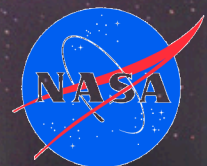


# Inner Source Pickup Ions

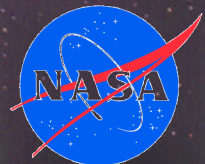
Pran Mukherjee





# Outline

- Introduction
- Current theories and work
- Addition of new velocity components
- Summary
- Questions

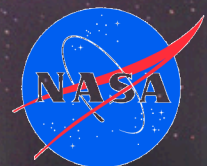




# Introduction

- First, a few definitions:
  - Pickup ion: A neutral atom in the heliosphere that becomes ionized and is then “picked up” by the solar magnetic field and swept outward
  - Inner source: A source of pickup ions near the sun, primarily inside 0.5 AU.
  - Alfvén wave: A noncompressive disturbance wave propagating along a magnetic field line with a speed of  $V_A = \frac{B_0}{\sqrt{\mu\rho}}$
  - bAdiabatic cooling: Adiabatic cooling occurs when the pressure of a gas is decreased, such as when it expands into a larger volume. The relation is:

$$PV^\gamma = \text{const}$$





# Introduction

## Interstellar pickup ions

From outside the heliosphere

Generally ionized between 0.5-4 AU

Flat distribution with cutoff at  $W=2$

Composition thought to match interstellar medium

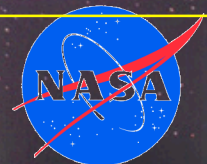
## Inner source pickup ions

From interplanetary dust, comet tails

Ionized at 50 solar radii or less

Distribution peaks at or before  $W=1$  (critical region  $W=0.6-0.8$ )

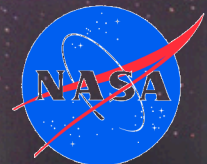
Composition largely matches solar wind, including volatiles





# Current Theories

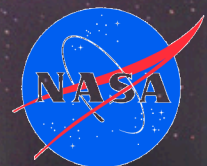
- Work to date takes into account dust cloud population from 10-50 solar radii
- Stationary neutrals assumed for both interstellar and inner source pickup
- $C^+$ ,  $N^+$ ,  $Ne^+$ ,  $O^+$  population indicates solar wind embed/release process with dust grains since in the SW those ions are highly charged, and  $Ne^+$  wouldn't be in interplanetary dust





# Addition of new velocity components (1)

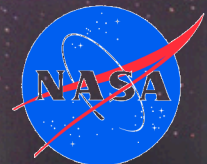
- Current theories assume stationary neutrals
- Neutrals arise from dust grains spiraling into the sun on Keplerian orbits
- These orbits become much faster as they get closer to the sun, approaching and even surpassing the speed of the solar wind
- The neutrals MUST have the same initial speed as the dust grains, and this translates into significant velocity perpendicular to the B-field





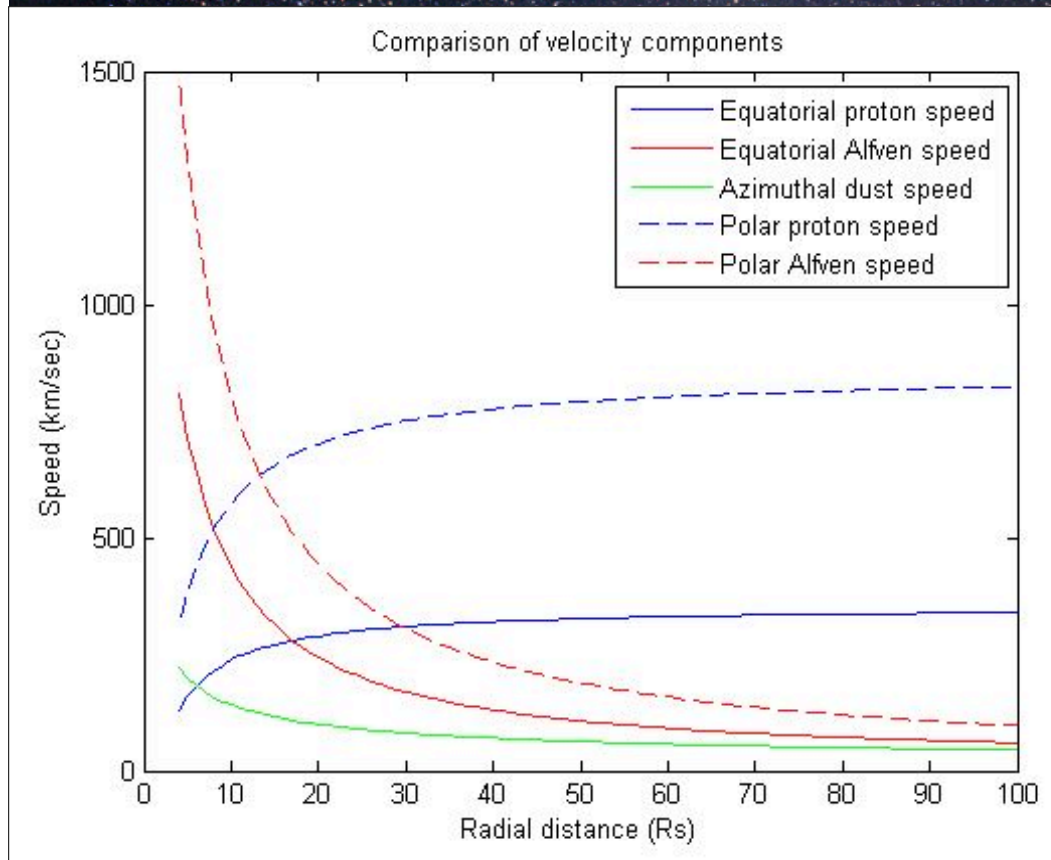
# Addition of new velocity components (2)

- Most models of PUI distributions assume a frame moving with the solar wind, in which we can remove the motional electric field  $E = -\overline{U} \times \overline{B}$
- As one gets closer to the sun, the Alfvén wave speed rises significantly, and these waves impart an electric field to the particles as they pass
- We propose that the full thermal motion of newly picked up inner source ions must take into account both the Alfvén wave speed and the rotational motion of the particles
- Result: far higher initial thermal velocity than previously considered, which relates to the adiabatic cooling rate



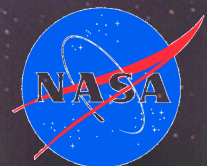


# Velocity Comparison



Solar wind and Alfvén wave speeds in the near solar region.

The field-aligned speed of ions is the sum of  $U_p$  and  $V_a$ , and is thus dominated by  $V_a$ , while the perpendicular velocity at injection will depend on the azimuthal speed of the source dust.





# Relevant Formulae

Proton Speed:

$$U_p = 130 * (2.5 - 1.5e^{\frac{-\lambda}{30}}) * e^{(1-\frac{4}{R})}$$

Alfven Speed:

$$V_a = 20 * \sqrt{(B_r^2 + B_{\phi}^2) / N_e}$$

where

$$B_r = \frac{2 * 10^5}{R^2}$$

$$B_{\phi} = \frac{2 * R * B_r * \cos(\lambda)}{U_p}$$

$$N_e = \frac{2 * 10^8 * (0.7 + 0.3 * e^{\frac{-\lambda}{30}})}{U_p * R^2}$$

R: radial distance in solar radii

B: magnetic field in nanoTesla (nT)

U: flow speed in km/s

V<sub>a</sub>: Alfvén speed in km/s

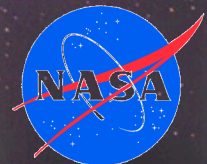
N: number density in cm<sup>-3</sup>

Lambda: latitude in degrees  
(0 at equator)

G: Gravitational constant

Orbital speed:

$$V_{\text{orbit}} = \sqrt{\frac{G * M_{\text{sun}}}{R}}$$





# Neutral Source Population

Dust distribution

$$D = \frac{D_0 e^{\frac{-\lambda}{r}}}{r}$$

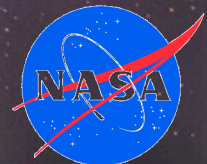
Neutral Production Rate

$$P \cong P_0 \left( \frac{r_0}{r} \right)^\alpha$$

Neutral Population

$$N_n = D * P = \frac{D_0 P_0 r_0^\alpha}{r^{1+\alpha}} e^{\frac{-\lambda}{r}}$$

We considered profiles for  $\alpha=1$  and  $\alpha=2$ ,  $\lambda=6-30$  solar radii, and scaled the constant  $D_0 P_0$  as needed to match values measured at 1 AU.





# Pickup Ion Flux Density

$$\nabla \cdot (n_i u) = N_n \beta \left( \frac{r_0}{r} \right)^2$$

Continuity eqn.

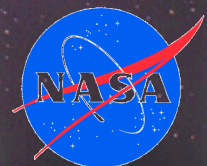
$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 n_i u) = N_n \beta \left( \frac{r_0}{r} \right)^2$$

Assume radial  
variance

$$\int \frac{d}{dr'} (r^2 n_i u) dr' = \int_1^r N_n \beta r_0^2 dr'$$

$$r^2 n_i u = \beta r_0^2 \int_1^r N_n dr'$$

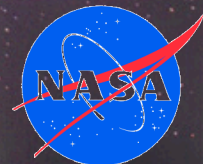
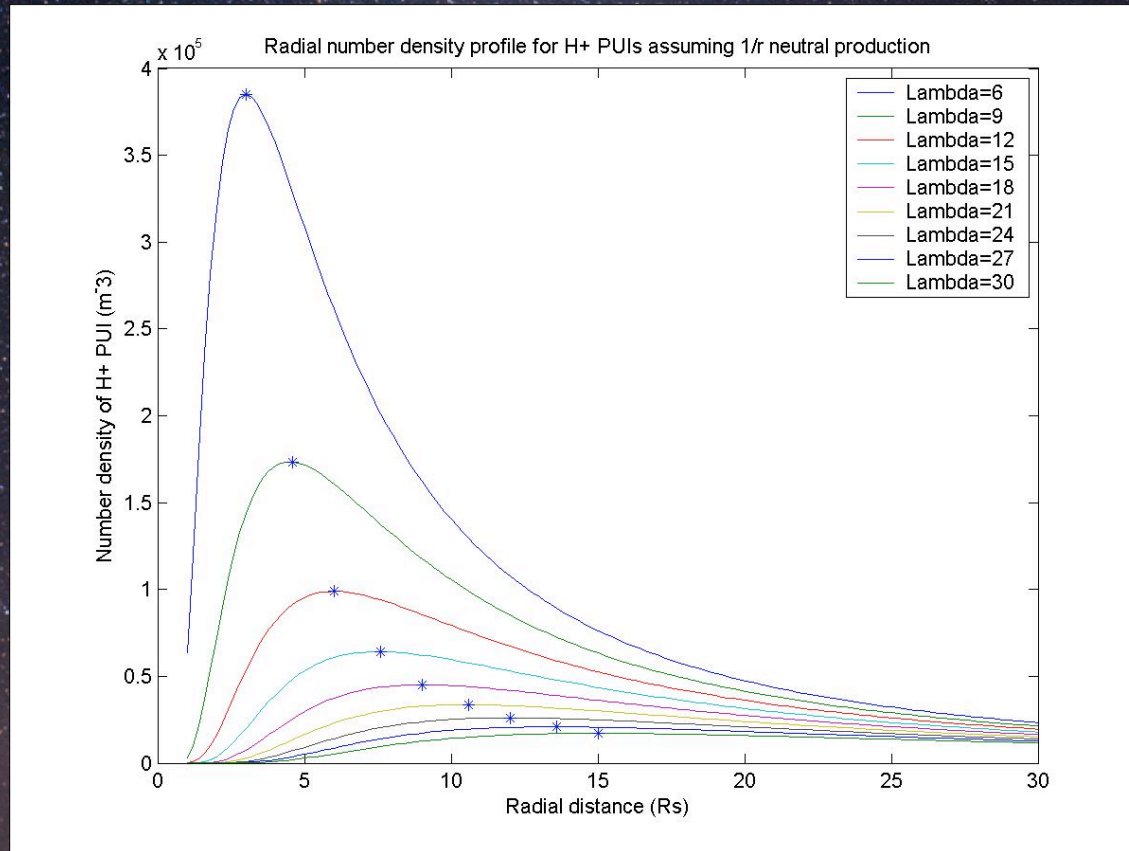
$$n_i = \frac{\beta}{u} \frac{r_0^2}{r^2} \int_1^r N_n dr'$$





# $\alpha=1$ case: $1/r$ neutral production

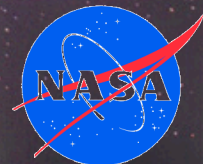
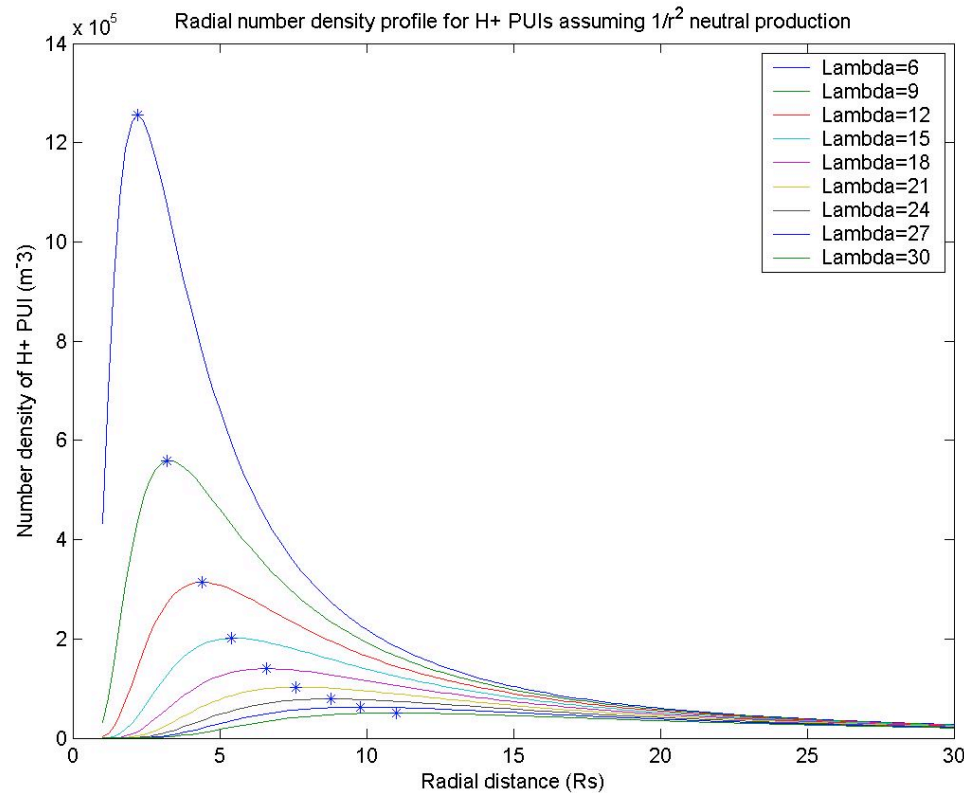
$$n_i = \frac{D_0 P_0 r_0^3 \beta \left( e^{\frac{-\lambda}{r}} - e^{-\lambda} \right)}{\lambda r^2 u}$$





# $\alpha=2$ case: $1/r^2$ neutral production

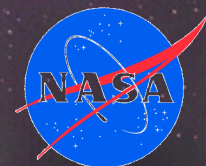
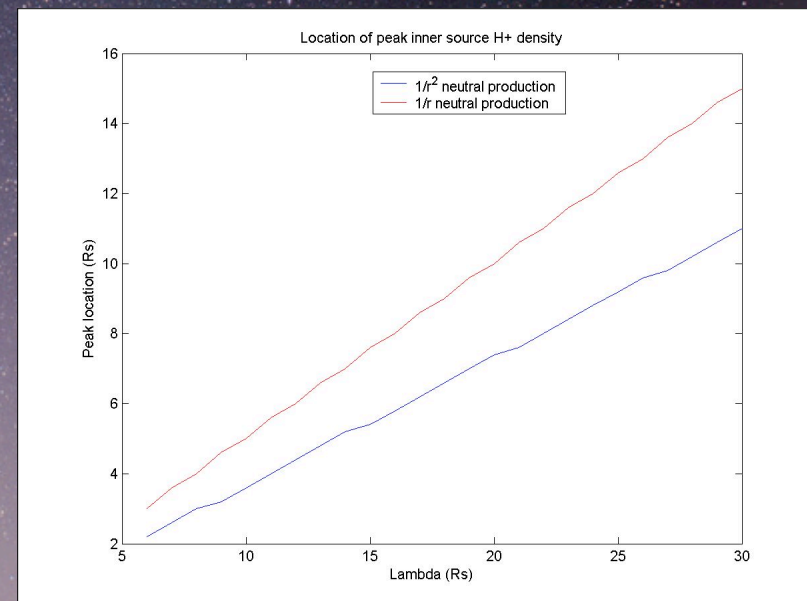
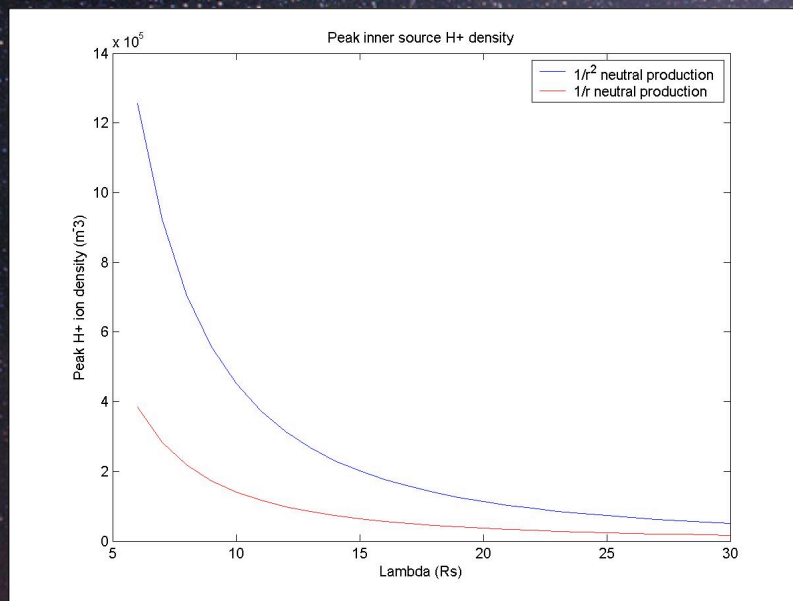
$$n_i = \frac{D_0 P_0 r_0^4 \beta \left( (\lambda + r) e^{\frac{-\lambda}{r}} - r(\lambda + 1) e^{-\lambda} \right)}{\lambda^2 r^3 u}$$





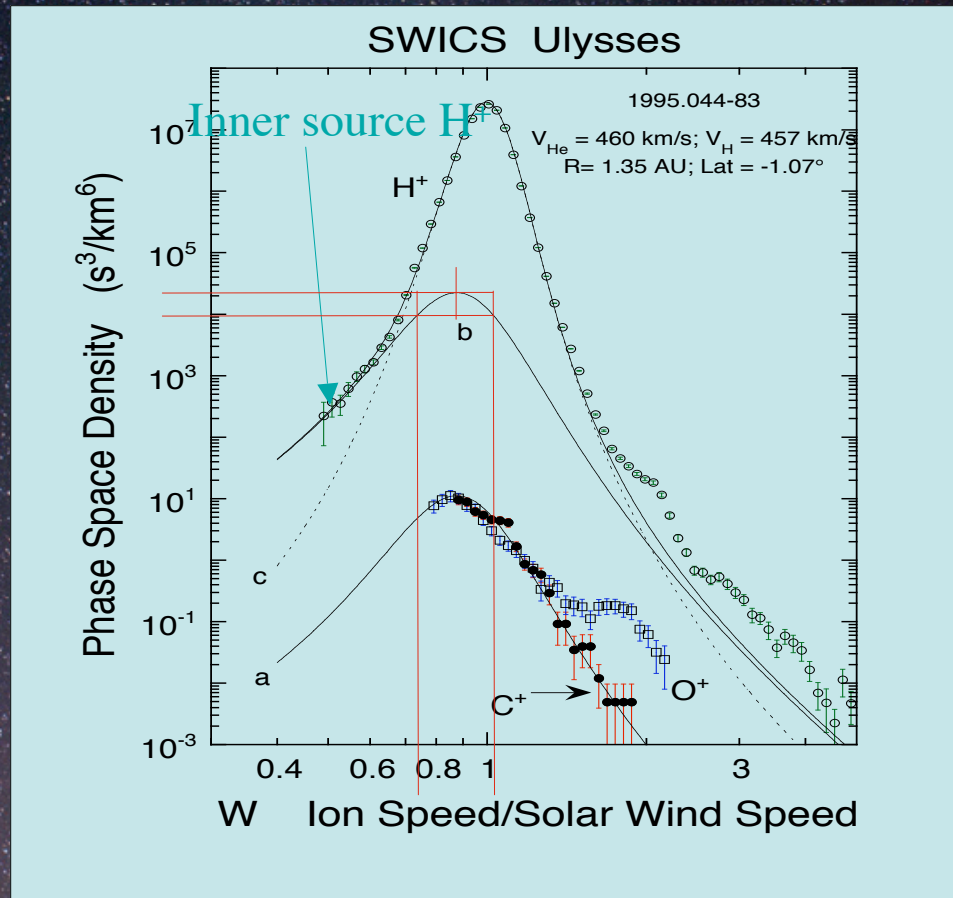
# Observations

- Increasing lambda decreases peak density
- Increasing lambda moves peaks outward
- $\alpha=1$  case uniformly has lower peaks at further radial distances than  $\alpha=2$

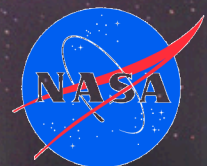




# Observed $H^+$ distribution and fit



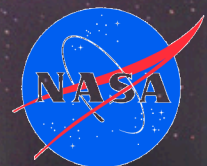
The  $1/e$  width of the inner source distribution is approximately  $0.33 * \text{Solar Wind Speed}$ . Thanks to Dr. George Gloeckler for this data.





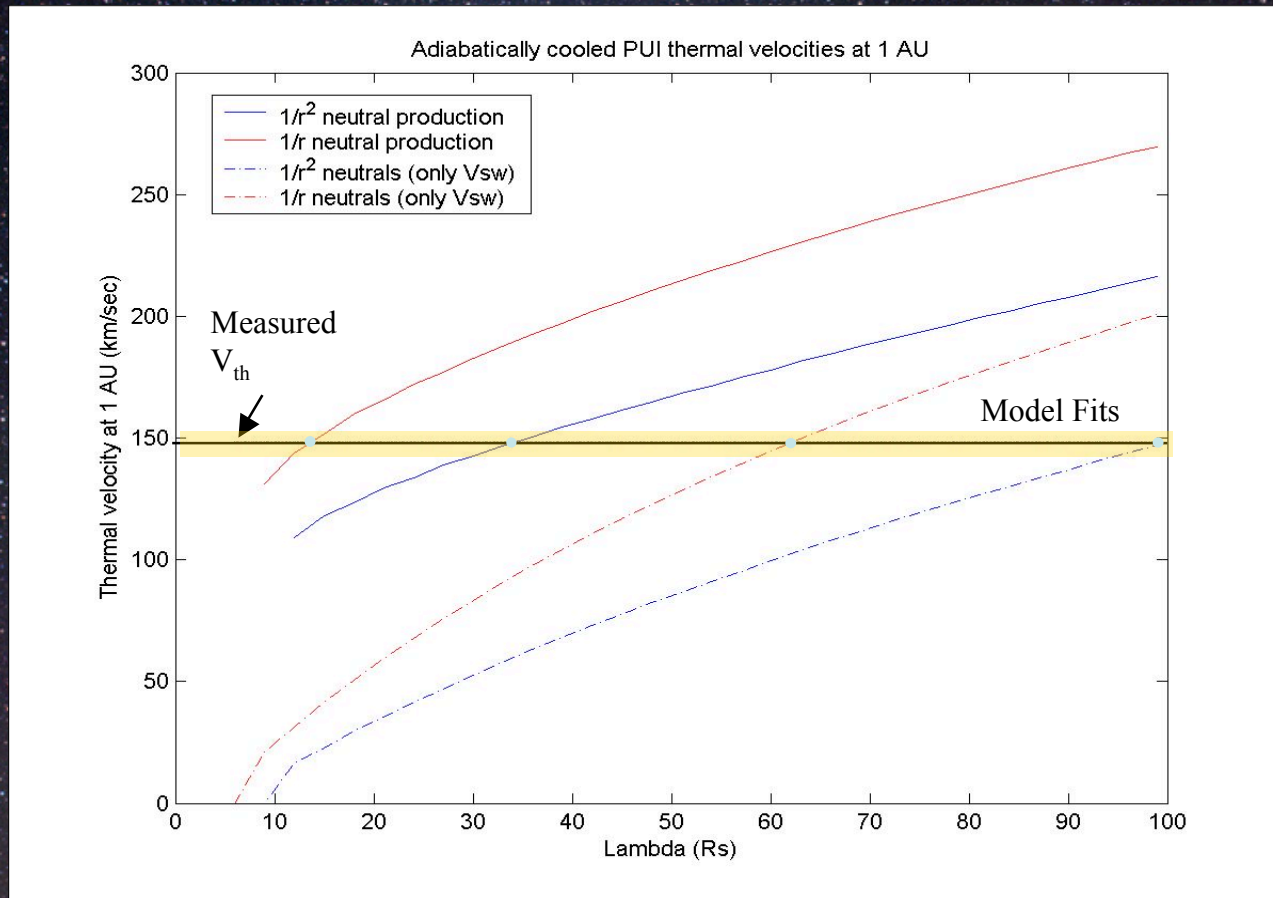
# Adiabatic Cooling

- Adiabatic relation: 
$$\left( \frac{V_{th,1AU,obs}}{V_{th,peak}} \right)^2 = \left( \frac{n_{1AU}}{n_{peak}} \right)^{\gamma-1}$$
- With the Gloeckler result, we now have all the values necessary
- Solve for the thermal velocity at 1 AU
- Lambda values where the model fits the measured data can be traced back to a given pickup ion peak location

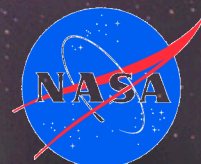




# Model Results



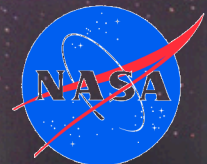
Modeled thermal velocities at 1 AU for  $\alpha=1$  and  $\alpha=2$ . Dotted lines include only the standard  $V_{sw}$  velocity component, solid lines include proposed additional components.





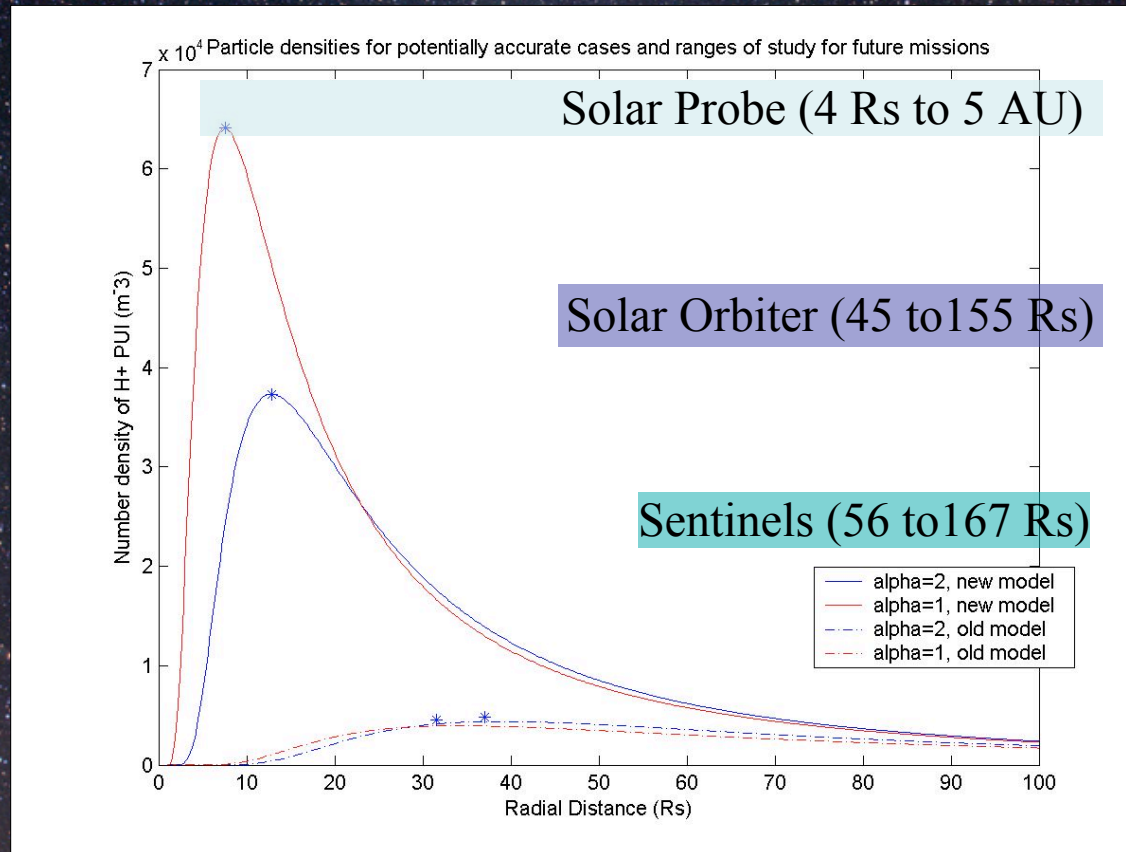
# Observations

- Lambda values for our model at 15Rs and 35Rs
- Lambda values for traditional model at 63 Rs and 101Rs.
- Peak locations: 7.6, 12.8, 31.6, and 37 Rs respectively
- Pickup peaks far closer for new model than traditional model
- Three missions planned for near-solar observation: Sentinels, Solar Orbiter, and Solar Probe.

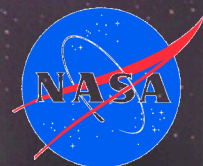




# Model matches and upcoming missions



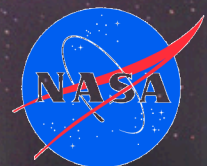
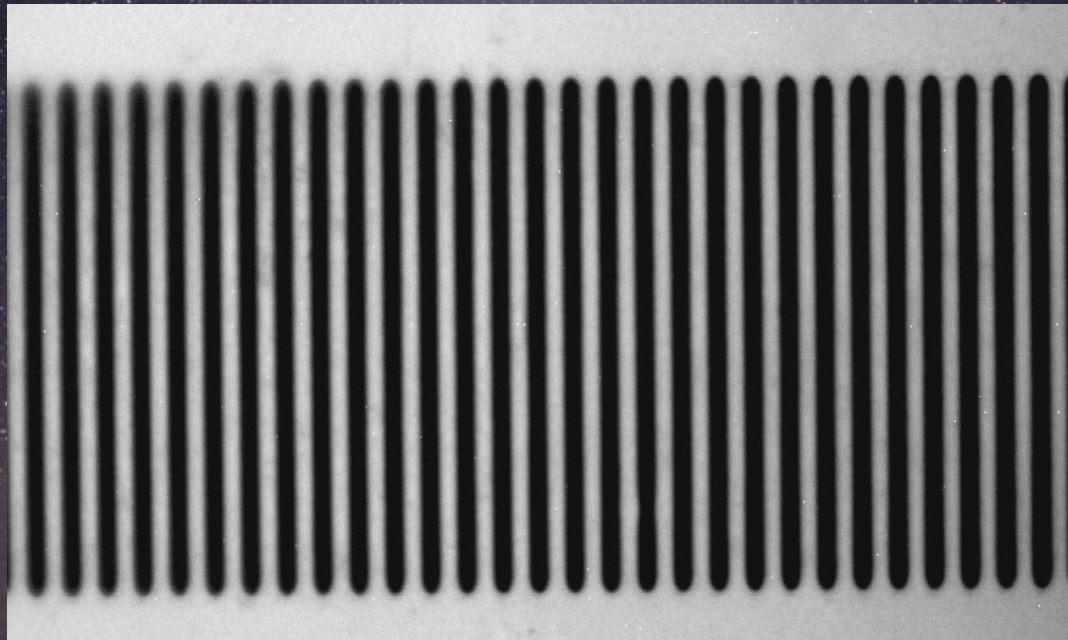
Particle density curves for  $\lambda$  values of model matches.  
 $\alpha=1$  cases have higher peaks than  $\alpha=2$  cases;  $\lambda$  values for the two cases do not match as in previous figures.  
Also displayed are orbit ranges for upcoming missions.





# Hardware work

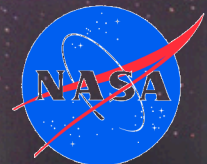
- I am working on nanoscale ultraviolet filters that may be of significant use on those missions





# Summary

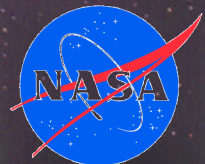
- Near the Sun pickup ions have velocity components not seen in the outer heliosphere
- We modeled H<sup>+</sup> PUI densities for a wide range of parameters and used an adiabatic cooling model to determine which parameters match conditions measured at 1 AU
- Results indicate a pickup process happening far closer to the sun than traditional models predict
- Upcoming measurements will determine who is right





Thank you.

Questions?





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