The Life Cycle of Dust in the Diffuse ISM

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- ***Evolution of Solid Material in the ISM***
- ***Implications for Dust in Galaxies with Near-Solar Metallicity***
- ***Implications for Dust in Low-Metallicity Galaxies***
- ***Some Issues...***

Where Does Solid material in the ISM Come From?

Stellar Sources: Well-Established

- *AGB stars with $O > C$*
- *AGB stars with $O < C$ (“carbon stars”)*
- *Core-Collapse Supernovae*
- *Novae*
- *Winds from Wolf-Rayet stars*
- *exotica...*

What Happens to Solid Material in the ISM?

Sputtering...

- **Substantial erosion by sputtering in gas shock-heated to** $T \gtrsim 10^{5.5}\,\mathrm{K}$
  $v_s \gtrsim 180\,\mathrm{km\,s^{-1}}$ (mainly SN blastwaves)

- ***Estimated lifetime of*** $\sim$ ***0.2μm grain in the Milky Way:*** $\tau_{\mathrm{lifetime}} \approx 10^{8.5\pm0.2}\,\mathrm{yr}$.
  Many papers, e.g.,
  M. J. Barlow & J. Silk (1977),
  M. J. Barlow (1978),
  B. T. Draine & E. E. Salpeter (1979),
  C. G. Seab & J. M. Shull (1983),
  A. P. Jones et al. (1994),
  M. Bocchio et al. (2014),
  S. Zhukovska et al. (2016),
  ....

- Multiphase ISM and correlated supernovae: complications, but
  general agreement that dust lifetime $\tau_{\mathrm{lifetime}} < 10^9$ ***yr in solar neighborhood.***

What Else Happens to Solid Material in the ISM?

Grain-Grain Collisions

Physics

- low-speed :
  coagulation (growth)

- higher speed:
  - ***cratering***
    (removal of some material)
  - ***fragmentation***
    (shatter into smaller pieces)

- very high speed ($\Delta v \gtrsim 10\,\mathrm{km\,s^{-1}}$):
  vaporization

- ***Physics of grain-grain collisions:***
  Important, complicated,
  but poorly understood

Where?

- $v_s \lesssim 100\,\mathrm{km\,s^{-1}}$ ***Shock Waves:***
  - sputtering not important (except ices)
  - grain-grain collisions with $\Delta v \gtrsim 0.1 v_s$ can affect $\sim$1-10% of the grain mass passing through the shock
- ***MHD turbulence in ISM:***
  - can "pump" $a \gtrsim 0.1\mu\mathrm{m}$ grains to gyrovelocities $v \gtrsim 1\,\mathrm{km\,s^{-1}}$ in CNM and WNM (H. Yan et al. 2004)
  - fast grain-grain collisions: large grains shatter $\rightarrow$ many small grains (H. Yan et al. 2004; H. Hirashita 2010).

Coagulation and fragmentation can regulate grain size distribution in ISM

Example: Consider Solid Fe in the ISM

- ***"Grain Lifetime"*** $\equiv$ time for atom in solid to return to gas as result of sputtering or vaporization in ISM

$$\tau_{\rm lifetime} \approx 3\times 10^8\,{\rm yr}$$

- ***ISM "turnover time"***

$$\tau_{\rm ISM} \approx \frac{M_{\rm ISM}}{\rm SFR} \approx \frac{5\times 10^9 M_\odot}{1.5 M_\odot\,{\rm yr}^{-1}} \approx 3\times 10^9\,{\rm yr}$$

- Injection from stars: perhaps $\sim$50% of Fe in solid form
- **If no growth of solid material in ISM**, then in steady-state *(very simplistic...)*

$$\begin{aligned}
\text{removal of solid Fe} &\approx \text{injection of solid Fe}\\
f_{\rm Fe\,solid}\times\left(\tau_{\rm lifetime}^{-1}+\tau_{\rm ISM}^{-1}\right) &\approx 0.5\times\tau_{\rm ISM}^{-1}\\
f_{\rm Fe\,solid} &\approx \frac{0.5}{1+\tau_{\rm ISM}/\tau_{\rm lifetime}} \approx \frac{0.5}{1+10} \approx 0.05
\end{aligned}$$

- But: we observe $f_{\rm Fe\,solid} > 0.90$ i.e., >90% of Fe is "depleted" (missing from gas)

Ergo: MUST be substantial grain growth in the ISM

(e.g., M. J. Barlow 1978; B. T. Draine & E. E. Salpeter 1979; E. Dwek & J. M. Scalo 1979, 1980; E. Dwek 2016, ...).

Growth of Interstellar Grains

- ***Timescale for "accretion" from gas.***

$\Sigma_d \;\equiv\;$ dust geometric cross section per H. In Milky Way: $\Sigma_d \gtrsim 10^{-21}\,\mathrm{cm}^2$.

$v \;\equiv\;$ mean speed of gas atoms relative to grain.

$$\tau_{\rm accretion} \;=\; \frac{1}{\langle n_{\rm H}\rangle_{\rm m}\,\Sigma_d\,v} \qquad\qquad \langle n_{\rm H}\rangle_{\rm m} \;\approx\; 0.5\times 0.3\,\mathrm{cm}^{-3} + 0.5\times 30\,\mathrm{cm}^{-3}$$

$$\approx\; \frac{1}{15\,\mathrm{cm}^{-3}\times 10^{-21}\,\mathrm{cm}^2\times 1\,\mathrm{km\,s}^{-1}} \;\approx\; \mathbf{2\times 10^7\,yr} \;\ll\; \tau_{\rm lifetime}$$

- ***"Balance" equation for*** $f_{\rm Fe\,solid}$:

$$\text{removal of solid Fe} \;\approx\; \text{addition of solid Fe}$$

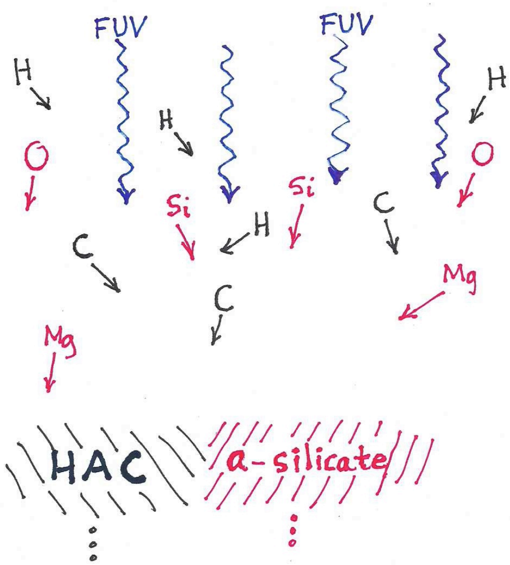
$$f_{\rm Fe\,solid}\times\left(\tau_{\rm lifetime}^{-1}+\tau_{\rm ISM}^{-1}\right) \;\approx\; 0.5\times\tau_{\rm ISM}^{-1} + \left(1-f_{\rm Fe\,solid}\right)\times\tau_{\rm accretion}^{-1}$$

$$f_{\rm Fe\,solid} \approx \frac{0.5+\tau_{\rm ISM}/\tau_{\rm accretion}}{1+\tau_{\rm ISM}/\tau_{\rm lifetime}+\tau_{\rm ISM}/\tau_{\rm accretion}} \;\approx\; \frac{0.5+150}{1+10+150} \;\approx\; 0.93$$

$\tau_{\rm accretion} \ll \tau_{\rm lifetime}$: ***can maintain high levels of "depletion".***

Composition of Interstellar Grains

- In diffuse ISM, "refractory elements" (C, Mg, Al, Si, Fe, ...) accrete
- UV photodesorption: remove species that are ***not UV-tolerant*** (e.g., ices)
- *UV photolysis is FAST:*
  Each atom in grain: electronic excitation every $\sim 10^{11}\,\mathrm{sec} = 3000\,\mathrm{yr}$.
- UV photolysis: ***evolve to UV-tolerant material(s)***
  (e.g., ***hydrogenated amorphous carbon*** (HAC), ***amorphous silicate***).



add C,H to HAC, add Mg,Fe,Si,O to amorphous-silicate

Dust Composition in the Milky Way: Some Key Points

- *A small fraction ($\lesssim$ 10%?) of interstellar dust is "stardust"*

- **Most Milky Way dust material was *grown in the ISM***

- **Larger a $\gtrsim$ 0.05μ grains are expected to contain *both amorphous silicate and hydrocarbon materials.***

- **Polarization predictions:**
  - ***p(3.4μm)/p(V)*** *?*
  - ***p(10μm)/p(V)*** *?*
  - ***p(FIR)/p(V)*** *Confirmed*

- **Smallest grains: fragmentation products from grain-grain collisions some of the fragments must be the observed *PAHs*.**

Evidence of Dust Evolution in Diffuse ISM: Regional Variations

- **Gas-Phase Abundances (*"Depletions"*)**

- ***Extinction curves***
  (variations in size distribution and/or composition).

- ***3.4μm feature:***
  - **Stronger in H I clouds (hydrogenation?)**
  - **Weaker in H_2 clouds (dehydrogenation/aromatization?)**

- ***Spectrum of 3.4μm emission* from nanoparticles**

- ***Deuteration of aliphatic hydrocarbons***

Dust in Other ∼Solar-Metallicity Star-Forming Galaxies

- Expect to often have

$$t_{\rm accretion} < t_{\rm lifetime} < t_{\rm ISM}$$

as in Milky Way.

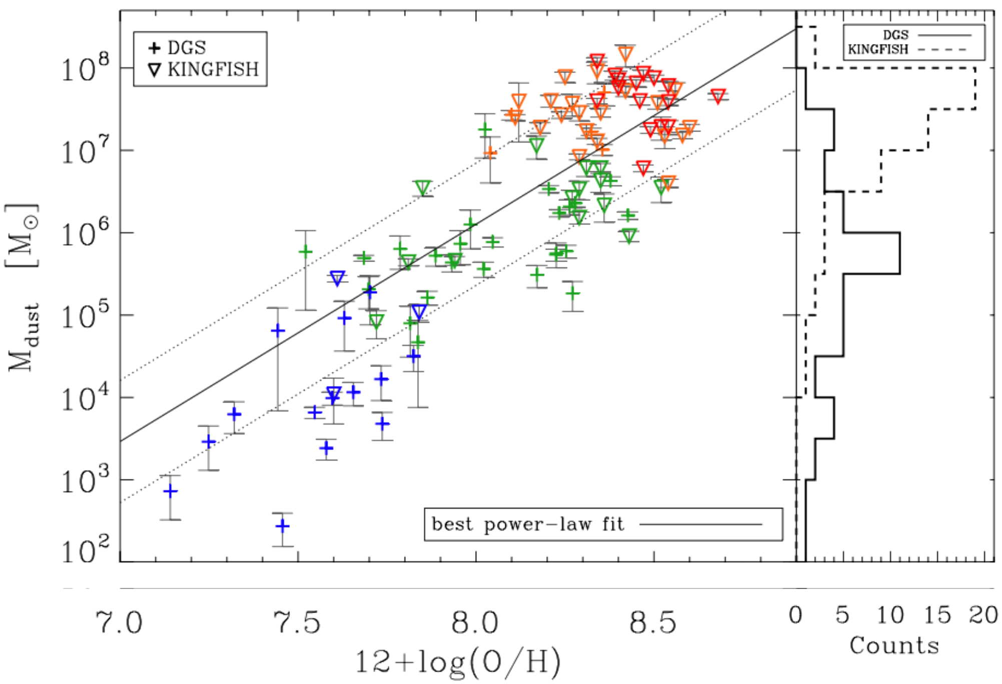
- Therefore: expect most dust material to be ***grown in the ISM***.

- Elemental abundance ratios (e.g., Mg:Si, Si:O) will be similar to MW
Physics of UV photolysis will be the same
Expect dust composition to be similar to Milky Way dust
(i.e., amorphous silicates, hydrogenated amorphous carbon...).

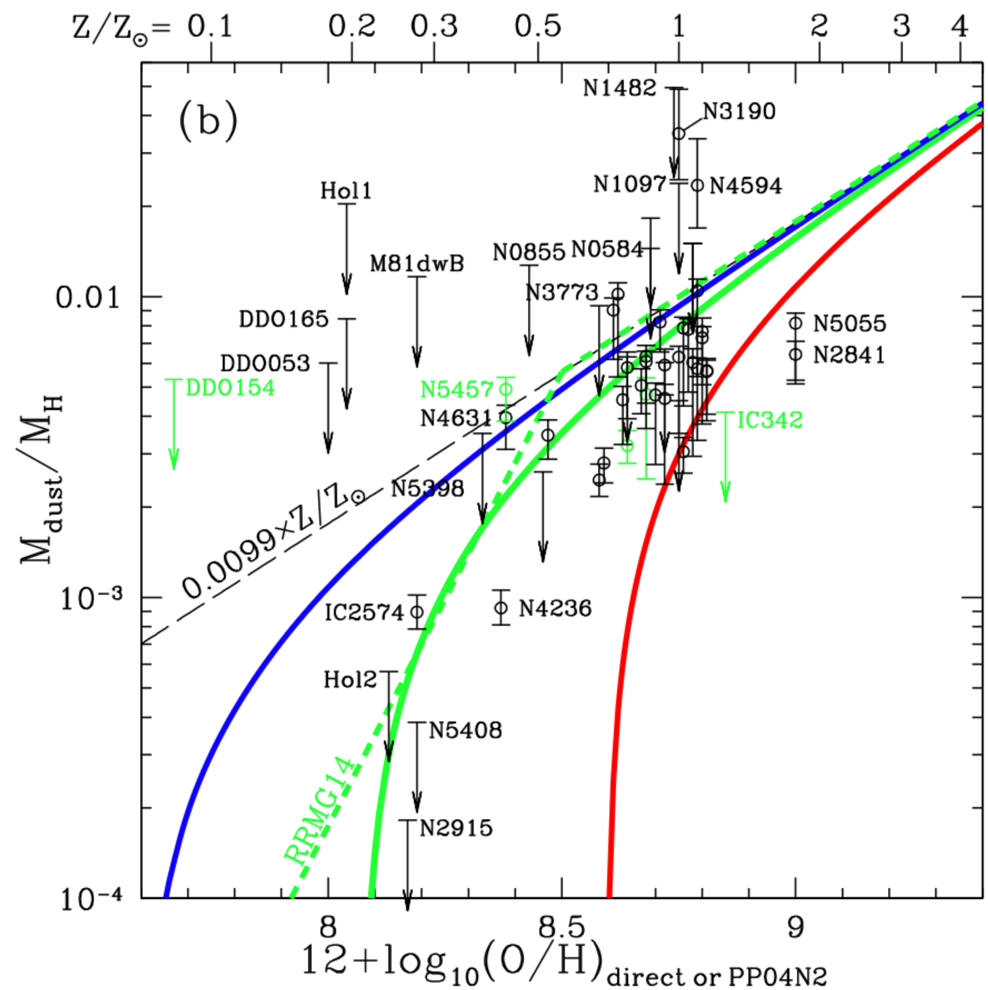
- If physics of grain collisions (in shocks, MHD turbulence) is similar, then even grain size distribution (extinction curve) may be similar....

Dust Abundance in Low-Metallicity Galaxies

- **$Z \approx Z_\odot$ galaxies have $Z_{\rm dust} \approx Z/3$**
- **$Z \ll Z_\odot$ galaxies: grain growth very slow $\rightarrow$ $Z_{\rm dust} \ll Z/3$**
- **Observations:**



(A. Rémy-Ruyer et al. 2015)



(G. Aniano et al. 2020)

Composition of Dust in Low-Metallicity Galaxies

- $Z \ll Z_\odot$: growth in ISM is suppressed.
  Most stardust grains are destroyed, but ***Remaining dust is presumably dominated by stardust***.

- Example: **I Zw 18**
  (L. K. Hunt et al. 2025)

$$M_{\rm H} \approx 10^8 M_\odot$$

$$Z \approx 0.03 Z_\odot$$

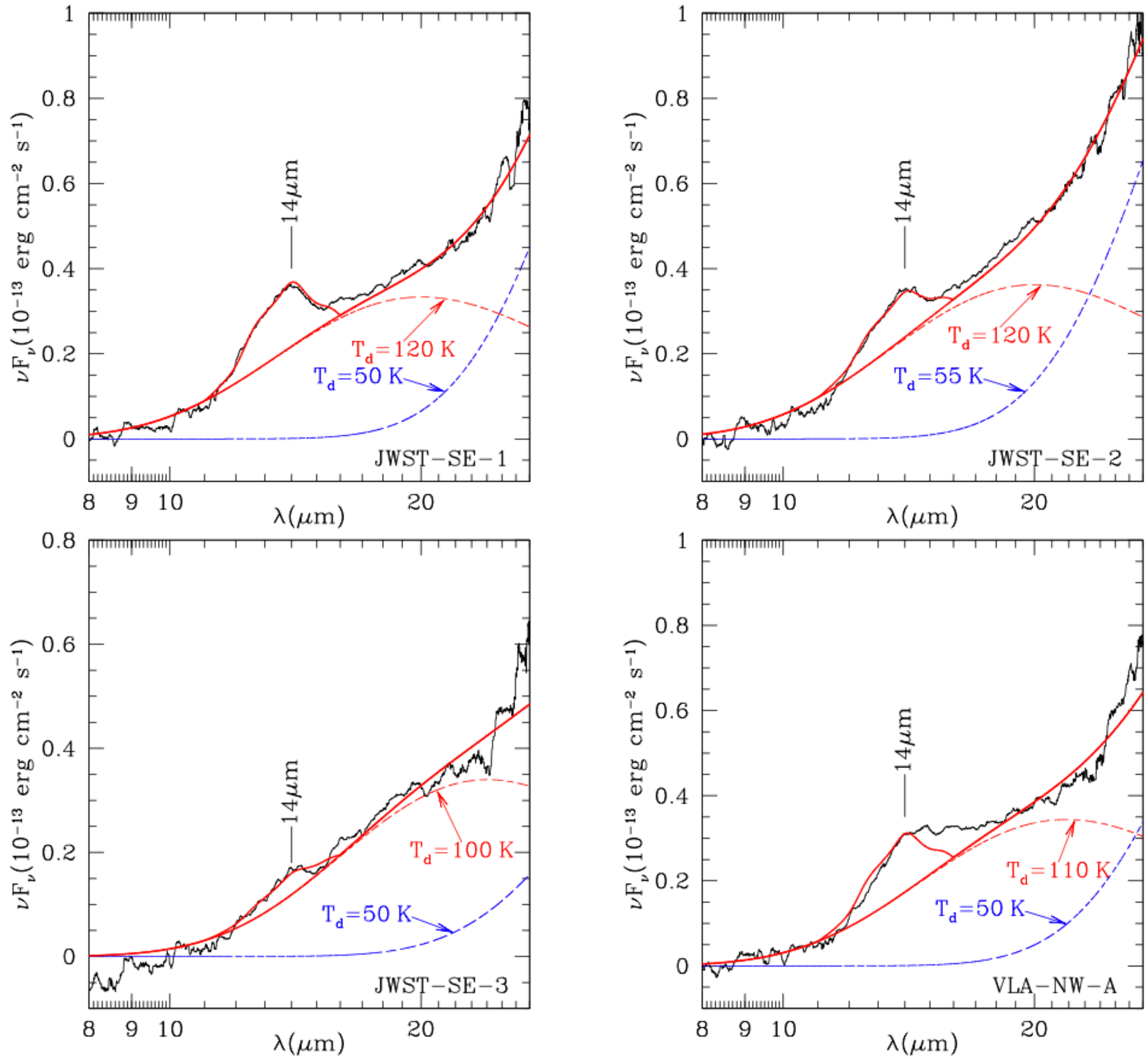
$$M_{\rm dust} \approx 10^3 M_\odot$$

(D. B. Fisher et al. 2014)

$$Z_{\rm dust}/Z \approx 0.012 \ll 1/3$$

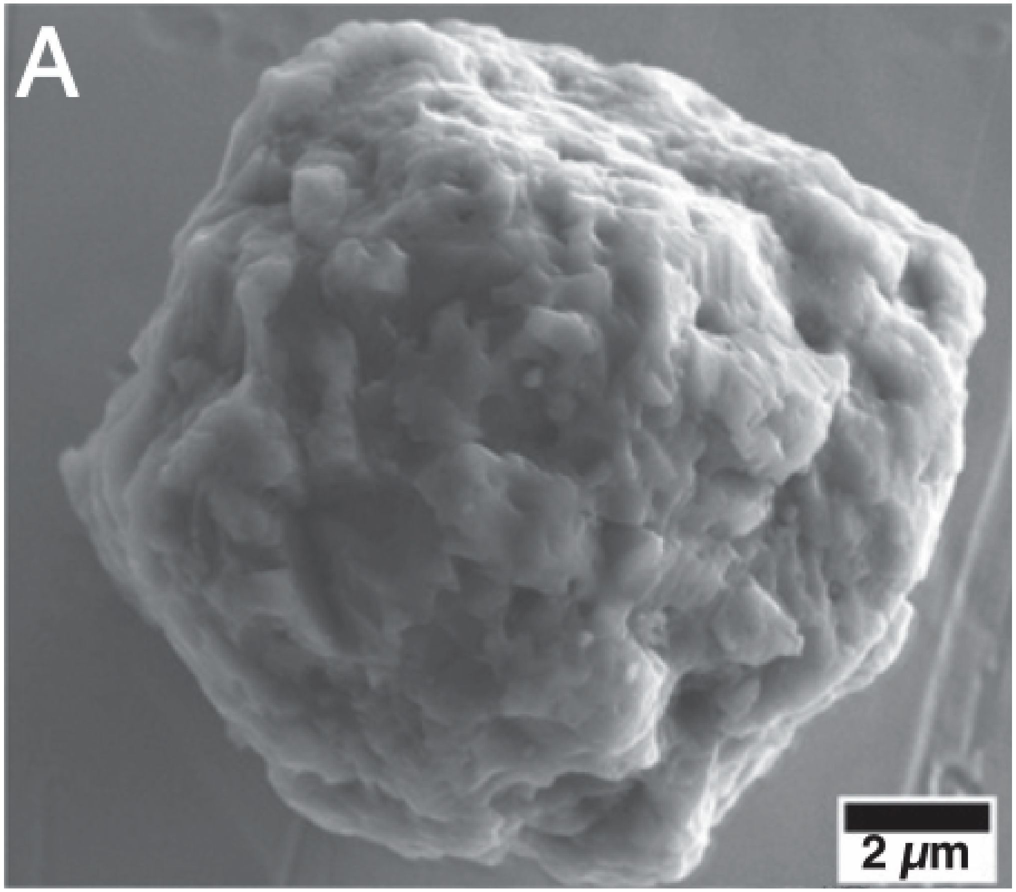
No PAHs detected.
No silicates detected.

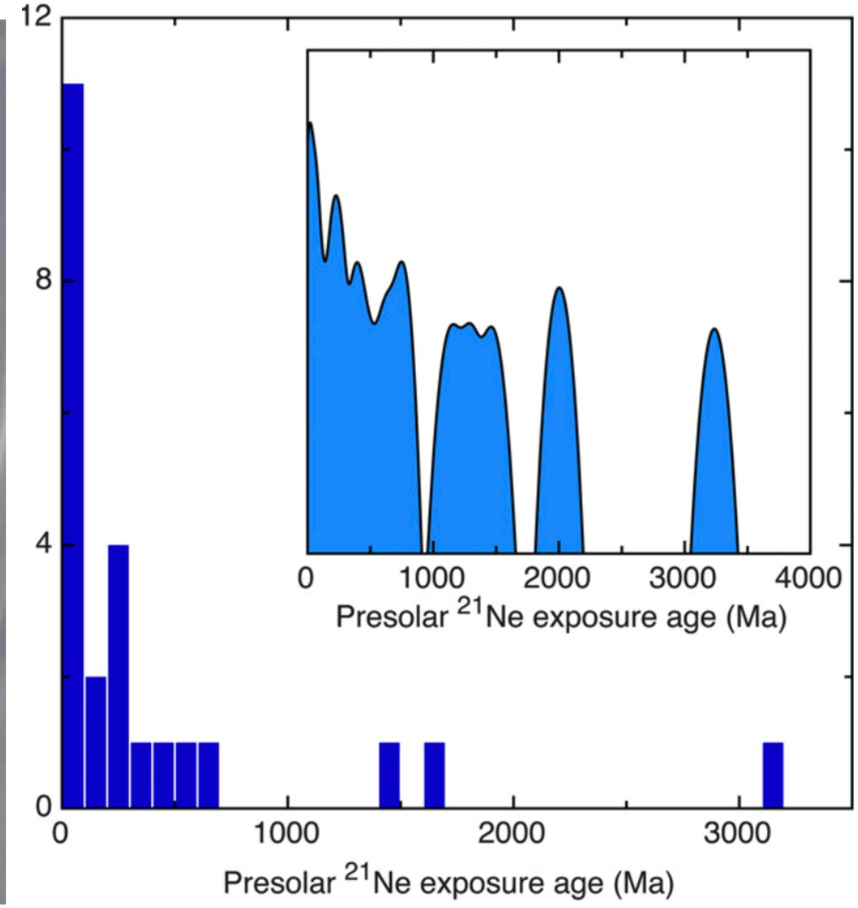
14 μm emission feature possibly Al_2O_3
$M(Al_2O_3)/M_{\rm dust} \approx 0.07$



(L. K. Hunt et al. 2025)

Some Issues...





CR exposure ages of presolar SiC grains (P. R. Heck et al. 2020).

Median age: ~150 Myr *~Consistent with expections!*

Longest age: **3.2 Gyr!!** ***How did it escape cratering/shattering in grain-grain collisions?***

Polarization Issues...

If amorphous silicate and carbonaceous materials are mixed together:

- ***Predict p(10μm) from starlight polarization p(V)***

  Problem:

  p(10μm)=(1.24$\pm$0.28)% toward Cyg OB2-12 (C. M. Telesco et al. 2022)

  vs.

  Predicted p(10μm)=(2.1$\pm$0.3)% (B. T. Draine & B. S. Hensley 2021).

  (but Cyg OB2-12 is an enigmatic object; may have variable intrinsic polarization...)

  Need p(10μm)/p(V) on other sightlines

- ***Predict p(3.4μm)/p(10μm)*** (B. T. Draine & B. S. Hensley 2021).

  Problem:

  3.4μm polarization upper limit **(J. E. Chiar et al. 2006) below prediction unless** ***3.4μm feature carrier is confined to outer $\sim$100 Å.***

  (as suggested by V. Mennella et al. 1999, 2002).

  Deeper 3.4μm polarimetry should detect 3.4μm feature polarization

High Redshift Issues...

- ***Expect star-forming galaxies with near-solar metallicity to have rapid dust growth in ISM and***

$$M_{\rm dust}/M_{\rm gas} \approx 0.007\ (Z/Z_\odot)$$

- ***But:*** **K. E. Heintz et al. (2025) report**

  $M_{\rm dust}/M_{\rm gas} \approx 5\times10^{-4}$ in galaxy at $z = 7.13$ with $Z/Z_\odot = 0.45$

  – $M_{\rm dust} = 1.5\times10^{7} M_\odot$ ***: estimated from ALMA continuum.***

  – $M_{\rm gas} = 3\times10^{10} M_\odot$ ***: estimated from ALMA [C II]158μm***

  – $M_{\rm dust}/M_{\rm gas}$ ***: only $\sim$1/6 of expected value***

- ***Has $M_{\rm gas}$ perhaps been overestimated ?***

Summary

- ***Near-Solar Metallicity Galaxies:***

  Stardust is a minority constituent

  Growth of UV-tolerant materials in ISM:

  amorphous silicates + hydrogenated amorphous carbon

  $a \gtrsim 0.1\mu$m grains should contain both silicate and HAC material.

  Predictions for polarization: $p(3.4\mu m)/p(V)$ and $p(10\mu m)/p(V)$.

- ***Very Low Metallicity Galaxies: Dust will be different:***

  Dominated by surviving stardust grains.

- ***Some Issues:***

  Is silicate polarization consistent with composite grains?

  Is 3.4μm polarization consistent with composite grains?

  Do $\sim$solar-metallicity galaxies at high z have as much dust as we expect?

Thank You!

References

Aniano, G., Draine, B. T., Hunt, L. K., et al. 2020, Modeling Dust and Starlight in Galaxies Observed by Spitzer and Herschel: The KINGFISH Sample, *Ap. J.*, 889, 150, doi: http://doi.org/10.3847/1538-4357/ab5fdb

Barlow, M. J. 1978, The destruction and growth of dust grains in interstellar space. I - Destruction by sputtering. II - Destruction by grain surface reactions, grain-grain collisions and photodesorption. III - Surface recombination, heavy element depletion and mantle growth, *M.N.R.A.S.*, 183, 367

Barlow, M. J., & Silk, J. 1977, Sputtering in interstellar shocks - A model for heavy element depletion, *Ap. J. Lett.*, 211, L83

Bocchio, M., Jones, A. P., & Slavin, J. D. 2014, A re-evaluation of dust processing in supernova shock waves, *Astr. Ap.*, 570, A32, doi: http://doi.org/10.1051/0004-6361/201424368

Chiar, J. E., Adamson, A. J., Whittet, D. C. B., et al. 2006, Spectropolarimetry of the 3.4 micron Feature in the Diffuse ISM toward the Galactic Center Quintuplet Cluster, *Ap. J.*, 651, 268

Draine, B. T., & Hensley, B. S. 2021, The Dielectric Function of "Astrodust" and Predictions for Polarization in the 3.4 and 10 μm Features, *Ap. J.*, 909, 94, doi: http://doi.org/10.3847/1538-4357/abd6c6

Draine, B. T., & Salpeter, E. E. 1979, Destruction Mechanisms for Interstellar Dust, *Ap. J.*, 231, 438, doi: http://doi.org/10.1086/157206

Dwek, E. 2016, Iron: A Key Element for Understanding the Origin and Evolution of Interstellar Dust, *Ap. J.*, 825, 136, doi: http://doi.org/10.3847/0004-637X/825/2/136

Dwek, E., & Scalo, J. M. 1979, Interstellar depletions and the filling factor of the hot interstellar medium, *Ap. J. Lett.*, 233, L81, doi: http://doi.org/10.1086/183081

Dwek, E., & Scalo, J. M. 1980, The evolution of refractory interstellar grains in the solar neighborhood, *Ap. J.*, 239, 193, doi: http://doi.org/10.1086/158100

Fisher, D. B., Bolatto, A. D., Herrera-Camus, R., et al. 2014, The rarity of dust in metal-poor galaxies, *Nature*, 505, 186, doi: http://doi.org/10.1038/nature12765

Heck, P. R., Greer, J., Kööp, L., et al. 2020, Lifetimes of interstellar dust from cosmic ray exposure ages of presolar silicon carbide, Proceedings of the National Academy of Science, 117, 1884, doi: http://doi.org/10.1073/pnas.1904573117

Heintz, K. E., Watson, D., Valentino, F., et al. 2025, Inefficient dust production in a massive, metal-rich galaxy at $z = 7.13$ uncovered by JWST and ALMA, arXiv e-prints, arXiv:2510.07936, doi: http://doi.org/10.48550/arXiv.2510.07936

Hirashita, H. 2010, Shattering by turbulence as a production source of very small grains, *M.N.R.A.S.*, 407, L49, doi: http://doi.org/10.1111/j.1745-3933.2010.00902.x

Hunt, L. K., Draine, B. T., Navarro, M. G., et al. 2025, The Interstellar Medium in I Zw 18 seen with JWST/MIRI: II. Warm Molecular Hydrogen and Warm Dust, arXiv e-prints, arXiv:2509.02690, doi: http://doi.org/10.48550/arXiv.2509.02690

Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1994, Grain destruction in shocks in the interstellar medium, *Ap. J.*, 433, 797, doi: http://doi.org/10.1086/174689

Mennella, V., Brucato, J. R., Colangeli, L., & Palumbo, P. 1999, Activation of the 3.4 Micron Band in Carbon Grains by Exposure to Atomic Hydrogen, *Ap. J. Lett.*, 524, L71

Mennella, V., Brucato, J. R., Colangeli, L., & Palumbo, P. 2002, CH Bond Formation in Carbon Grains by Exposure to Atomic Hydrogen: The Evolution of the Carrier of the Interstellar 3.4 Micron Band, *Ap. J.*, 569, 531, doi: http://doi.org/10.1086/339229

Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2015, Linking dust emission to fundamental properties in galaxies: the low-metallicity picture, *Astr. Ap.*, 582, A121, doi: http://doi.org/10.1051/0004-6361/201526067

Seab, C. G., & Shull, J. M. 1983, Shock processing of interstellar grains, *Ap. J.*, 275, 652, doi: http://doi.org/10.1086/161563

Telesco, C. M., Varosi, F., Wright, C., et al. 2022, Mid-Infrared Polarization of the Diffuse Interstellar Medium toward CygOB2-12, *Ap. J. Lett.*, 940, L26, doi: http://doi.org/10.3847/2041-8213/ac9b56

Yan, H., Lazarian, A., & Draine, B. T. 2004, Dust Dynamics in Compressible Magnetohydrodynamic Turbulence, *Ap. J.*, 616, 895, doi: http://doi.org/10.1086/425111

Zhukovska, S., Dobbs, C., Jenkins, E. B., & Klessen, R. S. 2016, Modeling Dust Evolution in Galaxies with a Multiphase, Inhomogeneous ISM, *Ap. J.*, 831, 147, doi: http://doi.org/10.3847/0004-637X/831/2/147