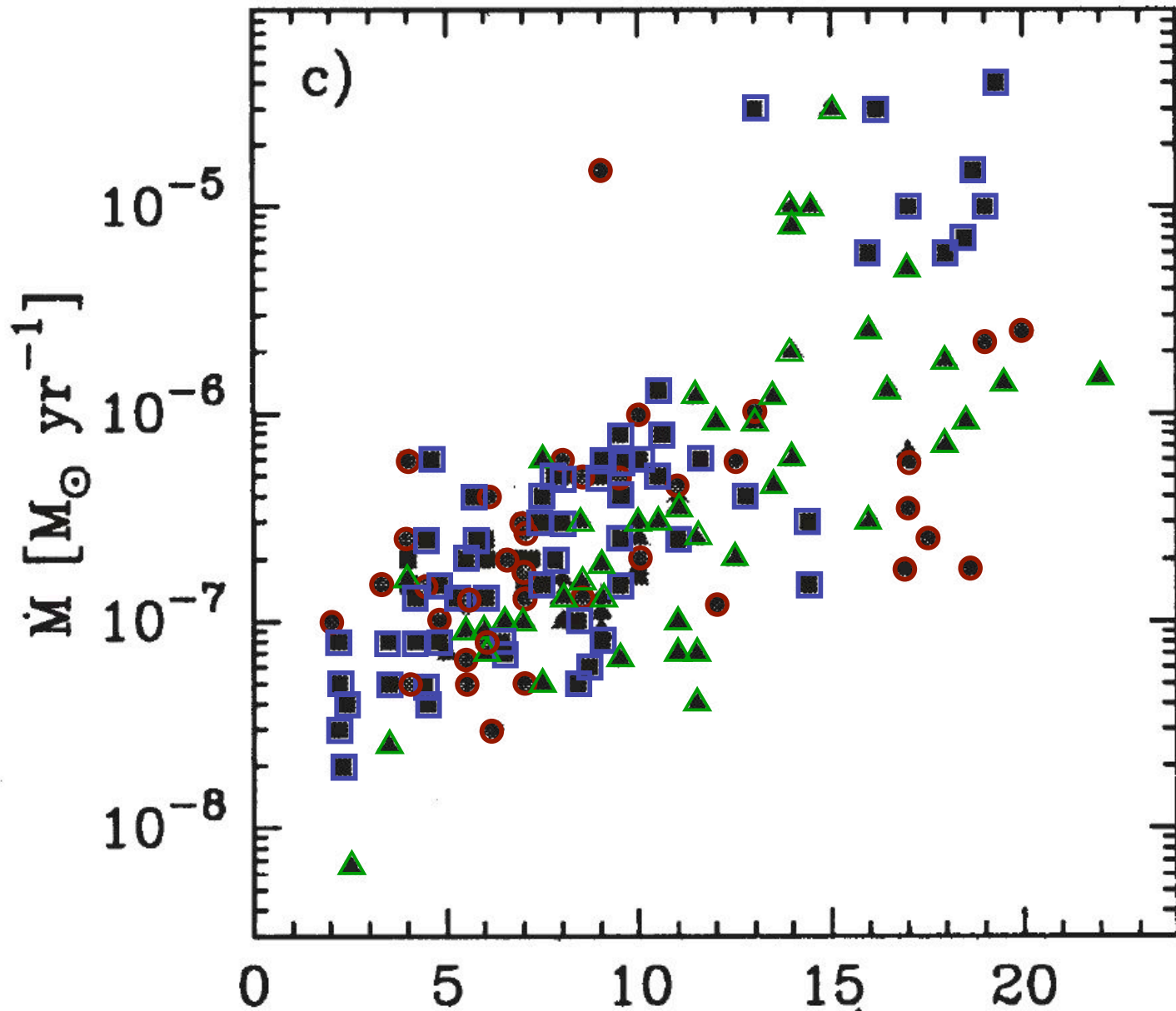
2006: A problem!

- Models for dusty winds from Carbon stars ($C > O$) appeared OK (although they required high C/O and large luminosity) but
- Same codes applied to M and S stars predicted no winds could be driven.

Discovered independently by S. Höfner and P. Woitke

Mass
loss rate
vs
expansion
velocity -
the same
for M, S,
and C
stars !?!?!

- M
- S
- △ C



From Ramstedt et al 2006

About the chemistry

- In equilibrium below about 4000K, C and O prefer to be CO
- For M stars, $O > C$ and O is left over
- For C stars, $C > O$ and C is left over
- For S stars, $C = O$ and nothing is left over

Dust forms from what is left after CO forms

A close-up photograph of numerous leaves covered in a layer of white frost. The leaves are in various shades of brown and tan, and the frost is most prominent along the edges and veins. The background is a dense field of these frost-covered leaves.

About the chemistry

- Observed: M, S, and C stars have similar, dusty winds.

How do the S stars do it?

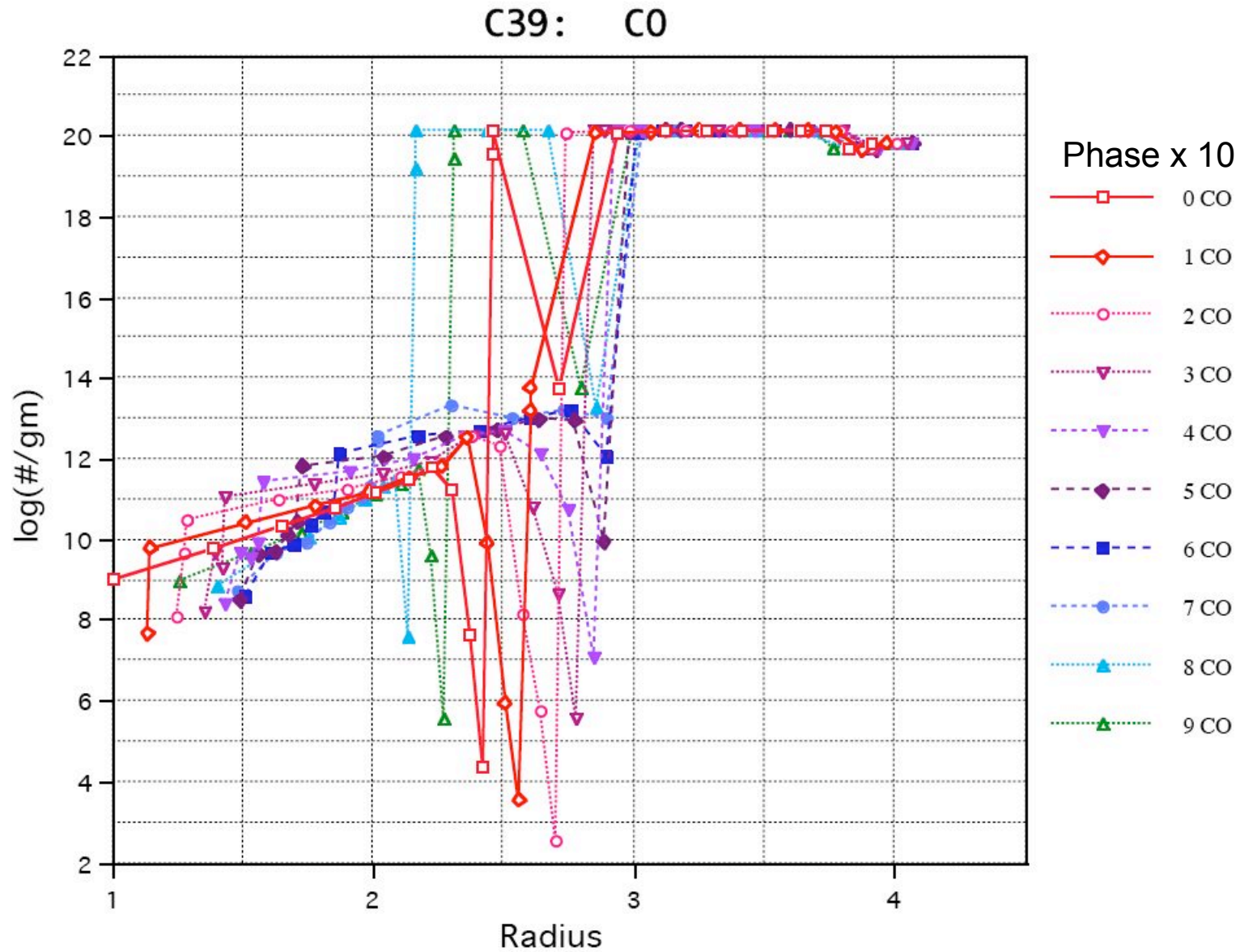
What does that mean for M and C stars?

Shocks allow S stars to form dust

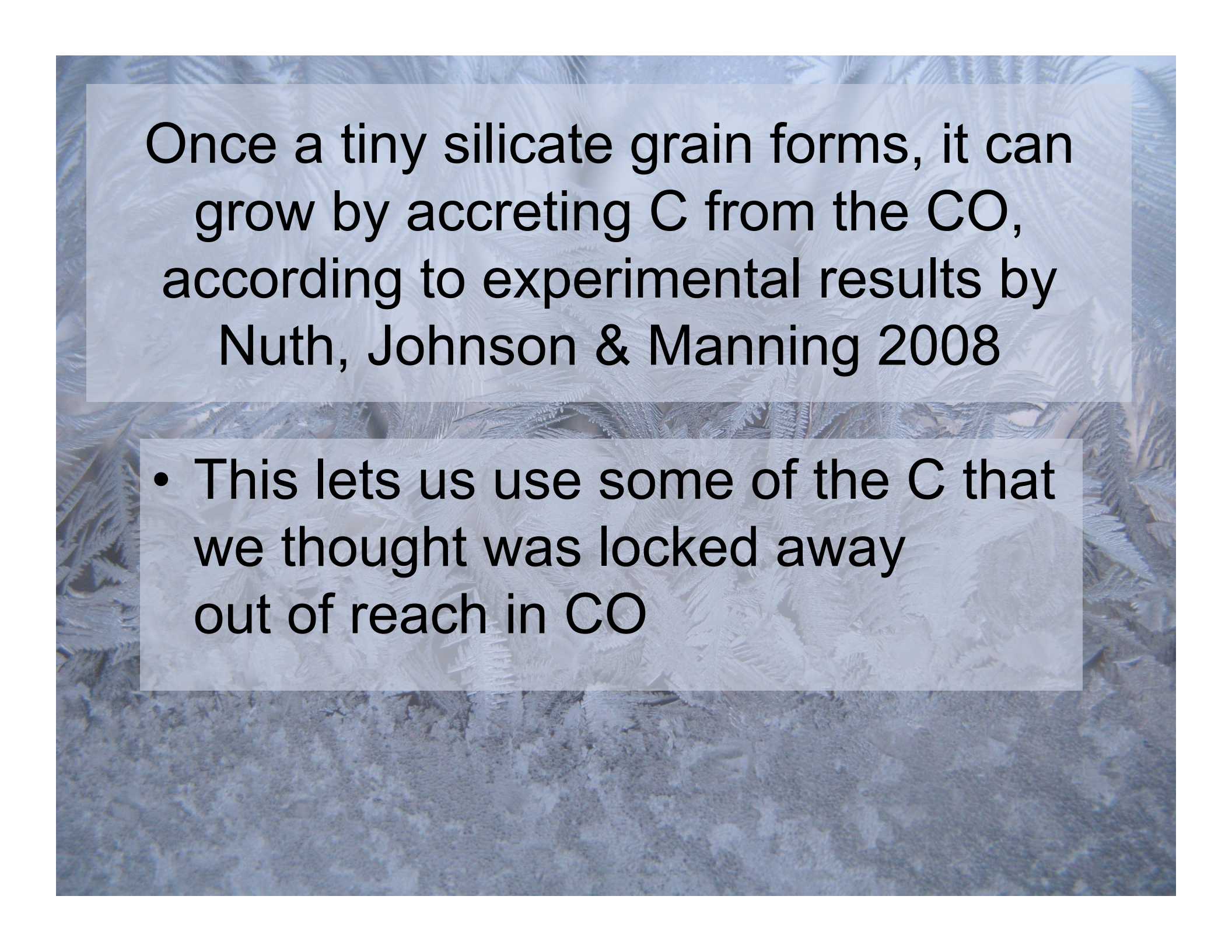
- In pulsating stars (the ones with dusty winds, the Miras), shocks break up H_2 and CO.

Therefore:

We have extra O and some C in M stars, extra C and some O in C stars, and some C and some O in S stars, to make dust from C_2H_2 , Al_2O_3 , and SiO.



Calculation by James Pierce 2008; model does not include dust



Once a tiny silicate grain forms, it can grow by accreting C from the CO, according to experimental results by Nuth, Johnson & Manning 2008

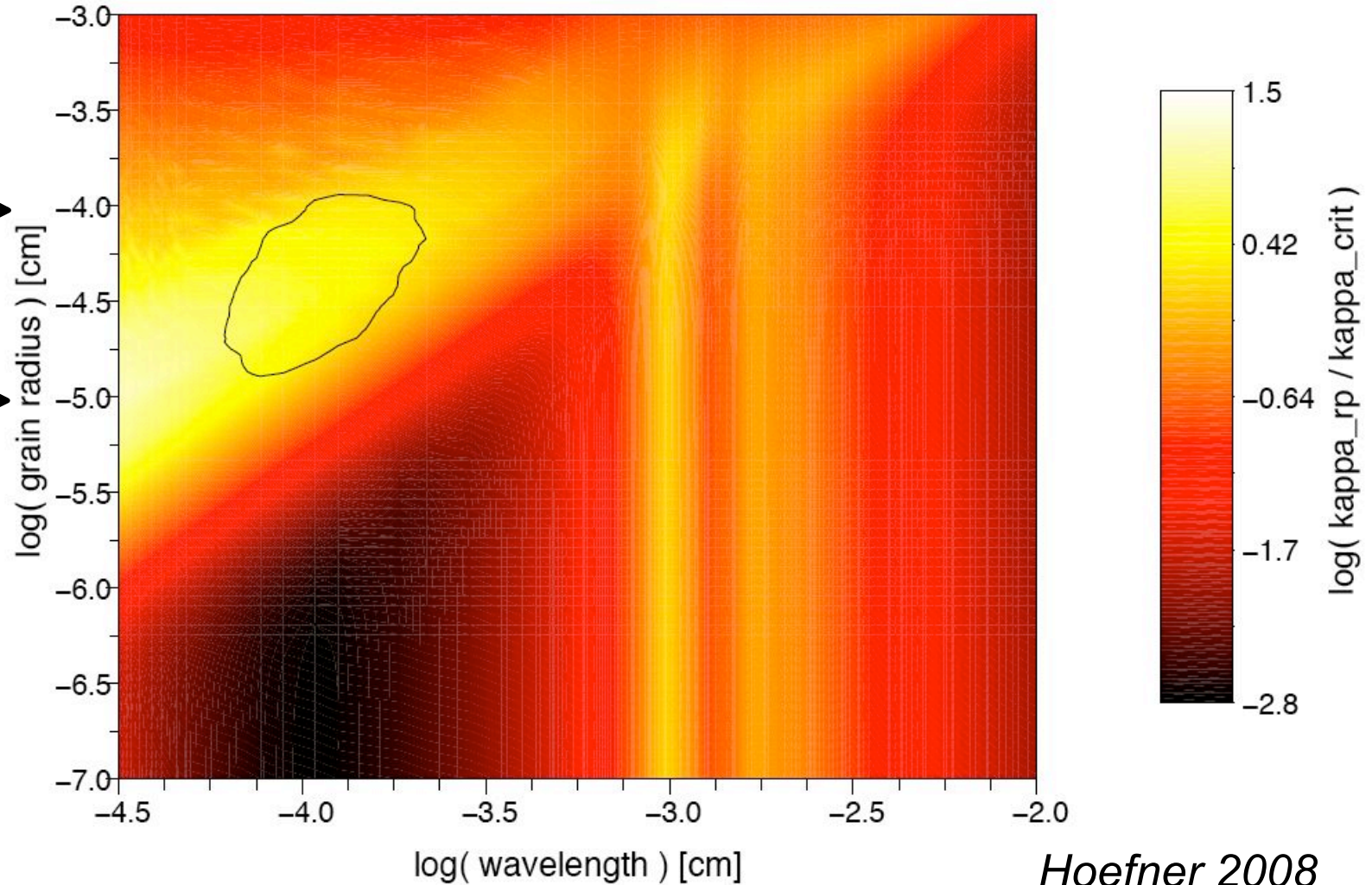
- This lets us use some of the C that we thought was locked away out of reach in CO

This is important because small silicate grains are not opaque enough to drive material off these stars

1.0 μ →

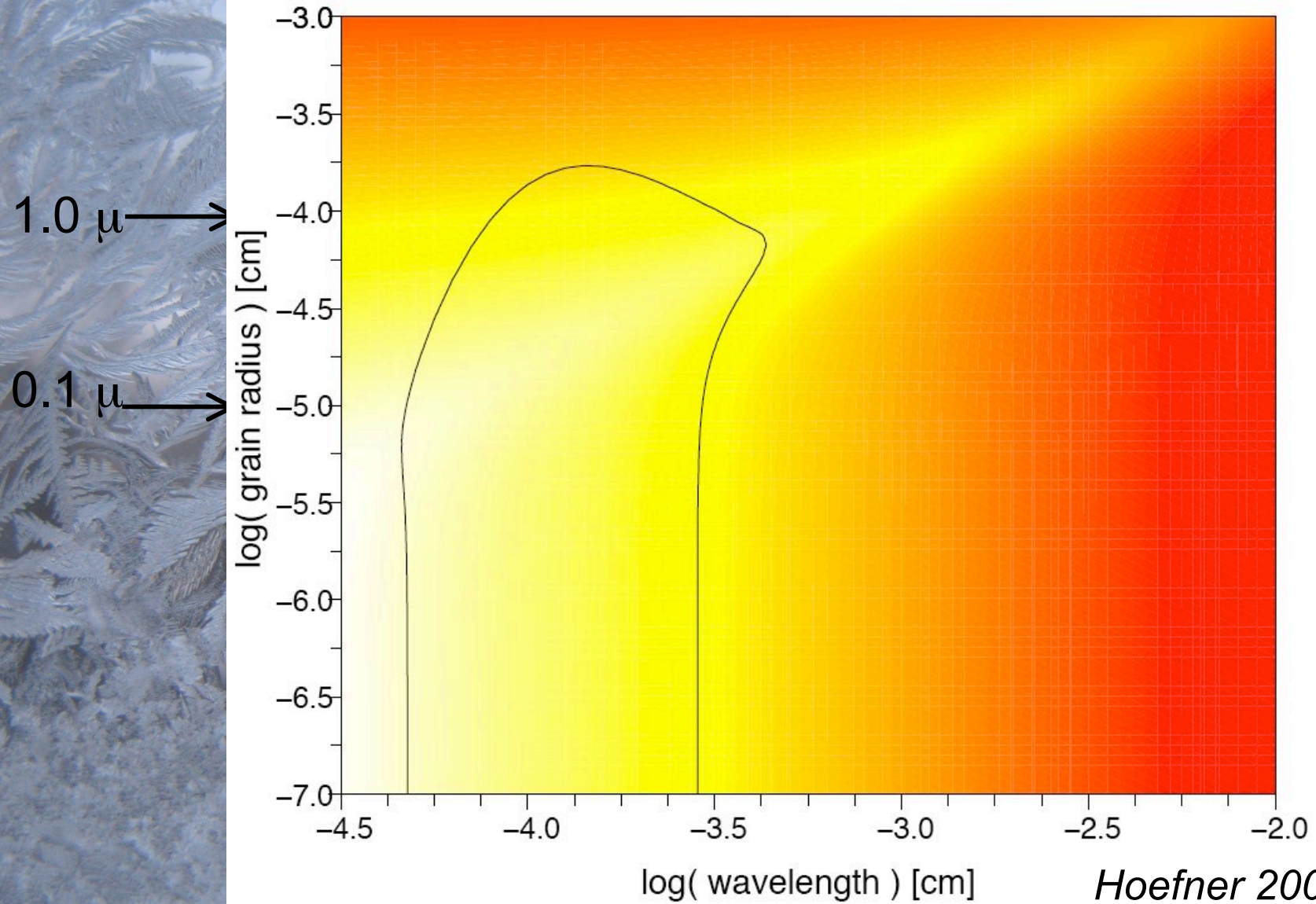
0.1 μ →

*0.1 m
is
about
1000
atoms*



Hoefner 2008

Small carbon grains are able to drive mass loss



Hoefner 2008



The models for C* that didn't work for M and S stars assumed

1. Standard nucleation theory (SNT)
2. Equilibrium chemistry in the grain-forming region
3. Grain opacity for absorption (not scattering) - carbon grains are black

Changing 3 may suffice, but in the meantime we learned more about 1 and 2.



Near saturation, only very large solids grow
- so how does the process get started??


- Two options:
- Grow on an existing solid, or wait until the vapor is super-saturated.

IN STARS ... SUPERSATURATION

- The higher the supersaturation, the smaller the particles that can grow.
- There is a critical cluster size, with $N=N^*$ atoms, that is stable.
- Clusters with $N>N^*$ grow. Clusters with $N<N^*$ are more likely to shrink than grow.
- An equilibrium for $N<N^*$ is possible, with more clusters of size N than of size $N+1$.

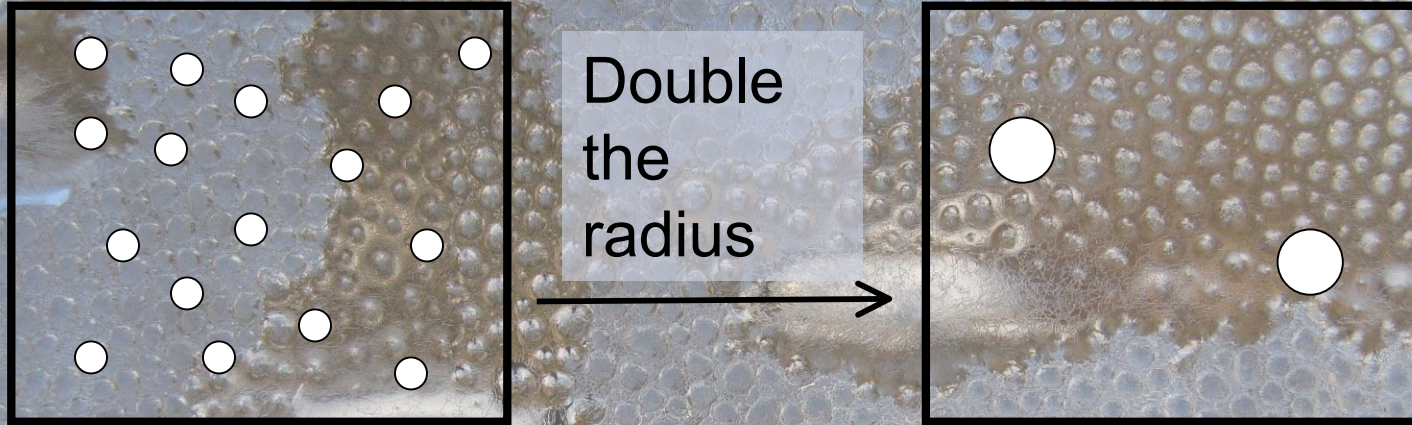
Standard nucleation theory

- Compute N^* from surface tension
- Assume $N < N^*$ are in equilibrium
- Higher supersaturation (usually, faster cooling) $\Rightarrow N^*$ is smaller
- Smaller N^* \Rightarrow more grains get to N^*
- $N \geq N^*$ grow until the material is all in grains.
- Higher supersaturation \rightarrow more, smaller grains

A micrograph showing a complex, dendritic structure of metal grains, likely formed during slow cooling. The grains are light blue and have a feathery, branching appearance. A semi-transparent grey box in the upper right corner contains text explaining the relationship between cooling rate and grain size.

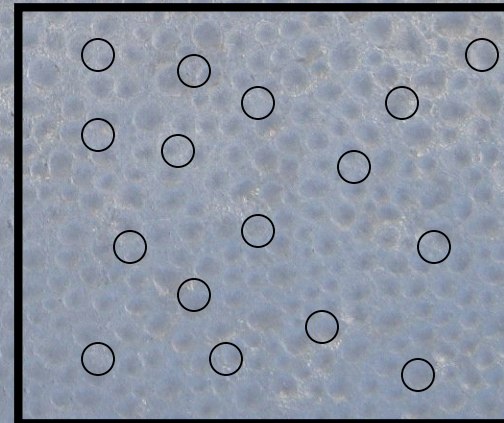
Slow cooling
=> slight supersaturation
=> fewer, bigger grains

How to get high opacity from the grains:
there is an optimal size

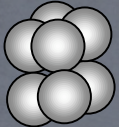


If they are opaque, many small grains intercept more light than a few large ones with the same total mass.

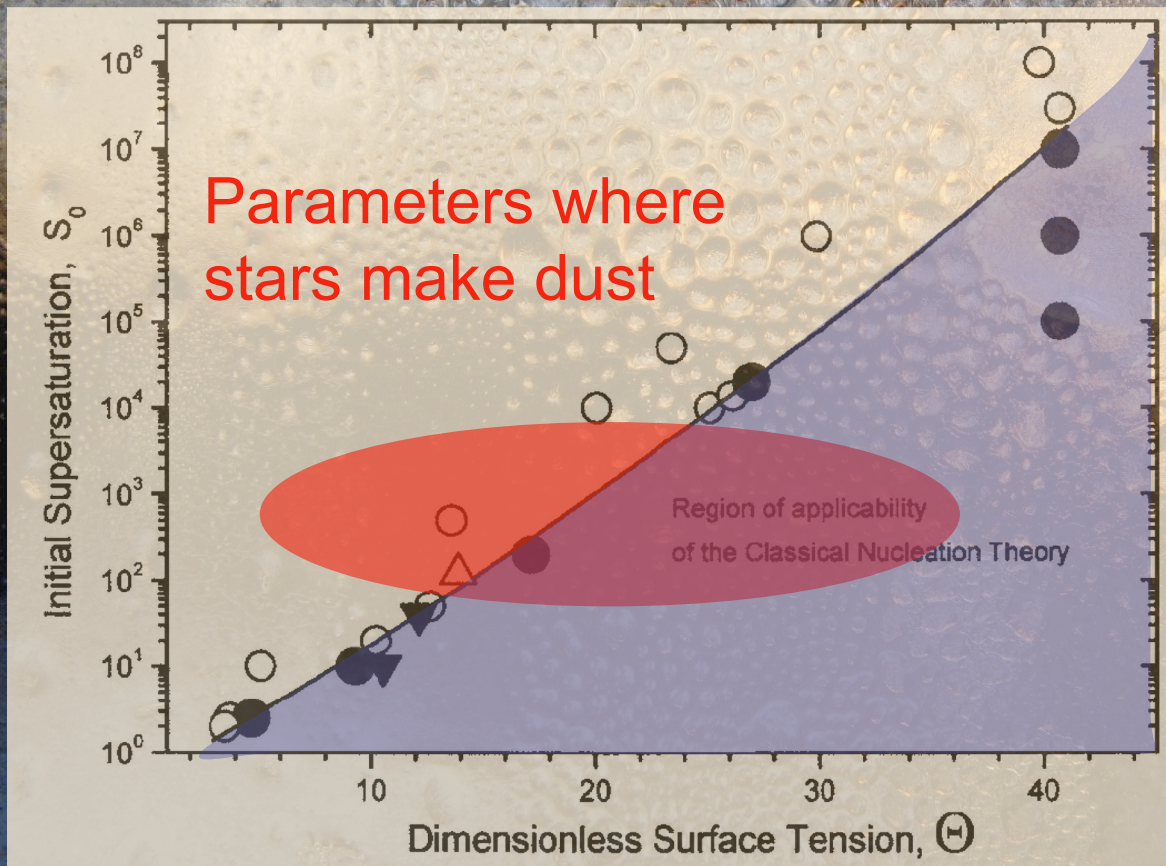
However, if the grains are too small, they will be transparent and intercept less light.



Problems with SNT for stars

- Calculations make use of macroscopic properties - surface tension etc. 
- In stars, N^* turns out to be ≤ 10 or so - lumpy & all atoms on the surface
- Also, at high supersaturation, $N < N^*$ don't achieve equilibrium concentrations

Chesnokov et al 2007 model for nucleation and growth at high supersaturation



Region where current theory is OK.

$$\Theta = \Delta G/kT \text{ where } G = \text{Gibbs Free Energy}$$



The problem was:

Not enough dust opacity in M stars and no dust expected in S stars, but M, S, and C stars have similar winds

We found 3 solutions to the problem:

1. Big silicate grains work via scattering in M stars.
2. Non-equilibrium chemistry => more C and O available to make grains.
3. Silicate and carbon grains can steal C from CO.

And also learned that the underlying Standard Nucleation Theory has some inconsistencies when applied to stars.



*Background photos taken by
L.A.W in 2007 © 2008*