Abundance of C$^+$/O$^+$ Inner Source Pickup Ions Produced by Solar Wind Recycling, Neutralization, and Sputtering

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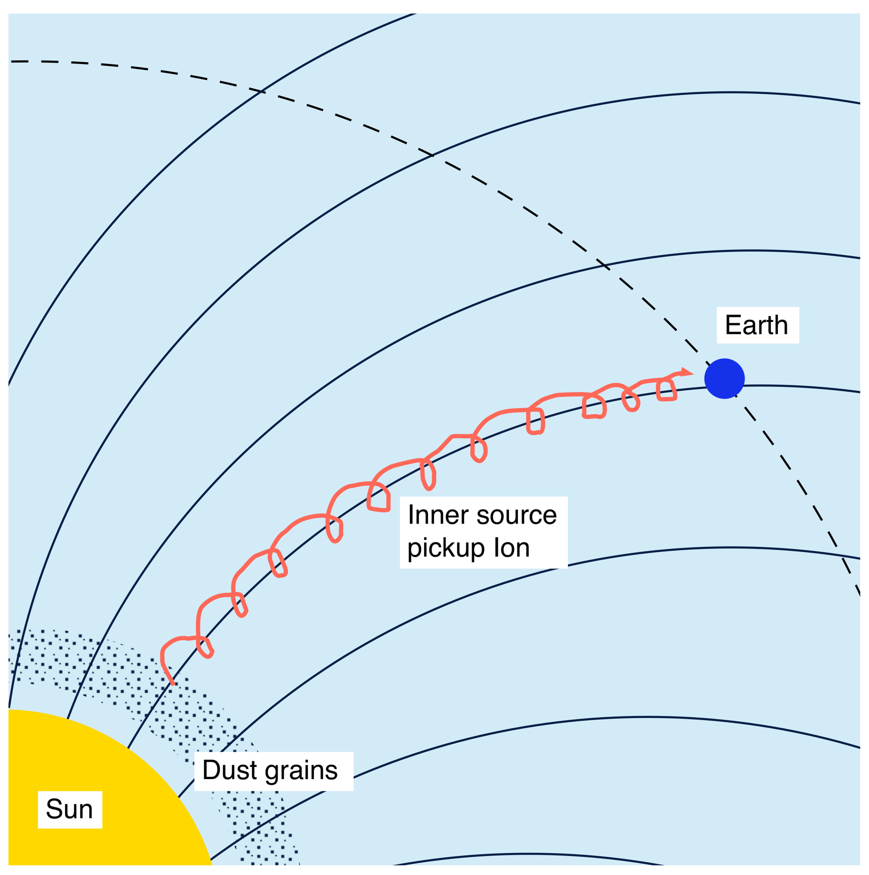
Motivation

- Inner source pickup ions 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 in dust grains
  - **Solar wind neutralization** – charge exchange through carbon foil-like dust grain population
  - **Sputtering** from grains
  - Dust-dust collisions
  - Sun-grazing comets



Question How does C$^+$/O$^+$ produced by solar wind recycling, neutralization, and sputtering compare to observations?

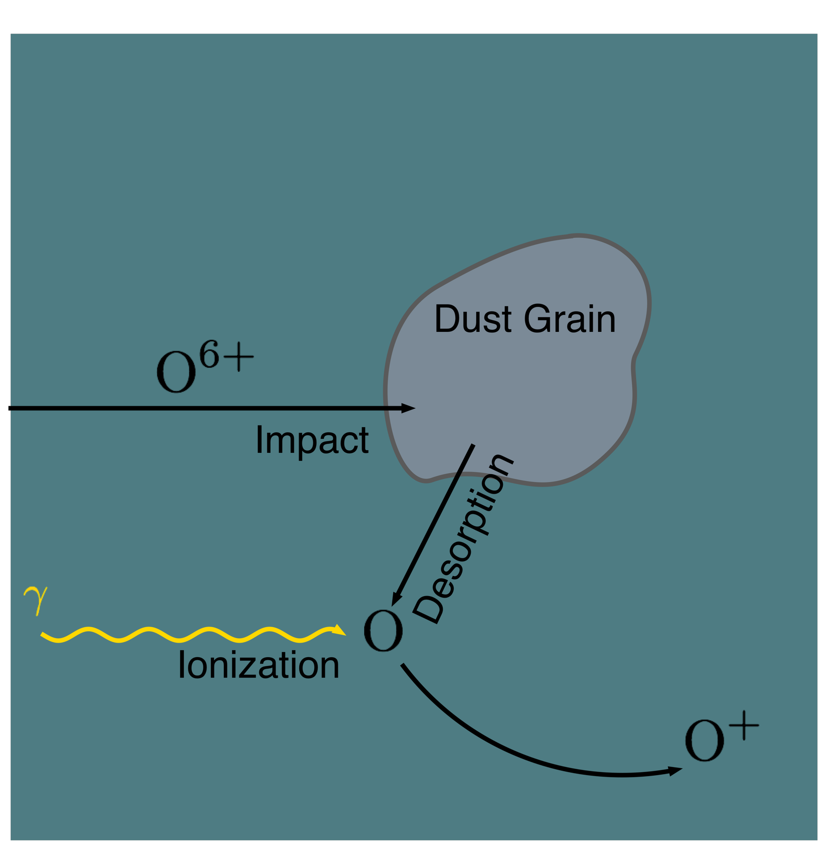
Question How does the flux of C$^+$ and O$^+$ at 1 AU compare to observations?

Question Is there a dominant mechanism?

Solar Wind Recycling

MECHANICAL PROCESS

- 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.
- Due to the very close proximity to the sun, ionization occurs almost immediately.
- After ionization, the ions are picked up and convected out with the solar wind.



FORMALISM

- Impact rate per unit volume depends on the flux of solar wind heavy ions and cross section of dust grains.

$$S_{\rm impact}(r) = \Xi u n_{\rm sw}(r_1)\left(\frac{r_1}{r}\right)^2 \frac{\Gamma n_{\rm d}(r)}{n_{\rm d}(r_1)} \quad (1)$$

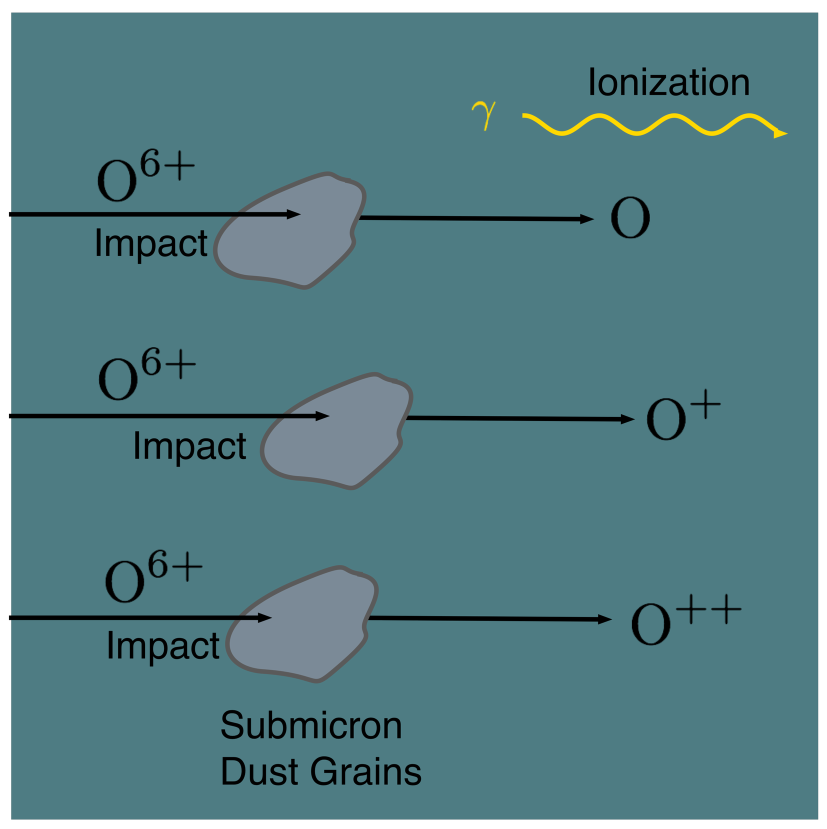
- Absorption, desorption, and ionization are assumed to be in equilibrium. Therefore the production rate of pickup ions equals the impact rate.

$$S^+_{\rm recy}(r) = S_{\rm impact}(r) \quad (2)$$

Solar Wind Neutralization

MECHANICAL PROCESS

- 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 neutral atoms become singly-charged ions, and the singly-charge ions becomes doubly-charged ions once ionized by photoionization, charge exchange with solar wind protons, or electron impact.



FORMALISM

- Production of singly-charged pickup ions depends on the impact rate, charge state fraction after penetration, and the loss rate probability due to ionization.
- Neutral atoms produced after grain penetration have a probability of becoming singly-charged pickup ions due to ionization – adding to the singly-charge pickup ions population.

$$S^+_{\rm neut}(r) = \eta^+ S_{\rm impact}(r) P^+(r) + \eta^0 S_{\rm impact}(r) P^0(r) \quad (3)$$

- The survival and production probabilities beyond penetrating the grains depend on the ionization rates, distance traveled, and solar wind speed.

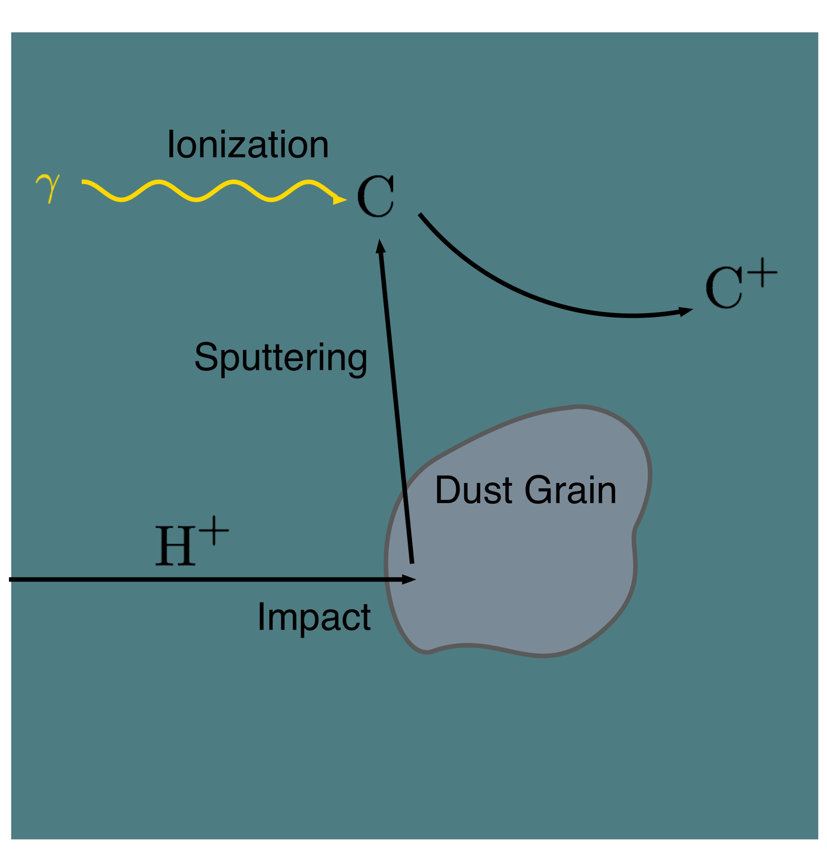
$$P^+(r) = \exp\left[-\frac{\beta^+_{ion} r_1^2}{u}\left(\frac{1}{r_i} - \frac{1}{r_f}\right)\right] \quad (4)$$

$$P^0(r) = 1 - \exp\left[-\frac{\beta^0_{ion} r_1^2}{u}\left(\frac{1}{r_i} - \frac{1}{r_f}\right)\right] \quad (5)$$

Sputtering

MECHANICAL PROCESS

- Solar wind protons bombard dust grains.
- Carbon is ejected from the grain when given an energy greater than the surface binding energy of the grain.



FORMALISM

- Assume an Fe-rich grain composition like that of asteroid belt grains.
- Assume these Fe-rich grains make up the entire grain population.
- The rate of sputtered carbon is related to the rate of impacting protons by the sputtering yield.

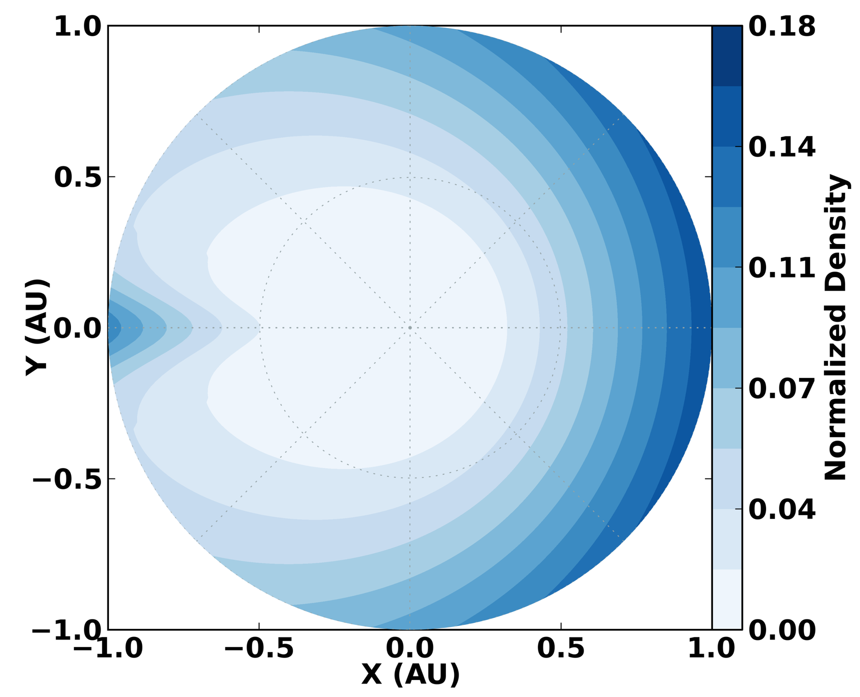
$$S^+_{\rm sput}(r) = Y S_{\rm impact}(r) \quad (6)$$

- Sputtering yield of carbon based on laboratory experiments.
- Assume that the sputtering of carbon is proportional to the percent of carbon within the grain.
- The sputtering of oxygen within Fe-rich grains is negligible.

Interstellar Source

MECHANICAL PROCESS

- Interstellar neutral atoms penetrate the heliosphere and follow hyperbolic orbits due to the sun's gravity.
- The neutral atoms becomes ionized due to photoionization, charge exchange, and electron impact.
- Once ionized, they are picked up by the solar wind.



FORMALISM

- The hot gas model calculates the spatial distribution of interstellar neutral atoms within the heliosphere.
- The production rate per unit volume depends on the ionization rates and neutral density.

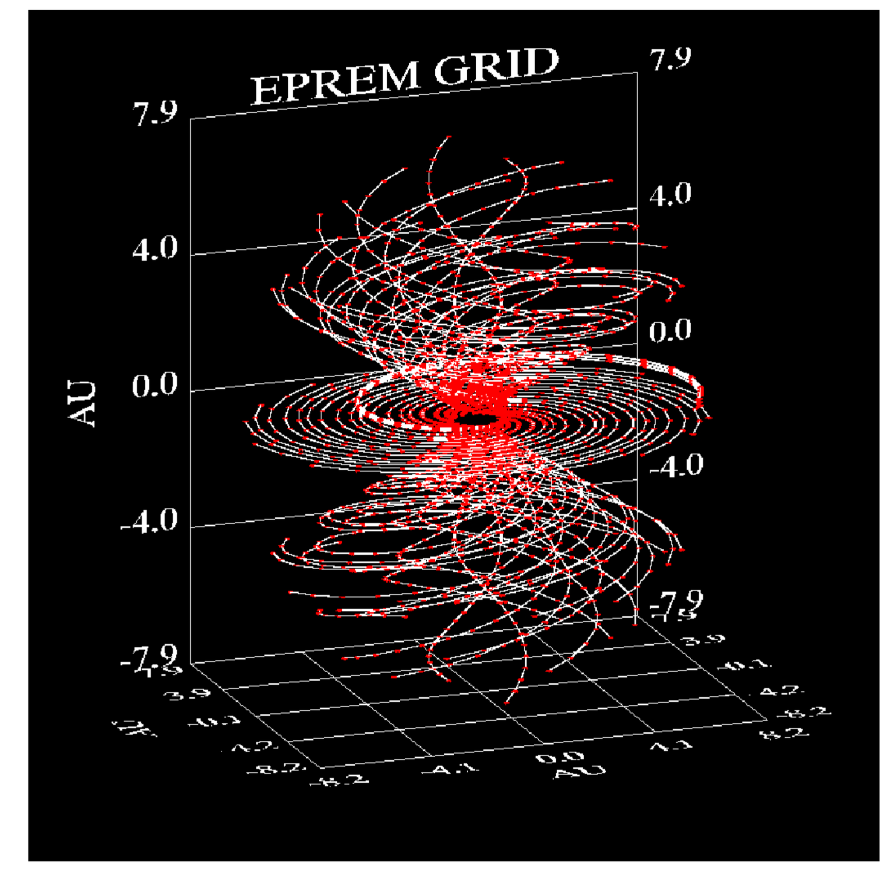
$$S^+_{\rm int}(r) = (\beta_{\rm ph} + \beta_{\rm ch} + \beta_{\rm el})\left(\frac{r_1}{r}\right)^2 n_{\rm O}(r,\theta). \quad (7)$$

- Although electron impact scales slightly steeper than r^{-2}, we assume it scales as r^{-2} for simplicity.

EPREM

Energetic Particle Radiation Environment Module (EPREM)

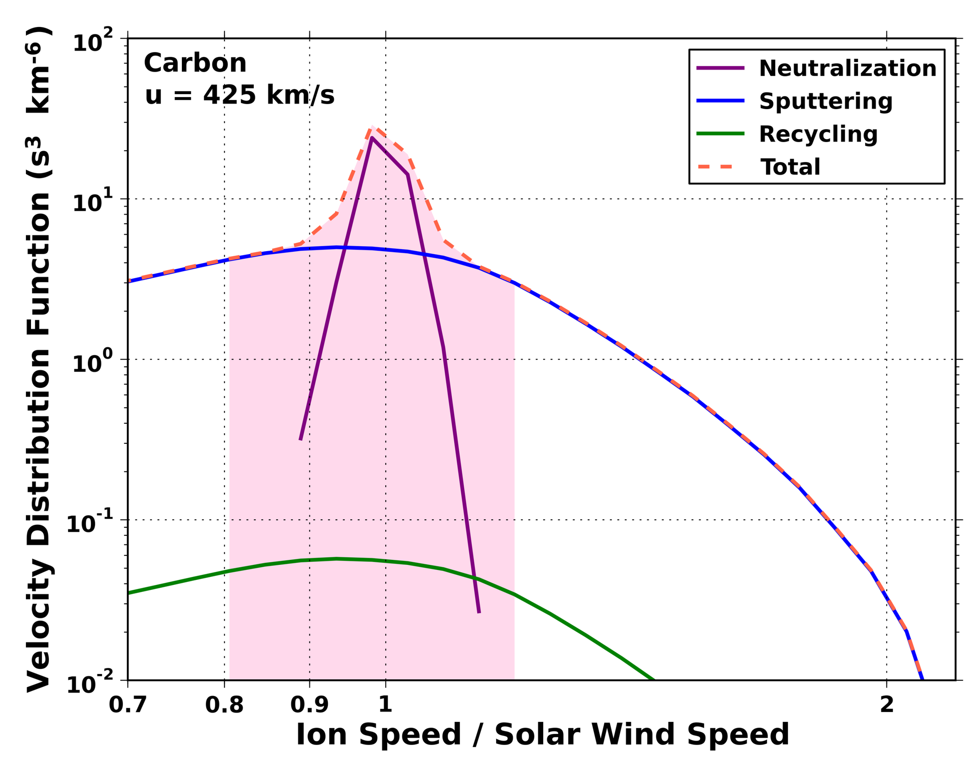
- Models particle transport throughout the heliosphere.
- Solves the focused transport equation and convection-diffusion equation.
- Takes into account: convection, streaming, adiabatic cooling, adiabatic focusing, pitch-angle scattering, perpendicular diffusion, and drift.

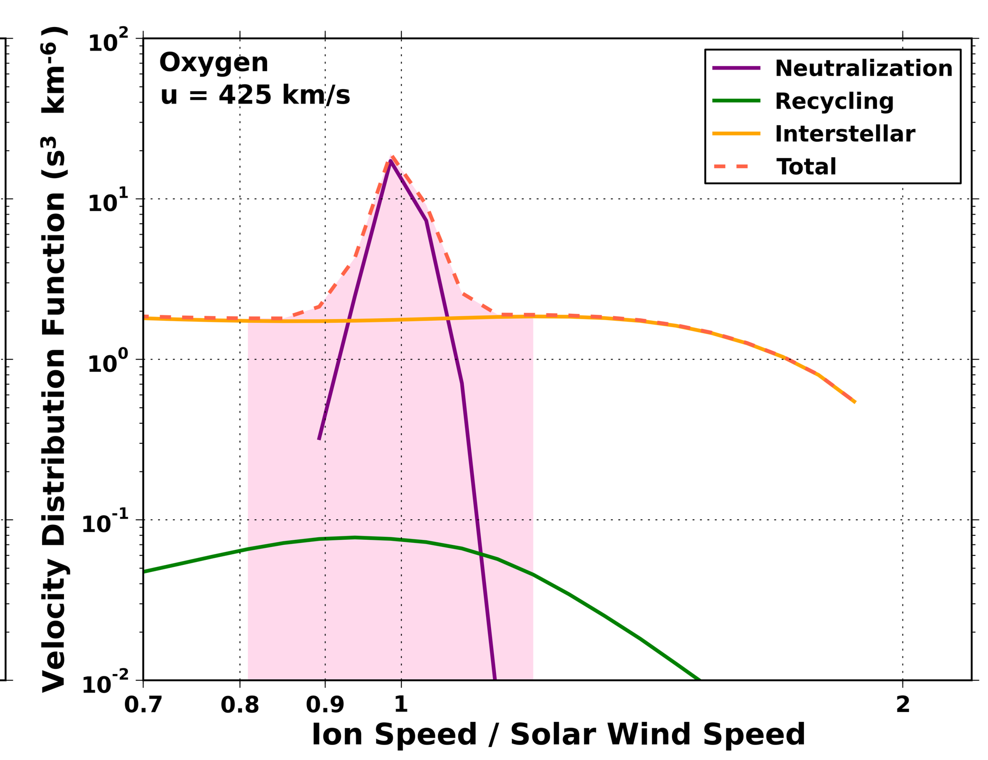


PROCEDURE

- Add the production rate per unit volume of inner source and interstellar carbon and oxygen into EPREM.
- 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 CTOF data.

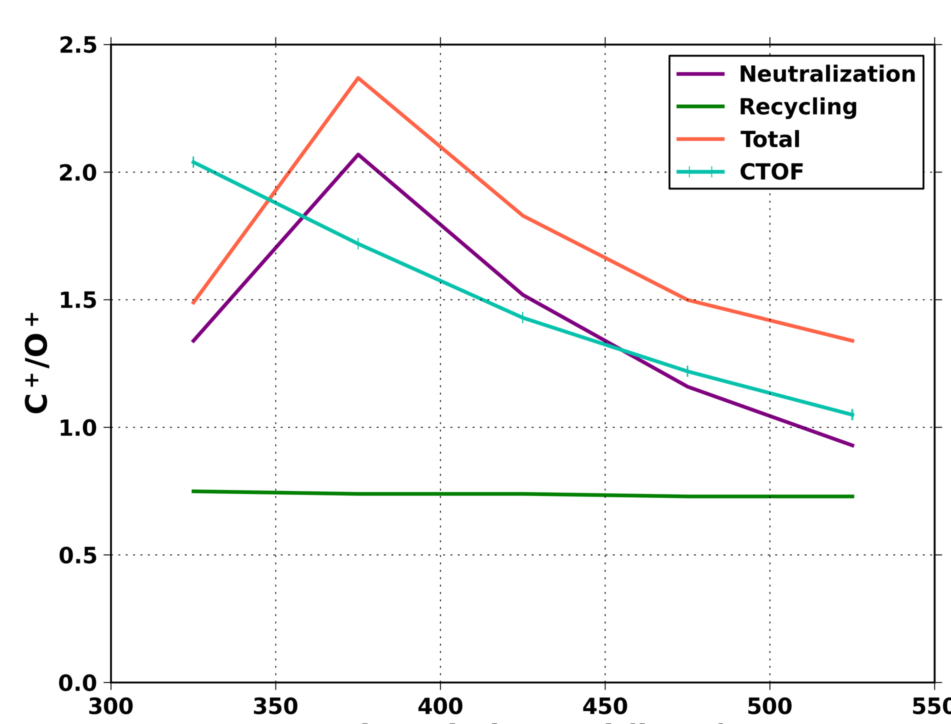
Results

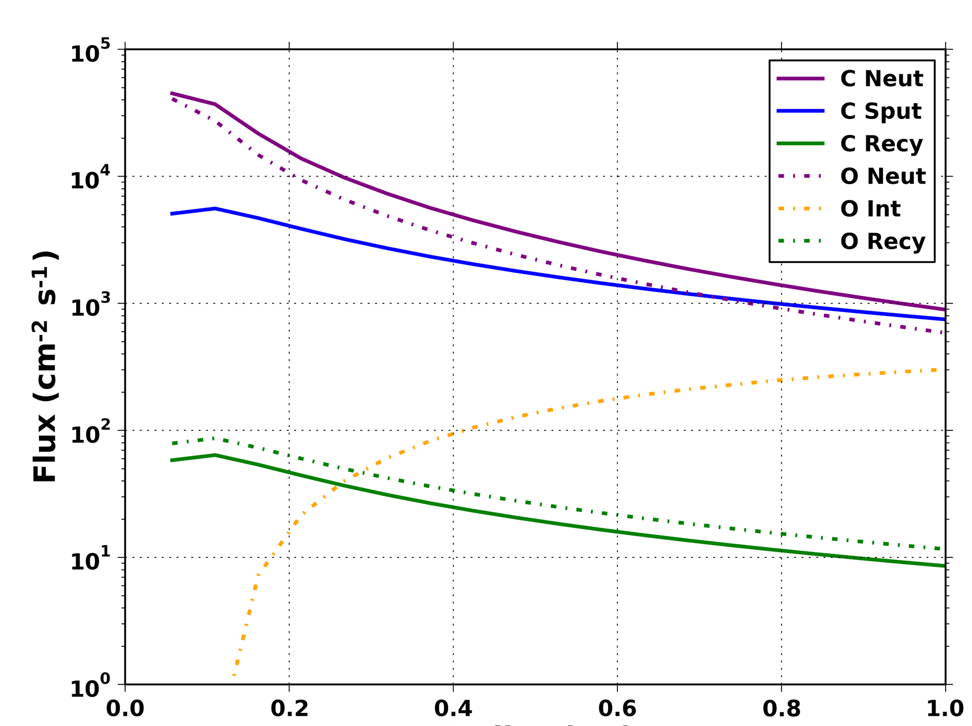




Flux and Abundance of Inner Source Carbon and Oxygen at 1 AU for u = 425 km/s

Ion	Neutralization	Recycling	Sputtering	Interstellar	Total	CTOF
C$^+$	8.95×10^2 cm^{-2}s^{-1}	8.59 cm^{-2}s^{-1}	7.50×10^2 cm^{-2}s^{-1}	-	1.65×10^3 cm^{-2}s^{-1}	-
O$^+$	5.87×10^2 cm^{-2}s^{-1}	1.16×10^1 cm^{-2}s^{-1}	-	3.03×10^2 cm^{-2}s^{-1}	9.02×10^2 cm^{-2}s^{-1}	-
C$^+$/O$^+$	1.52	0.74	-	-	1.83	1.43





Summary

- The total C$^+$/O$^+$ ratio is comparable to CTOF for varying solar wind speeds.
- The total C$^+$/O$^+$ ratio mainly follows solar wind neutralization.
- C$^+$/O$^+$ produced by solar wind recycling follows solar wind C/O.
- The majority of inner source pickup ions produced near the sun are from solar wind neutralization, followed by sputtering.
- C$^+$ and O$^+$ produced by solar wind recycling are negligible. However, sputtering may still release solar wind C and O imbedded in the surface of the grain.

Remaining Questions

- How does the velocity distribution of C$^+$ and O$^+$ measured by CTOF compare to the simulation results?
- What is the flux of C$^+$ and O$^+$ measured by CTOF?
- What causes C$^+$/O$^+$ to decrease for very slow solar wind speeds?
- How does each production mechanism depend on grain size?
- What is the distribution of each composition of grains near the sun, as compared to asteroid, meteoritic, and interstellar grains?
- Are implanted solar wind ions sputtered?