Inner Source Pickup Ions Produced from Chondritic Smooth Interplanetary Dust Particles

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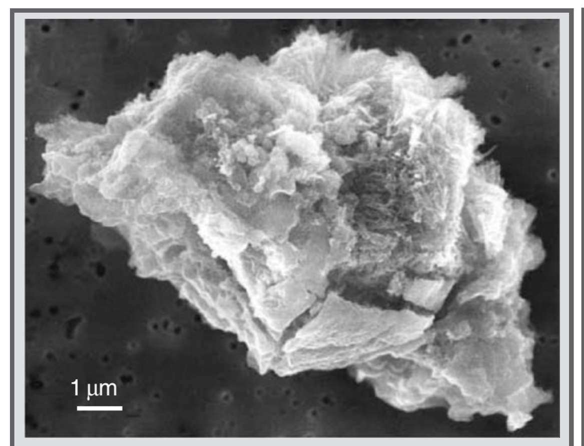
Motivation

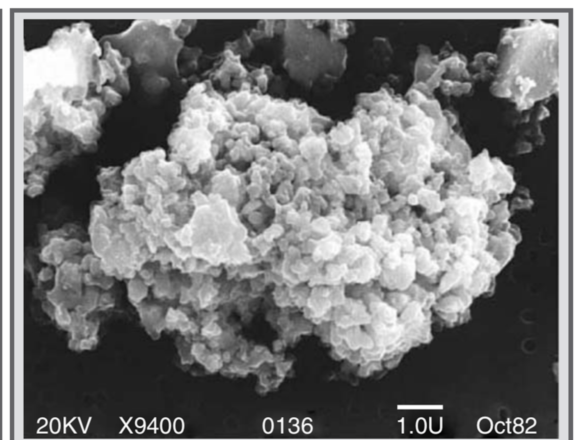
- **One-liner** – We simulate the production and transport of inner source pickup ions produced by the solar wind interacting with chondritic smooth dust grains, compare to observations, and demonstrate that the dust grain population near the sun may be dominated by chondritic porous grains.

- Inner source pickup ions (PUIs) are singly-charged ions produced by the interaction between solar wind ions and interplanetary dust grains.
- The production rate is highly dependent on the dust grain density, porosity, composition, and size.
- There are two types of dust grains: chondritic smooth ("compact") and chondritic porous ("fluffy").



Compact Grains

- High density
- Low porosity
- Typically asteroidal origin



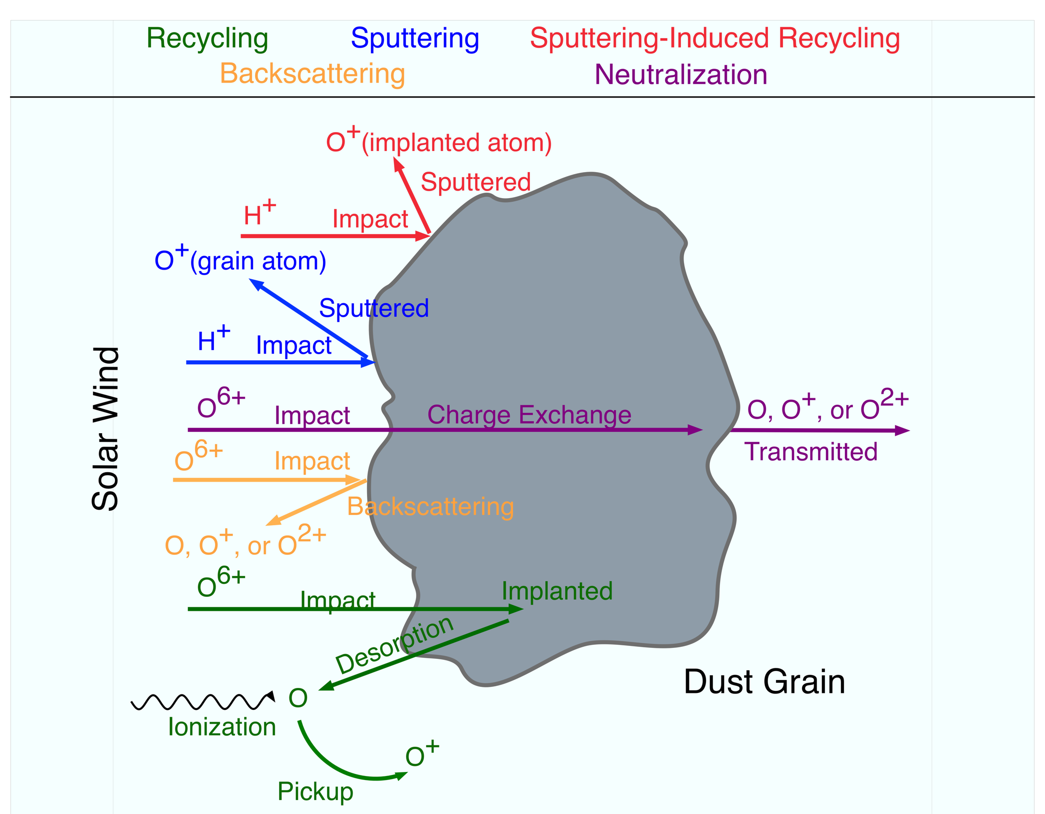
Fluffy Grains

- Low density
- High porosity
- Typically cometary origin

Question How does the composition of inner source PUIs produced by compact grains compare to fluffy grains?

Question Is there a dominant mechanism for inner source PUIs produced by compact grains?

Mechanisms



Recycling

- Solar wind ions are implanted in the grain and neutralized through charge exchange.
- Dust grains become saturated with neutralized solar wind atoms.
- Due to saturation, atoms diffuse to the surface, desorb, ionize, and are picked up by the solar wind.

Neutralization

- Solar wind ions completely penetrate submicron sized dust grains.
- Similar to carbon foil, charge exchange leaves a fractional residual charge state.

Backscattering

- Solar wind ions reflect off the grain surface.
- The ions gain electrons during the collision, leaving a fractional residual charge state.

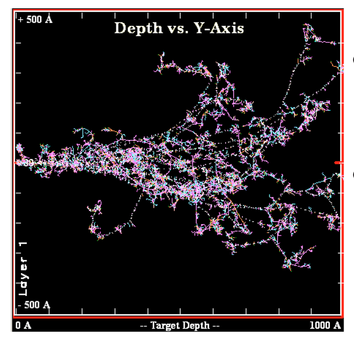
Sputtering

- Solar wind ions transfer energy to grain atoms during collisions.
- Surface grain atoms are ejected from the grain when given an energy greater than their surface binding energy.

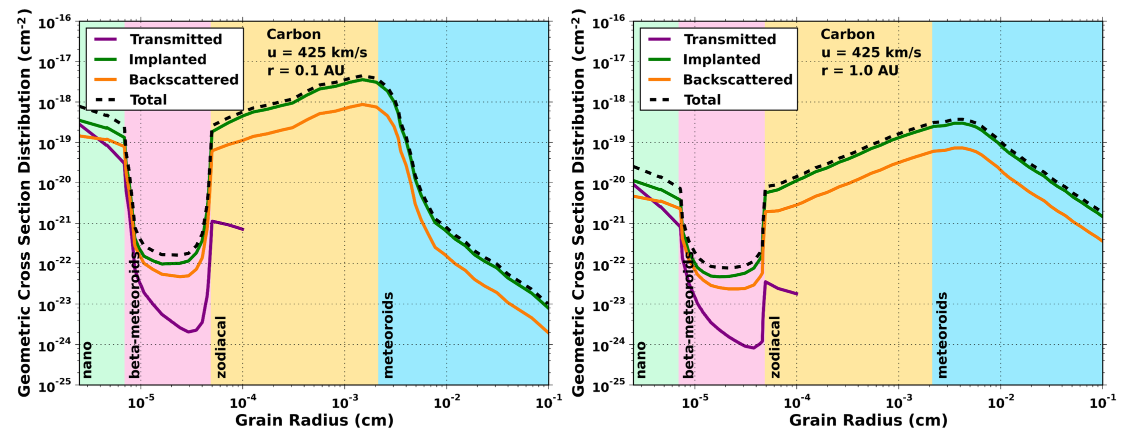
Sputtering-Induced Recycling (SIR)

- Exactly like sputtering, but implanted ions are removed rather than grain atoms.

SRIM



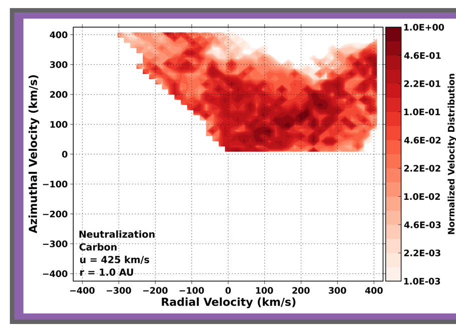
- Use the Stopping Range of Ions in Matter (SRIM) to simulate the interaction between solar wind ions and dust grains.
- Consider density of 2.5 g cm^{-3}, average composition based on stratospheric micrometeorite observations, and size distribution based on dust-dust collision model.



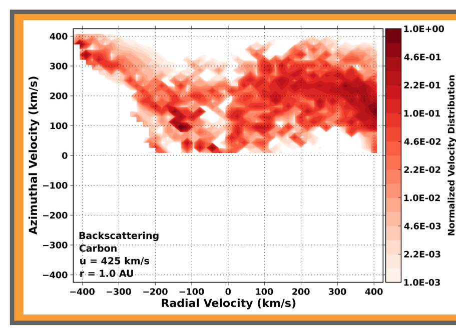
- SRIM gives the fraction of ions transmitted, implanted, and backscattered, along with the sputtering yield for every size grain, incident ion species, incident energy, and incident angle.
- Integrating over the geometric cross section distribution shown above gives the fraction of ions contributing to each mechanism as a function of solar wind speed and radial distance from the sun.

Residual Velocities

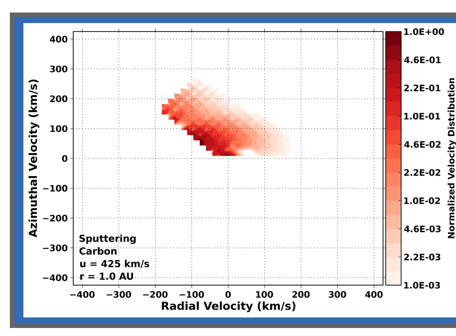
- The residual velocity of ions after interacting with dust grains depend on the mechanism, incident ion species, incident energy, and incident angle.



- Neutralized ions lose energy as they transmit through the grain.
- Ions that have just enough energy to transmit through the grain and typically reflected at an angle.
- Some ions are shown to even reflect back toward the sun.



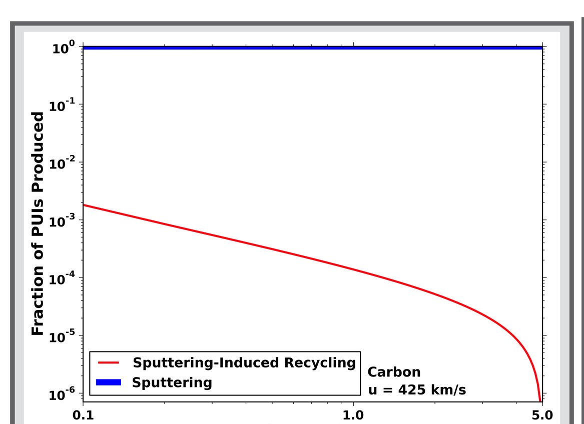
- Backscattered ions show a wide range of residual velocities for compact grains.
- Ions with low incident angles reflect of the grain surface back toward the sun.
- Ions backscattered off the grain edges lose little energy and remain moving away from the sun.



- Atoms ejected from the grain surface have small velocities toward the sun.
- Ions sputtered from the grain edges have residual velocities away from the sun.
- SIR shares this residual velocity.

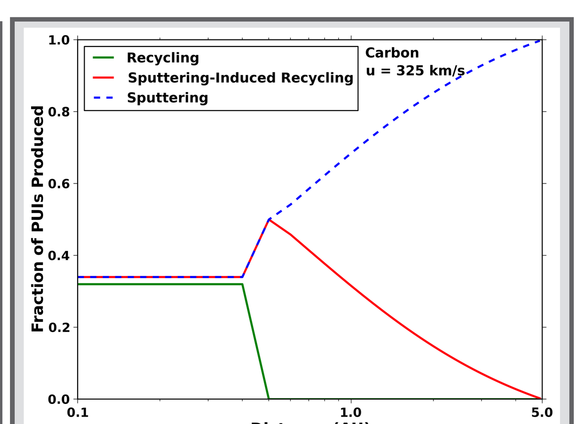
Saturation

- Saturation of dust grains occurs when there is a one-to-one correlation between grain atoms and implanted ions.
- Recycling is dependent on grain saturation.
- Saturation depends on the Poynting-Robertson lifetime, impact rate, implantation rate, sputtering rate, and number of grain atoms within the volume containing implanted ions.



Compact Grains

- Saturation is never reached.
- Recycling is impossible.
- Sputtering dominates due to high number of grain atoms.



Fluffy Grains

- Saturation occurs near 0.4 AU.
- Recycling contributes sigificantly within the saturation zone.
- Sputtering and SIR contribute equally in the saturation zone.

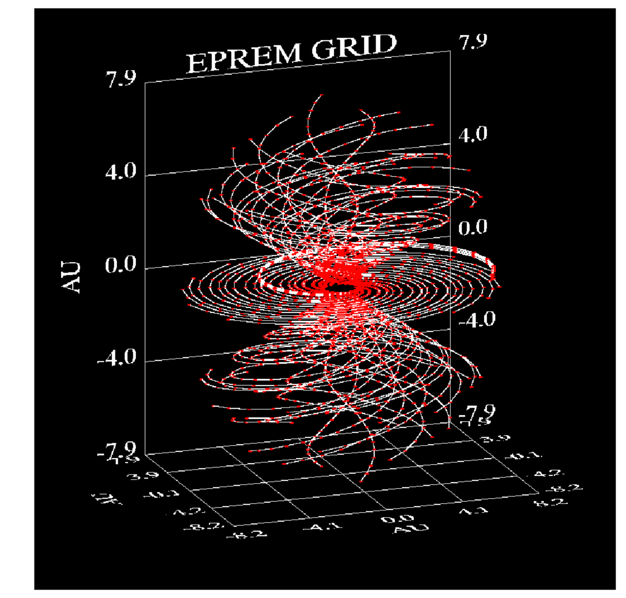
EPREM

Energetic Particle Radiation Environment Module (EPREM)

- Models particle transport throughout the heliosphere.
- Solves the focused transport equation and convection-diffusion equation.
- Takes into account: convection, streaming, adiabatic cooling, adiabatic focusing, pitch-angle scattering, perpendicular diffusion, and drift.

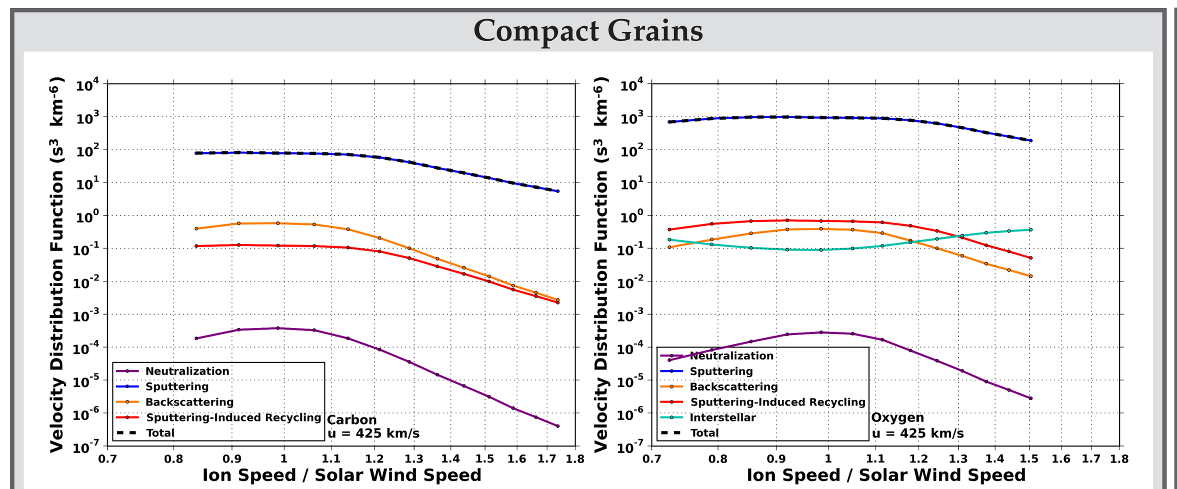
PROCEDURE

- Add the production rate per unit volume of inner source carbon and oxygen into EPREM. Also include interstellar oxygen.
- Simulate the transport of carbon and oxygen inside 1 AU.
- Integrate the velocity distribution function between $0.8 \leq w \leq 1.2$ to get the flux and abundance ratios.
- Compare to SOHO/CTOF data for solar minimum conditions when CTOF was active.

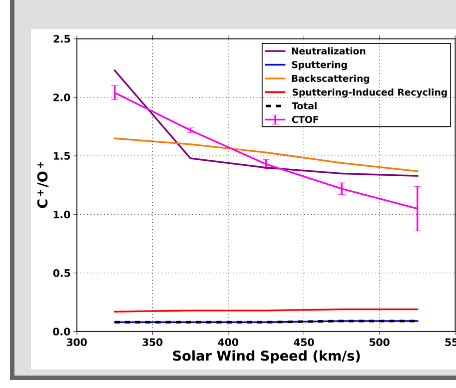


Results

Compact Grains

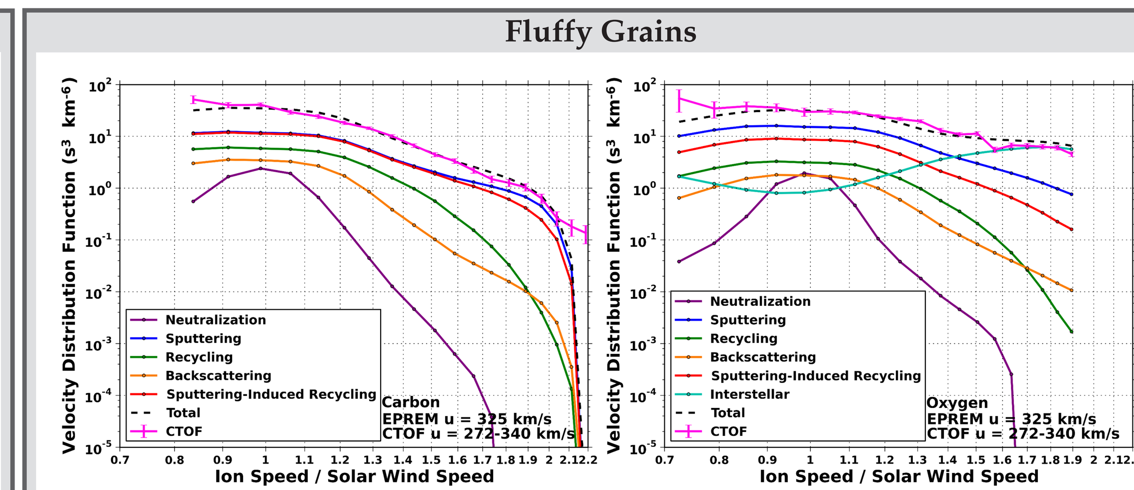


- Sputtering is the dominant mechanism by 2−3 orders of magnitude over the next production mechanism. This is due to the high number of grain atoms compared to implanted ions.
- Neutralization is negligible. Solar wind ions do not have enough energy to transmit through these dense grains.
- Recycling is non-existent.
- SIR is considerably lower for compact grains than fluffy grains.
- Backscattering is only slightly lower for compact grains than fluffy grains.

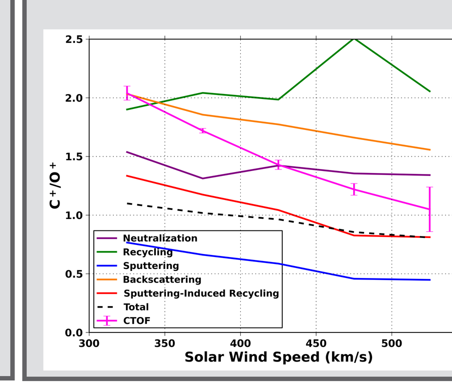


- C^+/O^+ for neutralization and backscattering follow CTOF observations very well.
- Sputtering and SIR produce more O^+ than C^+.
- The total C^+/O^+ ratio strictly follows sputtering since sputtering is the dominant mechanism. This contradicts observations which show a solar wind-like compositon, not a grain-like composition.

Fluffy Grains



- The shape of the total VDF matches CTOF observations very well.
- All mechanisms produce a comparable intensity of PUIs.
- A possible rollover is visible for C^+ at twice the solar wind speed signifying a cutoff. If this is true, then inner source PUIs are injected into the solar wind speed with near zero speed.
- A "shoulder" is seen in the CTOF VDF which matches nicely with the interstellar O^+ VDF.
- The neutralization VDF is narrow but may be due to our velocity approximation.

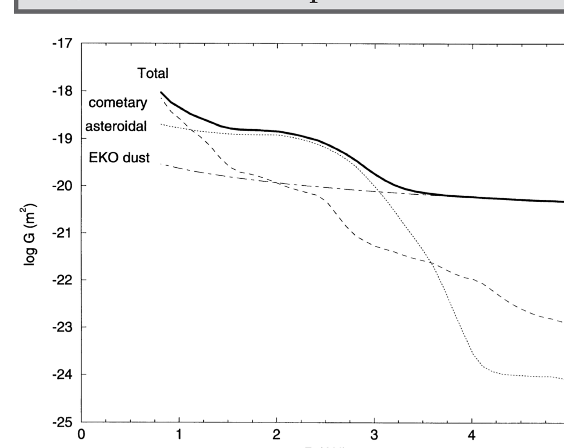


- Neutralization and backscattering follow CTOF observations well.
- SIR is close to observations, but falls below one for higher solar wind speeds.
- Recycling produces more C^+ than O^+ due to the higher dissociation rate of CH.
- We test the idea that silicates may break down during dust-dust collisions. The resulting C^+/O^+ ratio is closer to CTOF observations.

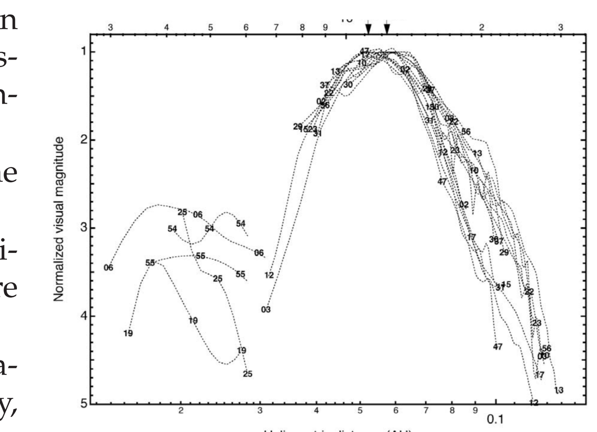
Discussion

- PUIs produced from compact grains show a composition that resembles that of the dust grain.
- PUIs produced by fluffy grains, on the other hand, show a composition that is much closer to observations than compact grains.

- It is then possible that the dust grain population close to the sun where the majority of inner source PUIs are produced is dominated by fluffy grains.
- **Question** – is this plausible?

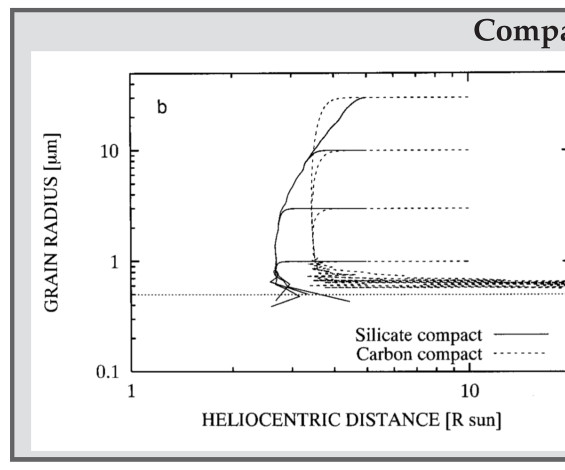


- Ishimoto (1999) modeled the dust grain population from three origins: asteroidal, cometary, and Edgeworth-Kuiper belt (EKB).
- The model considered all forces on the grains and dust-dust collisions.
- At 1 AU and possibly inside is dominated by cometary grains – which are expected to be fluffy grains.
- Stratospheric micrometeorite observations support this: about 45% fluffy, 37% compact, and 18% single mineral.



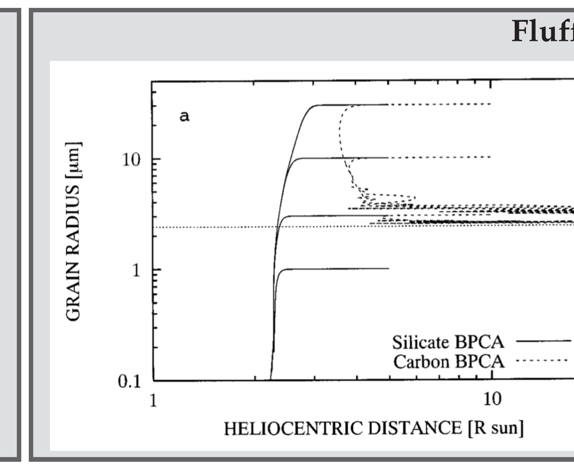
- Sun-grazing comets deposit about $10^8 - 10^{11}$ kg of grains near the sun.
- For grains larger than 10 microns, the number density distribution is increased by an amount comparable to the typical influx of dust grains.
- The dust grains deposited by sun-grazing comets are expected to be fluffy grains.
- The fragmentation rate is so high that larger grains break apart into submicron grains.

Compact Grains



- Model of compact dust grain dynamics near the sun.
- Compact carbon and silicate grains smaller than about 0.5 microns get pushed away from the sun due to radiation pressure.
- Compact carbon reaches about 4 solar radii.
- Compact silicates reach about 3 solar radii.

Fluffy Grains



- Model of fluffy dust grain dynamics near the sun.
- Fluffy carbon smaller than about 2.5 microns is affected by radiation pressure, but submicron fluffy silicate grains are not.
- Fluffy carbon reaches about 4 solar radii. Similar to compact carbon.
- Fluffy silicates reachs almost 2 solar radii – closer than compact silicates.

Conclusion

- Inner source PUI production from compact dust grains is dominated by sputtering, and therefore has a composition that is strictly grain-like – contradicting observations.
- These results suggest that there are more fluffy dust grains than compact grains close to the sun. This is supported by current models.