Suprathermal Electron Scattering: Helios Observations

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Abstract

Electron velocity distribution functions (eVDFs) in the ambient solar wind are comprised of core, halo, and strahl components. The core is known as the "thermal" population due to its Maxwellian shape, while the halo and strahl deviate from a Maxwellian and are each known as "suprathermal" populations. Coulomb collisions are a physical mechanism by which a distribution is expected to relax towards a single isotropic Maxwellian. We conduct statistical least-squares fits to Helios 1 eVDFs using a model function that describes the core, halo, and strahl separately. Using a generic estimation of the "collisional age", we then discuss the effect of Coulomb collisions on the thermalization of electron velocity distribution functions (eVDFs). We see that the fractional density of the suprathermals falls off dramatically with increasing collisional age.

1. Introduction

Our method involved fitting Helios eVDFs to a 3-component model:

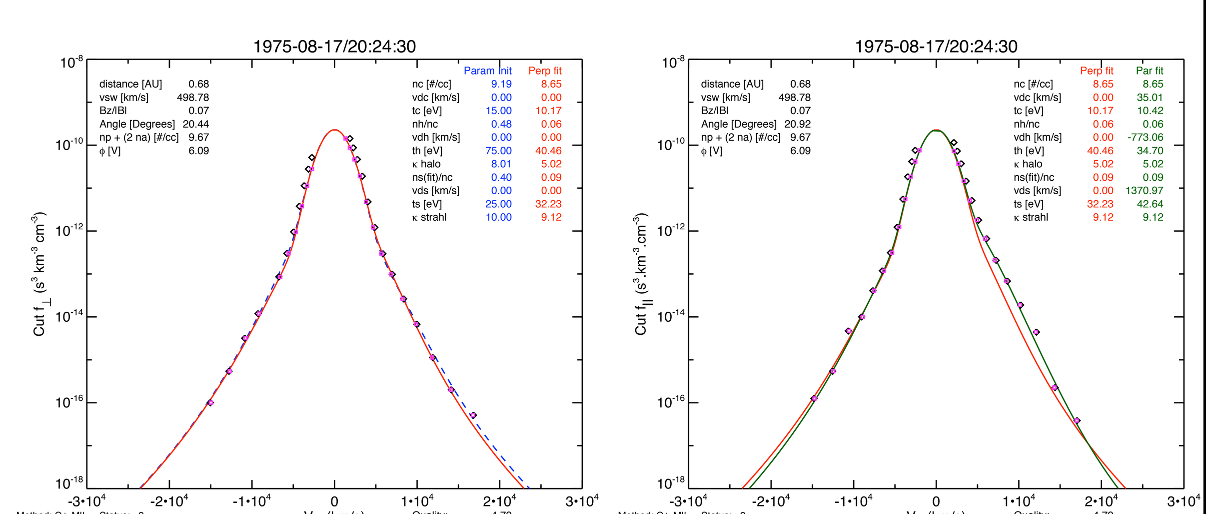
- bi-maxwellian core
- bi-kappa halo
- truncated bi-kappa strahl[6]

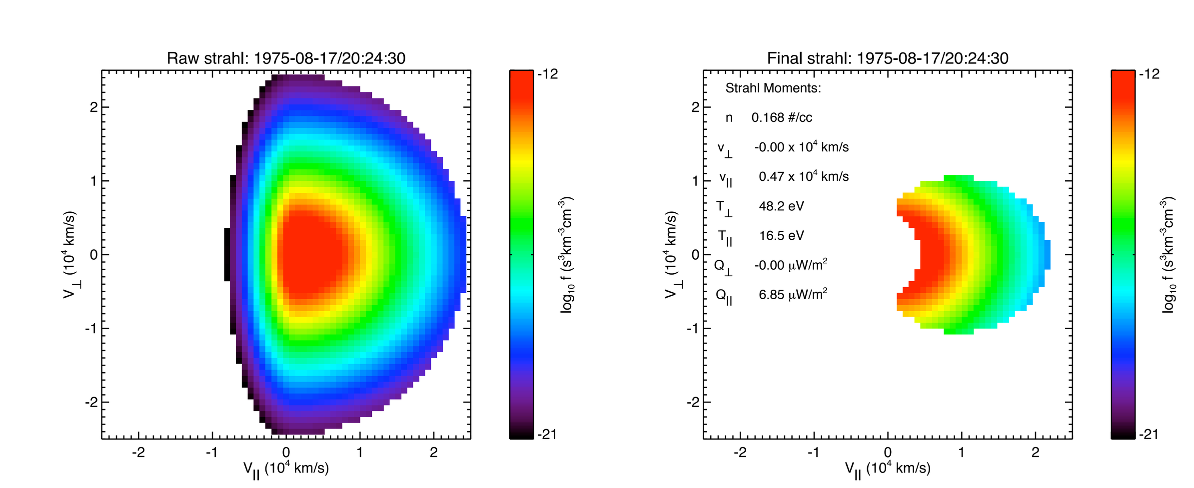
We use fit parameters obtained from the eVDFs to analyze general trends observed in the solar wind

2. Data

Our data covers a 6.5 year range, from Dec. 12, 1974 to Jun. 26, 1981. For this study, we include only data for which $\frac{|B_z|}{B} < .1$ and eVDF data was collected within a 10° angle of the $B_\|$ direction. We correct for a spherically symmetric spacecraft potential, which we estimate by finding the potential that matches the electron fit density to the ion moment density.

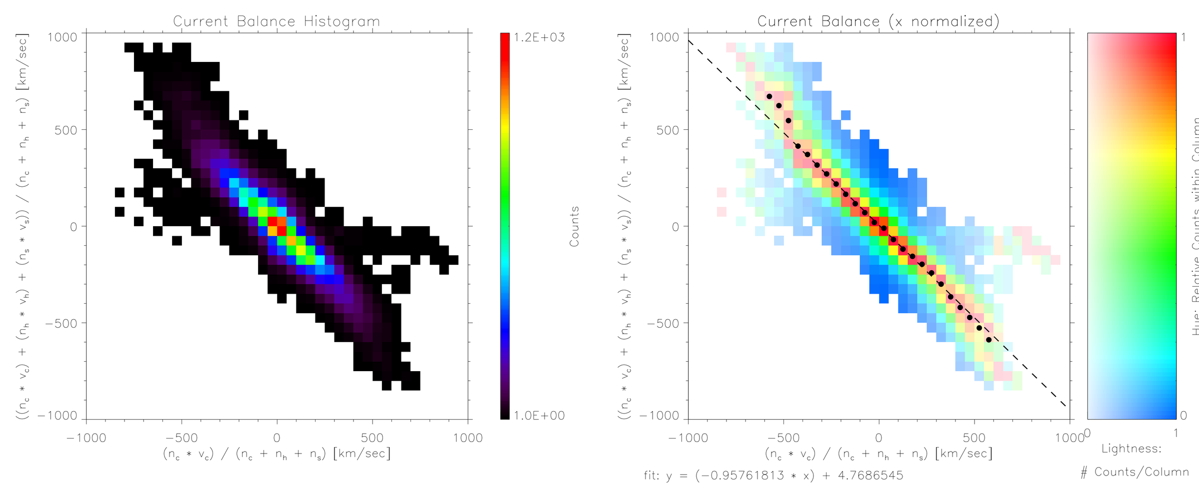
2.1 Fast Wind Example





We use an ad hoc model function to fit the strahl. After fitting, we calculate a parameter $\delta = \frac{f_s}{f_c+f_h}$ and define the strahl to be where $\delta > 1$. The strahl is obtained from the fit function at these points.

3. Current Balance



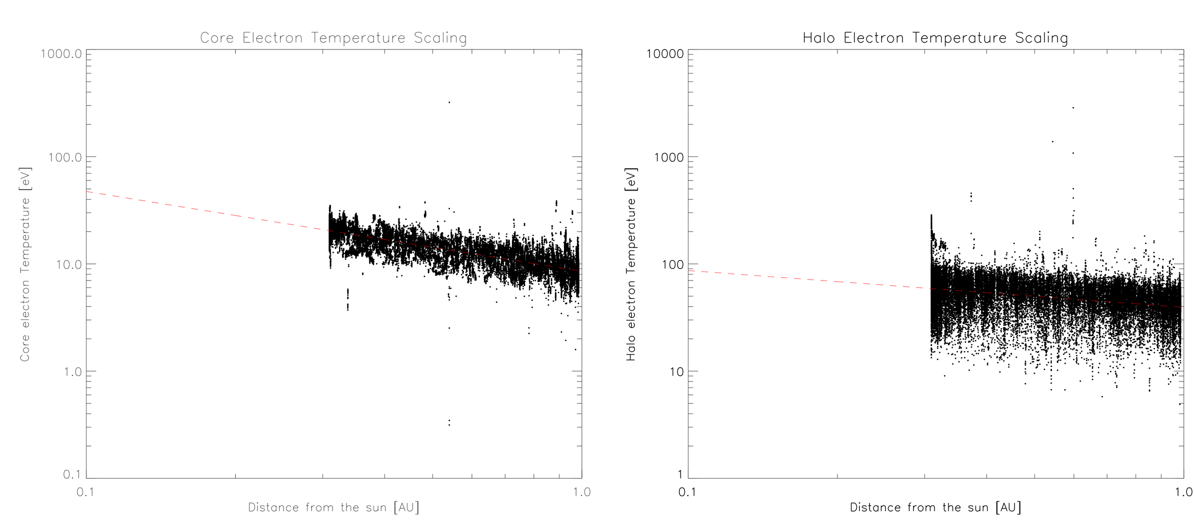
The condition for electron current balance is:

$$n_c v_c + n_h v_h + n_s v_s = 0 \qquad (1)$$

We plot a 2D histogram of the distribution of our fits (LHS), and that same distribution normalized by the peak bin in each vertical column (RHS). The fitted diagonal matches equation (1).

Our electron velocities are measured with respect to the ion charge drift velocity: $v_{ion} = \frac{n_p v_p + 2n_\alpha v_\alpha}{n_p + n_\alpha}$. Because the electrons do not tend to have a bulk drift relative to this frame, total current is zero on average.

4. Radial Temperature Scaling



Temperature is observed to scale as a power law with distance[3]. $T = T_0 r^{-\alpha_T}$ where T_0 is a constant. α_T depends on particle population and solar wind speed. Below we summarize our fit results.

-	all v_{sw}	$v_{sw} < 400$	$400 < v_{sw} < 550$	$550 < v_{sw}$
γ_{Te}	0.568 ± 0.003	0.651 ± 0.004	0.463 ± 0.003	0.284 ± 0.010
$\gamma_{Te,core}$	0.749 ± 0.003	0.789 ± 0.003	0.651 ± 0.005	0.516 ± 0.010
$\gamma_{Te,halo}$	0.330 ± 0.005	0.367 ± 0.007	0.297 ± 0.008	0.090 ± 0.016
γ_{Tp}	0.599 ± 0.010	0.967 ± 0.012	0.700 ± 0.004	0.317 ± 0.020

5. Collisional Age

The collisional frequency ν represents the rate of Coulomb collisions in a plasma. An electron distribution function measured in the solar wind by Helios will show the signature of the total number of collisions it has experienced. The "collisional age" A_e is defined:

$$A_e = \int_{t_1}^{t_2} \nu \, \mathrm{d}t \qquad (2)$$

The collisional frequency for electron-electron collisions of a Maxwellian distribution is[1]:

$$\nu = 2.91 \ln(\Lambda) n_e T_e^{-3/2} \qquad (3)$$

Where $\ln(\Lambda)$ is the Coulomb logarithm. We assume that the electron temperature of a single electron distribution evolves as a power law with r (see section 4). Assuming that $n = n_0\left(\frac{r}{r_{base}}\right)^{-2}$, we can integrate over the region where v_{sw} is constant to obtain the collisional age. Doing this, we get if $\alpha_T \neq \frac{2}{3}$:

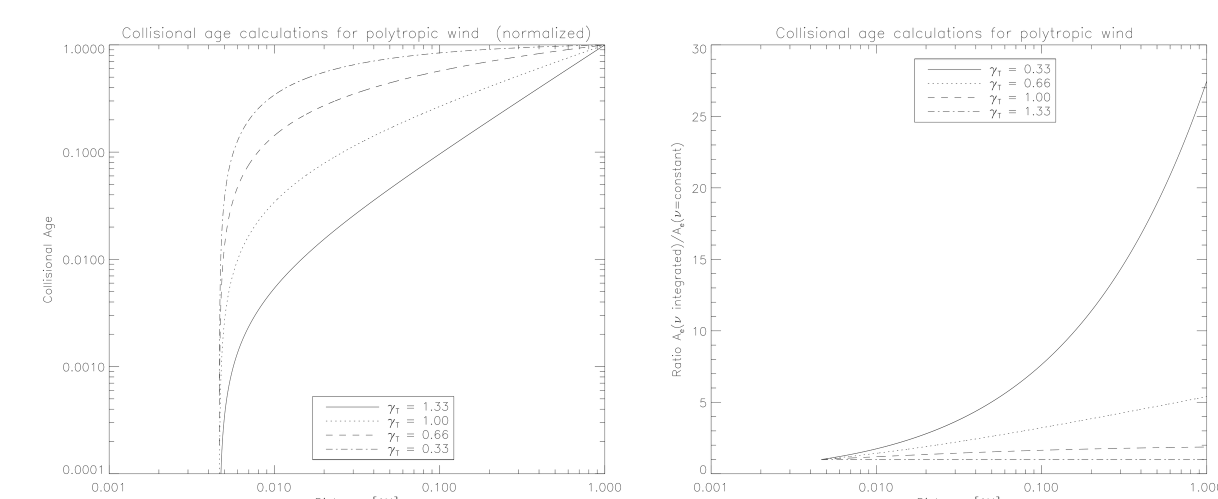
$$A_e = \frac{\nu r}{\left(\frac{3\alpha_T}{2} - 1\right) v_{sw}} \left(1 - \left(\frac{r}{r_{base}}\right)^{1-(3\alpha_T/2)}\right) \qquad (4)$$

And if $\alpha_T = \frac{2}{3}$:

$$A_e = \frac{\nu r}{v_{sw}} \ln\left(\frac{r}{r_{base}}\right) \qquad (5)$$

The above equations describe the inferred collisional age given locally measured paramaters. These equations can also be rewritten to show the evolution of the collisional age given the initial values at the base of integration. Doing this and defining $R \equiv \frac{r}{r_{base}}$, we see that the solar wind is divided into 3 collisional regimes. $2/3$ appears to be a special value for α_T (compare with table in section 4).

- Case 1: If $\alpha_T > \frac{2}{3}$, then $A_e \to \infty$ as $R \to \infty$ (Approximate power law)
- Case 2: If $\alpha_T = \frac{2}{3}$, then $A_e \to \infty$ as $R \to \infty$ (Logarithmic)
- Case 3: If $\alpha_T < \frac{2}{3}$, then $A_e \to$constant as $R \to \infty$ (Asymptote to a constant)



Above we compare the collisional age as a function of r for different α_T. r_{base} is approximated as the top of the photosphere. In the LHS plot, we see that for low values of α_T, the collisional age is already leveling off to a constant by the time the solar wind reaches 1 AU.

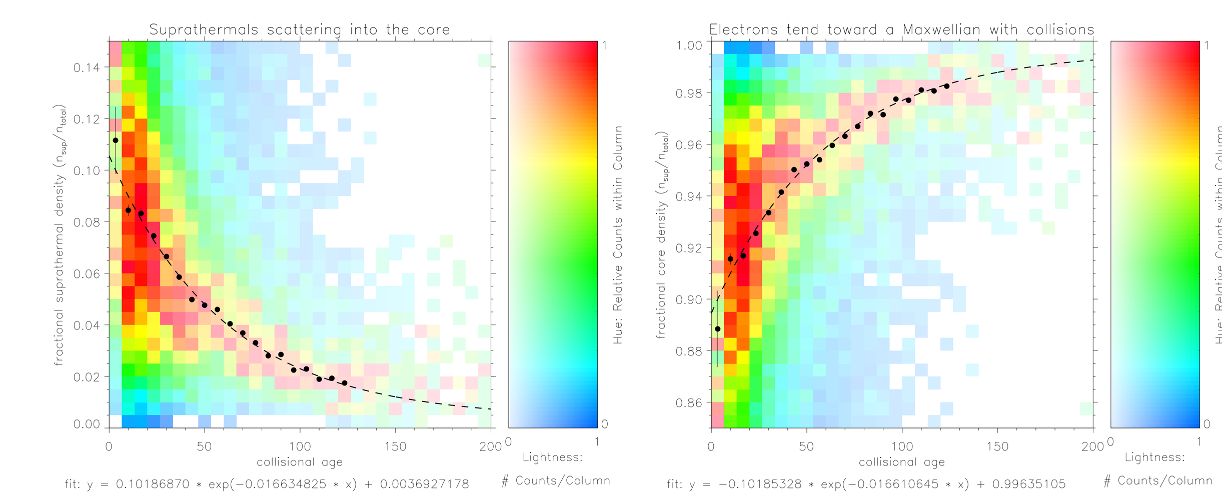
The collisional age is often approximated by assuming a constant collision frequency ν. This is only true if $\alpha_T = 4/3$, i.e. the particles expand adiabatically. In the RHS plot, we compare the integrated value for A_e with the value that would be obtained locally assuming constant collision frequency. The ratio between these two methods can be appreciable, especially for smaller values of α_T. For data from a mission covering a large range of distances (e.g. SPP), this ratio could vary widely over the entire range of data.

5.1 Scattering of Suprathermal Electrons

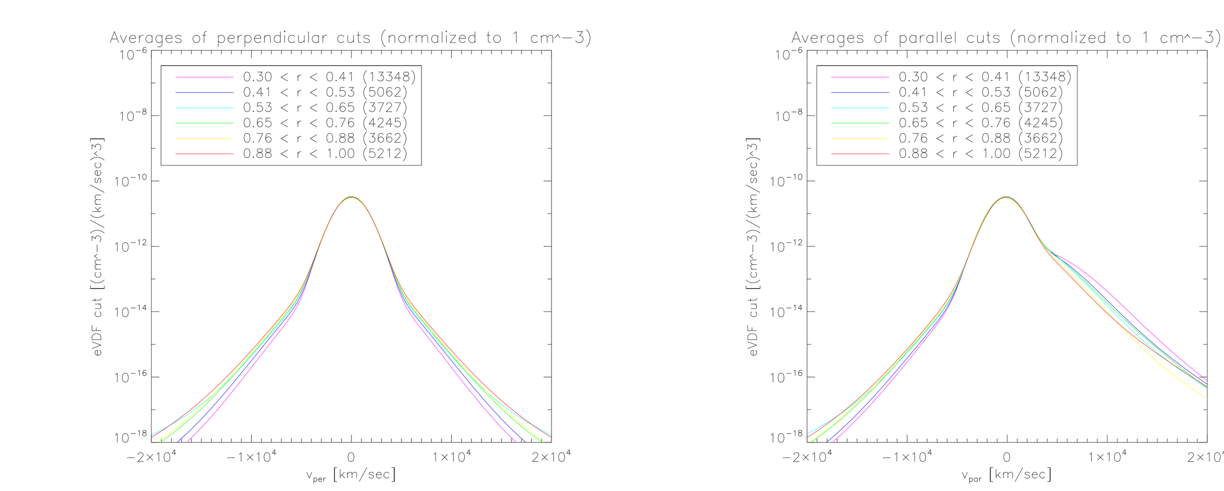
We calculate the collisional age using the core electron density and temperature in equation (3). We then examine how the fractional density densities of different electron populations vary with collisional age. Define the suprathermal density and velocity as $n_{sup} \equiv n_h + n_s$ and $v_{sup} \equiv \frac{n_h v_h + n_s v_s}{n_h + n_s}$, respectively. Then equation (1) can be recast as:

$$n_c v_c + n_{sup} v_{sup} = 0 \qquad (6)$$

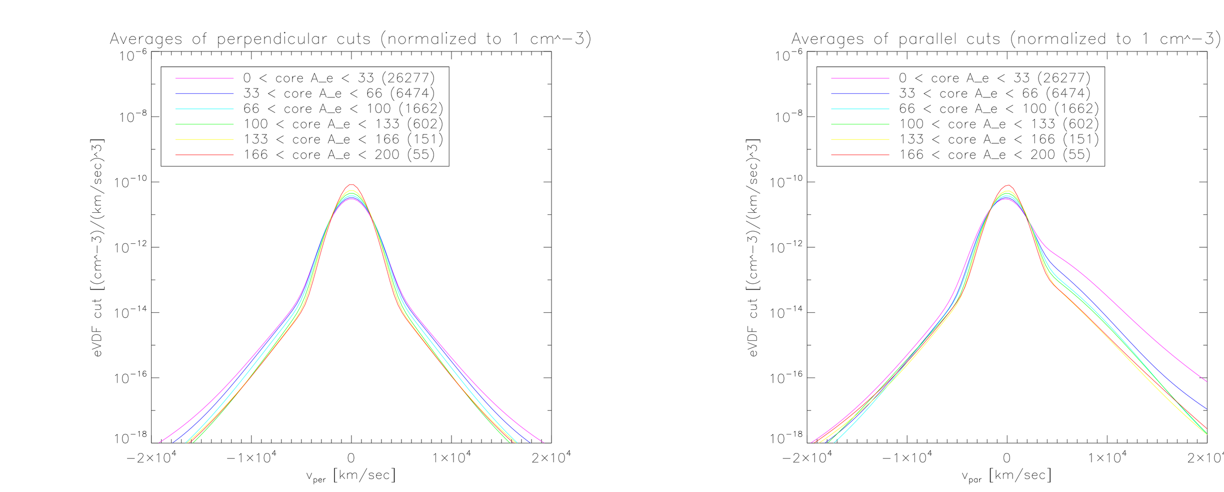
v_c and v_{sup} are observed to vary with collisional age (see poster by Marc Pulupa). Unless the velocity of each population varies in the exact right proportion with the other, n_c and n_{sup} must vary with collisional age in order to maintain current balance.



At higher collisional age, the suprathermal electrons account for a smaller fraction of the total electron density. The core complementarily increases in relative density. The suprathermal density fits well to an exponential function of collisional age. This exponential form is reminiscent of other collisional processes, such as the frictional slowing of a test particle beam by a Maxwellian background.



For visual aid, we plot perpendicular and parallel cuts of the eVDFs averaged into different bins of collisionality, similar to what has been published before[2]. Before averaging, we scale the core and halo temperatures to what would be observed at 1 AU, and normalize the electron density to 1 cm^{-3}. First notice that if we bin by distance, the normalized core appears to be constant while the halo grows at the expense of the strahl, in agreement with recent results[6].



Binning by collisional age using the same normalization, we see the suprathermal electrons appear to scatter into the core with collisions.

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