ABUNDANCE OF C^+/O^+ INNER SOURCE PICKUP IONS PRODUCED BY SOLAR WIND RECYCLING, NEUTRALIZATION, BACKSCATTERING, AND SPUTTERING

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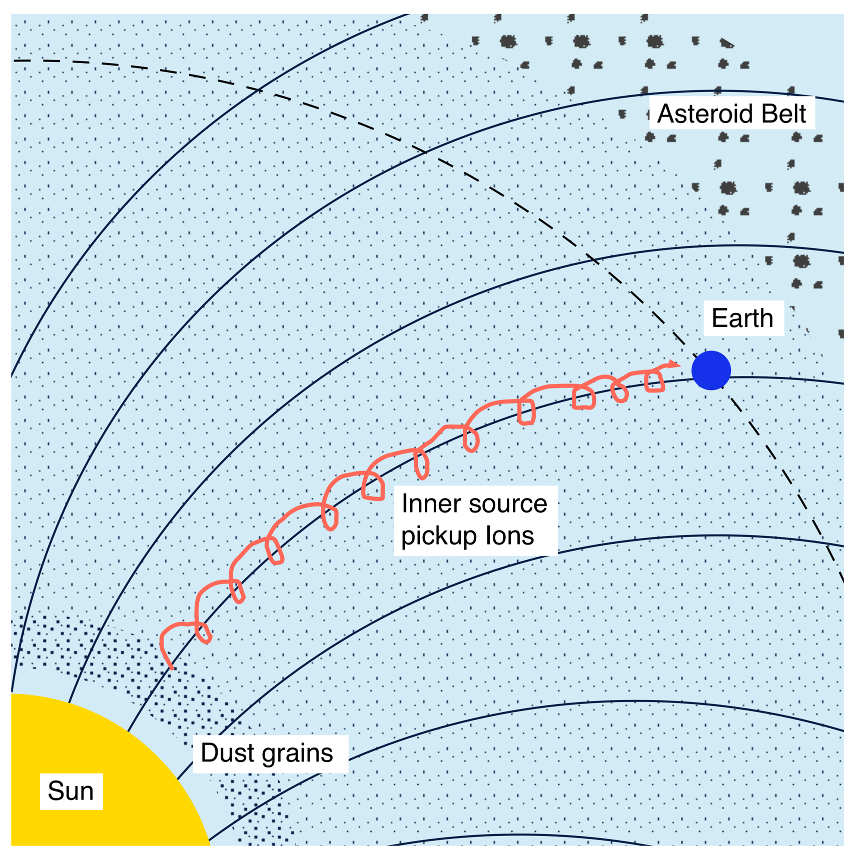
EMMREM

MOTIVATION

- Inner source pickup ions (PUIs) are singly charged ions that are produced near the sun.
- The mechanism behind the production of inner source pickup ions is not well understood.
- Possible production mechanisms include:
  - Solar wind recycling – absorption and desorption of solar wind ions implanted in dust grains.
  - Solar wind neutralization – charge exchange through carbon foil-like dust grain population.
  - Sputtering of grain atoms ejected from incident solar wind ions.
  - Backscattering of solar wind ions off grains.
- In situ observations cannot differentiate between production mechanisms – we must rely on simulations.
- For the first time, we compare the inner source PUI production mechanisms using a particle transport code.



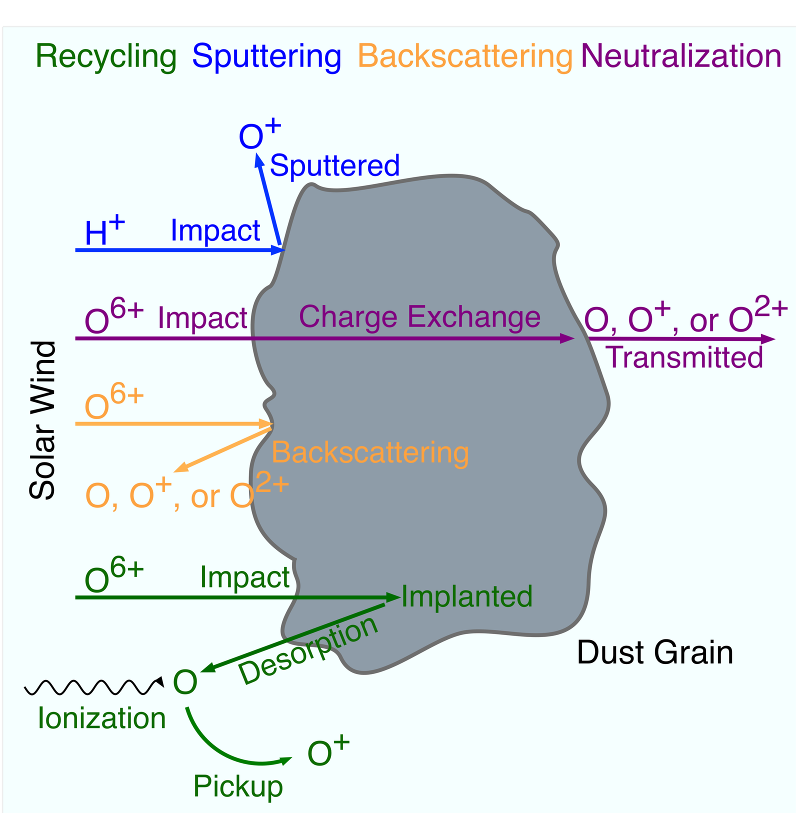
Question How does C^+/O^+ produced by each mechanism compare to observations?

Question How does the velocity distribution at 1 AU compare to observations?

Question How does the flux of C^+ and O^+ change with distance from the sun?

Question Is there a dominant mechanism?

MECHANISMS



Recycling
- Solar wind ions penetrate about 10-30 nm per keV and nucleon into the outer mineral layer of dust grains.
- Electron capture neutralizes the solar wind ion within the dust grain.
- Dust grains become saturated with neutralized solar wind atoms.
- Due to saturation, the solar wind atoms diffuse to the surface and desorb from the dust grain.
- Once desorbed, the neutrals are ionized by photoionization, charge exchange, or electron impact.
- After ionization, the ions are picked up and convected out with the solar wind.

Neutralization
- Solar wind ions completely penetrate submicron sized dust grains
- Charge exchange leaves a fraction of neutral atoms, singly-charge ions, doubly-charged ions, and so on. The process is similar to charge exchange through carbon foils.
- The transmitted atoms and ions lose little energy.
- Ionization from photoionization, charge exchange, or electron impact will turn neutrals to singles and singles to double (i.e. gain and loss rate, respectively).

Sputtering
- Solar wind protons bombard dust grains.
- Surface atoms are ejected from the grain when given an energy greater than their surface binding energy.

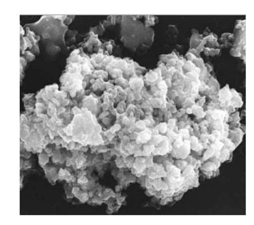
Backscattering
- Solar wind ions reflect off the grain surface.
- The ions gain electrons during the collision, leaving a fraction of neutral atoms, singly-charged ions, doubly-charged ions, and so on.

DUST GRAINS

- The amount of implanted, transmitted, backscattered, and sputtered ions depends on the size, composition, and porosity of the dust grains.
  - **Size** - To get the number density per grain size, use numerical results of dust-dust collisions as grains slowly move from the asteroid belt to the sun due to the Poynting-Robertson effect.
  - **Composition** - Use the average composition of chondritic porous (CP) dust grains relative to silicon. These aggregate grains are mainly composed of silicates (e.g. Forsterite Mg_2SiO_4, Fayalite Fe_2SiO_4) with carbon and refractory metals.

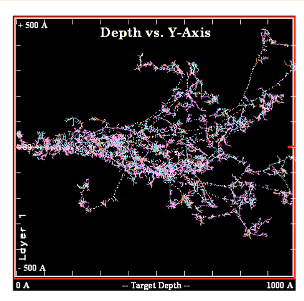
C	O	Na	Mg	Al	S	Ca	Cr	Fe	Ni
2.39	3.98	0.056	1.015	0.07	0.417	0.047	0.016	0.705	0.024

  - **Porosity** - Consider high porosity "fluffy" grains with equivalent density as low as 0.001 g/cm^{-3} as found by *Rosetta*/GIADA for cometary dust grains.

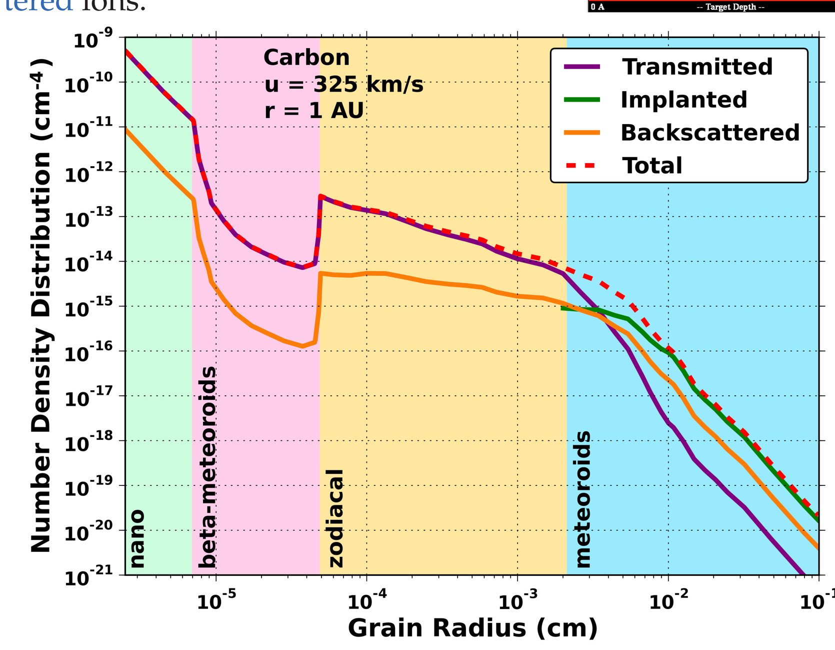


SRIM RESULTS

- Use Stopping Range of Ions in Matter (SRIM) to simulate the collisional processes of solar wind ions as they pass through dust grains.



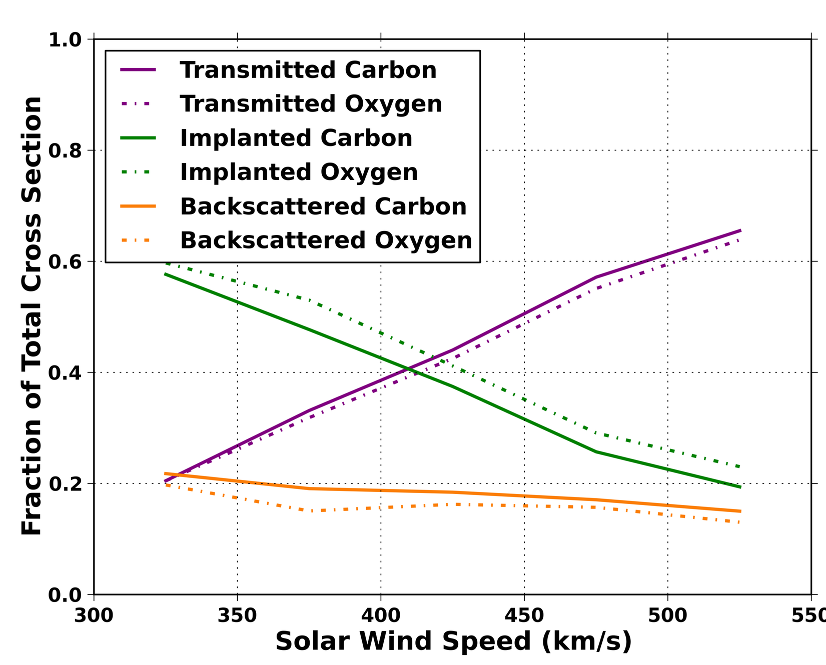
- SRIM outputs the number of implanted, transmitted, backscattered, and sputtered ions.



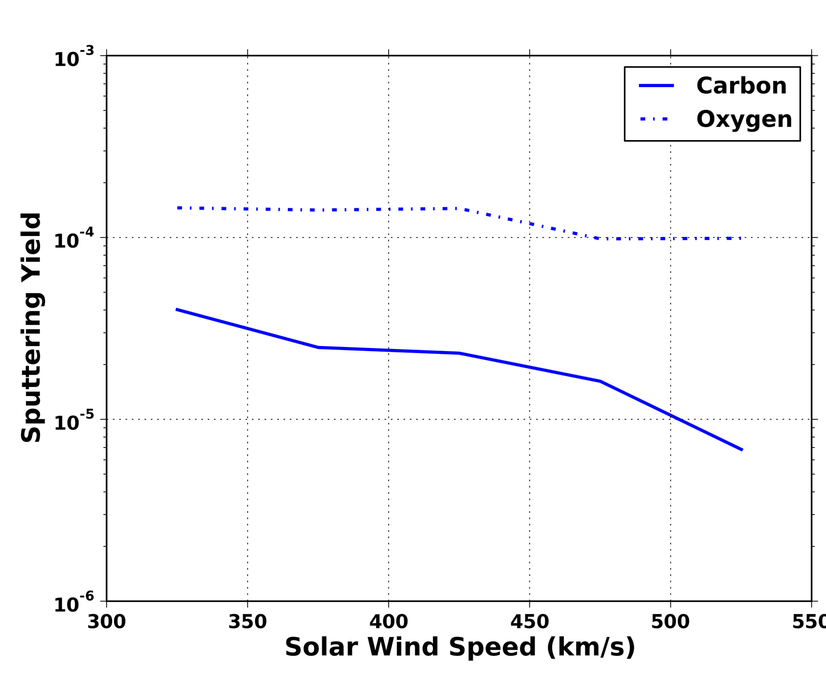
- An effective total geometric cross section for each mechanism is found by integrating the product of the number density distribution and cross section over the grain radius.

$$\Gamma_{\text{mechanism}}(r) = \int f_{\text{mechanism}}(s,r)\pi s^2 ds$$

- At slow solar wind speeds, the majority of ions are implanted into the grains.
- At fast solar wind speeds, the majority of ions are transmitted.
- More oxygen than carbon is implanted into grains.
- More carbon than oxygen is transmitted through the grains.
- More carbon than oxygen is backscattered.
- A significant percent of solar wind ions are backscattered, with more at slower solar wind speeds.



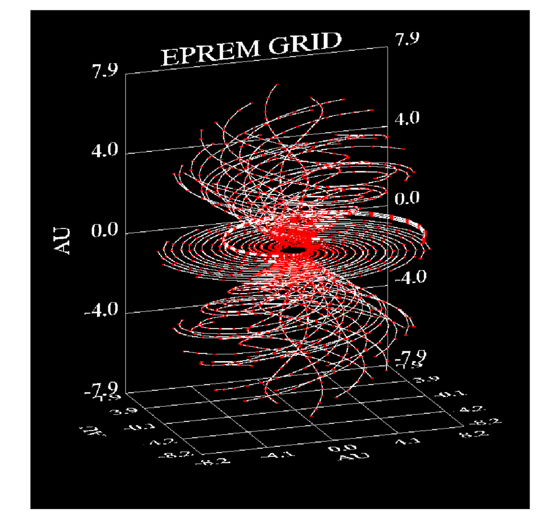
- The average sputtering yield is calculated by taking a weighted average over the total number density distribution.
- More oxygen than carbon is sputtered due to CP grains being mainly composed of silicates.
- The sputtering yield of both carbon and oxygen decreases with solar wind speed, with carbon decreasing faster.



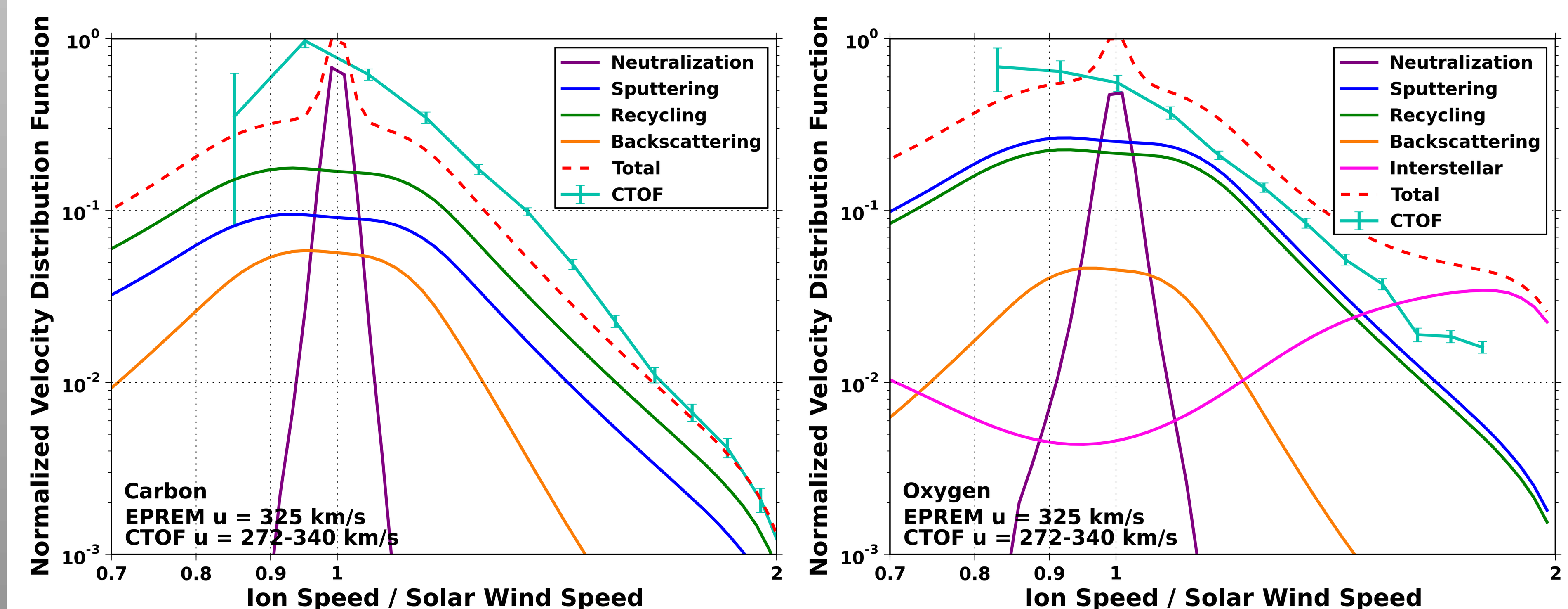
EPREM

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.

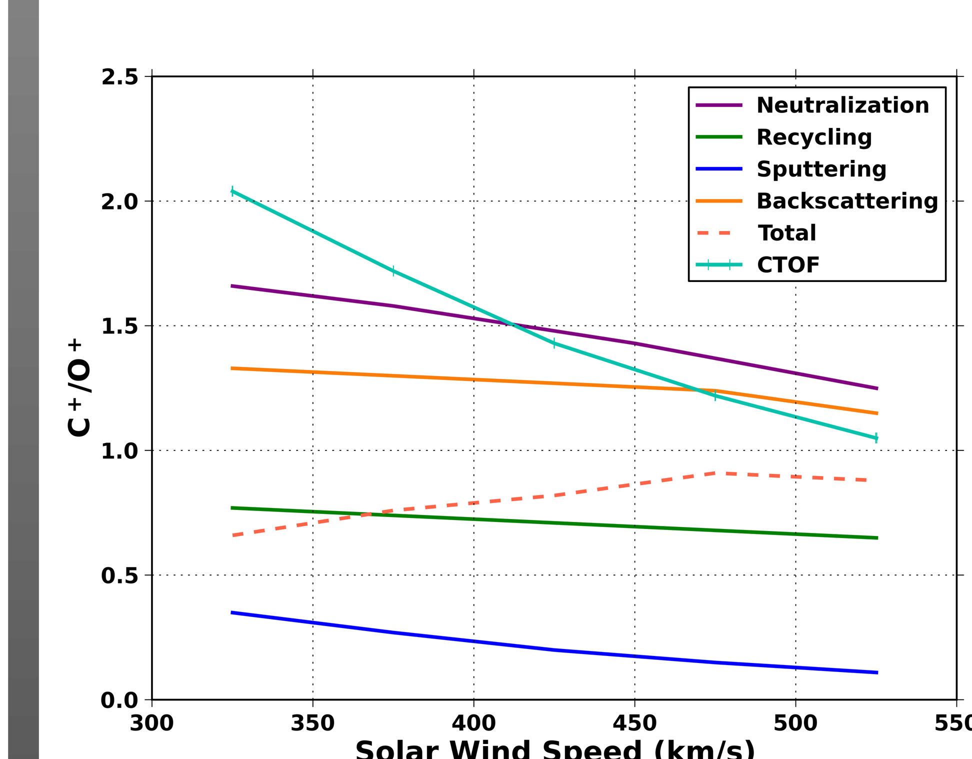
PROCEDURE
- Add the production rate per unit volume of inner source carbon and oxygen into EPREM. Also include interstellar oxygen.
- Simulate the transport of carbon and oxygen inside 1 AU.
- Integrate the velocity distribution function between $0.8 \le w \le 1.2$ to get the flux and abundance ratios.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

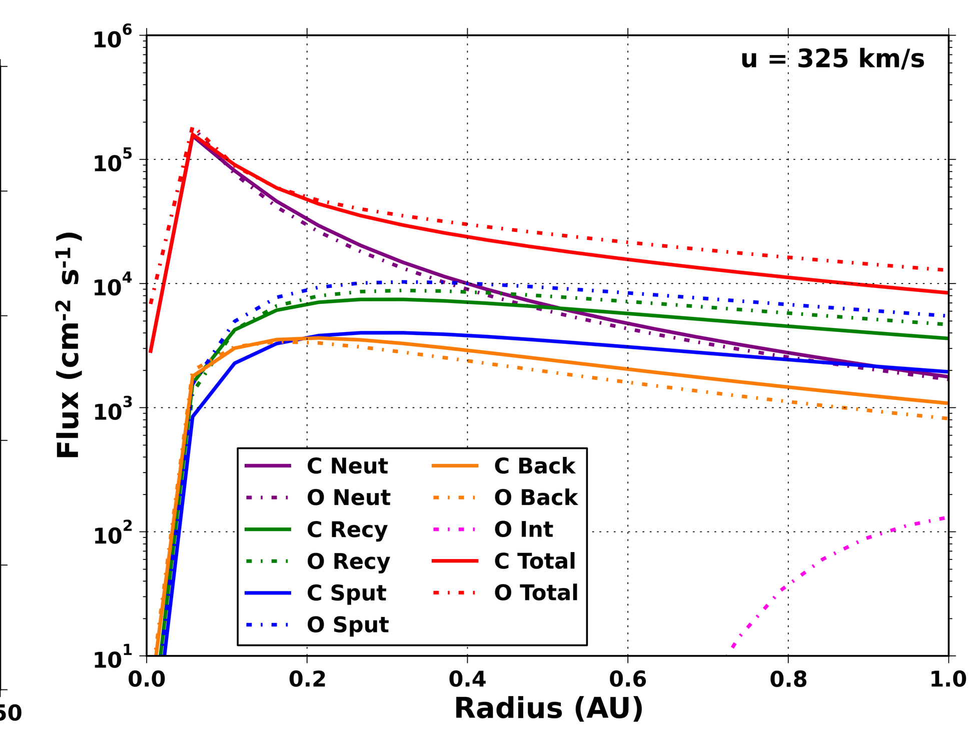


EPREM RESULTS



- The velocity distribution of each mechanism peaks near the solar wind speed with a slight favor towards lower speeds due to the PUIs being injected with speeds lower than the solar wind speed.
- Neutralization has a narrow distribution since the ions lose little energy as they pass through the grains.
- Recycling, backscattering, and sputtering have broad velocity distributions due to their low injection speed relative to the solar wind speed.
- CTOF observations show a broad velocity distribution – favoring recycling, backscattering, and sputtering.
- The shoulder seen in CTOF oxygen observations is most likely due to interstellar oxygen.





- Recycling produces more oxygen than carbon with C^+/O^+ approximately reflecting solar wind C/O.
- Sputtering produces more oxygen than carbon due to CP grains being mainly composed of silicates (e.g. Forsterite Mg_2SiO_4, Fayalite Fe_2SiO_4)
- Neutralization produces more carbon than oxygen similiar to CTOF observations, and C^+/O^+ decreases with solar wind speed.
- Backscatting produces more carbon than oxygen similar to CTOF observations, and C^+/O^+ decreases with solar wind speed.
- Neutralization has the highest flux close to the sun. This is due to the ions losing minimal energy as they pass through the high porosity fluffy grains. For compact grains of higher density, however, this may not be the case.
- The flux from recycling, backscattering, and sputtering close to the sun is gradual due to the low speed of the ions relative to the solar wind speed as they are picked up.
- Each mechanism produces comparable fluxes at 1 AU.
- Contribution from interstellar oxygen is low due to the high ionization rate.

SUMMARY & DISCUSSION POINTS

	Broad VDF	$C^+/O^+ > 1$	Decreasing C^+/O^+ with u	Significant flux	Criteria Fulfilled
CTOF					
Recycling	Yes	No	Yes	Yes	3
Neutralization	No	Yes	Yes	Yes	3
Backscattering	Yes	Yes	Yes	Yes	4
Sputtering	Yes	No	Yes	Yes	3

Recycling
- 3/4 criteria fulfilled.
- $C^+/O^+ < 1$ and approximately reflects solar wind C/O.
- Complication - Implanted solar wind ions are likely to create compounds. The compounds may desorb from the grain rather than atomic C or O. Each compound has a different survival probability. This more complex process may change the amount of C^+ and O^+ observed at 1 AU.
- Complication - Recycling depends on the saturation of implanted solar wind ions. If the sputtering rate is higher than the saturation rate, recycling may not be possible.

Neutralization
- 3/4 criteria fulfilled – possibly more.
- The narrow velocity distribution suggests that neutralization is not the dominant mechanism. However if considering compact grains with higher density, the velocity of transmitted ions is greatly reduced and will results in a broader velocity distribution. Although this will also reduce the intesity since less ions will be transmitted.

Sputtering
- 3/4 criteria fulfilled.
- $C^+/O^+ < 1$ and reflects the composition of the dust grain.
- Complication - Considering compact dust grains with higher density may increase the sputtering rate. If the intensity is higher than other mechanisms, this would not agree with observations which demonstrate a solar wind-like composition.

Backscattering
- 4/4 criteria fulfilled – the most promising out of all the mechanisms.
- Unlike neutralization which depends on smaller size dust grains that may be swept out with CMEs, backscattering occurs at all dust grain sizes. This allows for a stable flux over the solar cycle.
- Considering compact dust grains with higher density will increase the amount of backscattered solar wind ions.