Self-Similarity of the Electron Strahl: Wind Data

Konstantinos Horaites[1], Stanislav Boldyrev[1]

[1]University of Wisconsin-Madison

Abstract

The solar wind strahl is a narrow, field-aligned population of high-energy electrons that originate in the solar corona. The beam-like shape of the strahl in velocity space is believed to come from two competing factors: the mirror force tends to narrow this population, while Coulomb collisions and wave-particle interactions tend to broaden it. Using data from the Wind satellite's strahl detector, we investigate the detailed shape of the strahl and compare with predictions from a collisional "self-similar" model. The potential influence of wave-particle interactions is also discussed.

Background

As shown in [1], electron heat conduction in the solar wind is well described by the predictions of a proposed "self-similar" kinetic theory. This theory applies when the temperature Knudsen number $\gamma(x) \sim \frac{T(dT/dx)}{n}$ is nearly constant distance with distance x along the flux tube (this condition was observed to hold 0.3-1 AU). From this point of view γ, which characterizes the importance of Coulomb collisions, is the central parameter that determines the shape of the distribution function $f(x, \mathbf{V})$. The self-similar kinetic equation is the drift-kinetic equation written under a change of variables (see "Definitions" below), under the assumption $\gamma(x)$ =const.:

$$\frac{\partial F(\mu,\xi,\tau)}{\partial\tau} = \xi^{1/2}\Big\{\gamma\Big[-\alpha\mu F - \mu\xi\frac{\partial F}{\partial\xi} + \frac{-\alpha_B}{2}(\alpha+1/2)(1-\mu^2)\frac{\partial F}{\partial\mu}\Big] + \gamma_E\Big[\mu\frac{\partial F}{\partial\xi} + \frac{1-\mu^2}{2\xi}\frac{\partial F}{\partial\mu}\Big] + \frac{1}{\xi}\Big[\frac{\partial F}{\partial\xi} + \frac{\partial^2 F}{\partial\xi^2}\Big] + \frac{\beta}{2\xi^2}\frac{\partial}{\partial\mu}(1-\mu^2)\frac{\partial F}{\partial\mu}\Big\} \quad (1)$$

Definitions:

$$f \equiv \frac{NF(\mu,\xi,\tau)}{T(x)^{\alpha}}, \mu \equiv \cos\theta, \xi \equiv \left(\frac{V}{V_{th}}\right)^2$$
$$\gamma \equiv -\frac{T^2(dlnT/dx)}{2\pi e^4\Lambda n}, \gamma_E \equiv \frac{eET}{2\pi e^4\Lambda n}, B \sim x^{\alpha_B} \quad (2)$$

Asymptotic Solution

The theory predicts the shape of the "strahl" distribution, which forms a beam along the magnetic field direction. This corresponds to the regime $\mu \to 1$, $\xi >> 1$. In this limit, equation 1 has solutions for the distribution $F(\mu, \xi)$ of the form:

$$F(\mu,\xi) \sim C\xi^{\alpha'-\alpha}\exp\left\{\frac{\gamma\alpha'\xi^2(1-\mu)}{\beta}\right\} \quad (3)$$

At a given energy ξ, the strahl varies exponentially with $(1-\mu)$. The angle $\mu \approx 1 - \theta^2/2$ at which this exponential falls off by a factor of 1/2 sets the angular width of the strahl θ_{FWHM}:

$$\theta_{FWHM} \approx \frac{2}{\xi}\sqrt{\frac{2\beta\ln(1/2)}{\gamma|\alpha'|}} \quad (4)$$

The SWE Strahl Detector

The SWE strahl detector [2] was an electrostatic analyzer on board the Wind satellite devoted solely to observing the strahl. The detector measures electron counts in a 14x12 angular grid, with a nominal resolution of 3.5x4.5 degrees. With each rotation of the spacecraft, a different energy is sampled, until after 32 rotations the process restarts.

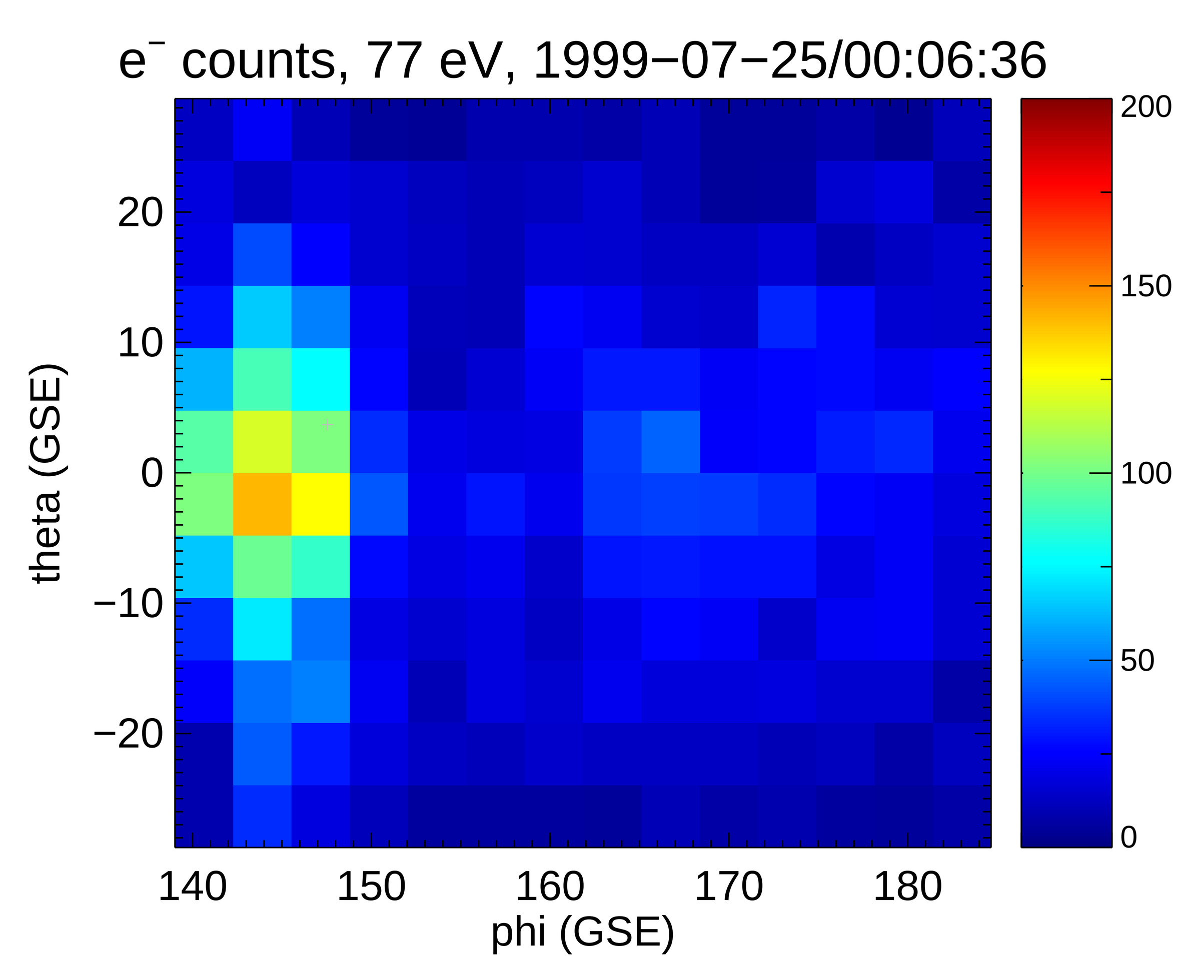

Figure: Example of an angular distribution (counts) measured by the SWE strahl detector.

Data Methods

For each strahl distribution, which is measured at fixed energy, we calculate a "Measured θ_{FWHM}" by fitting the angular distribution to a model function (equation 3).

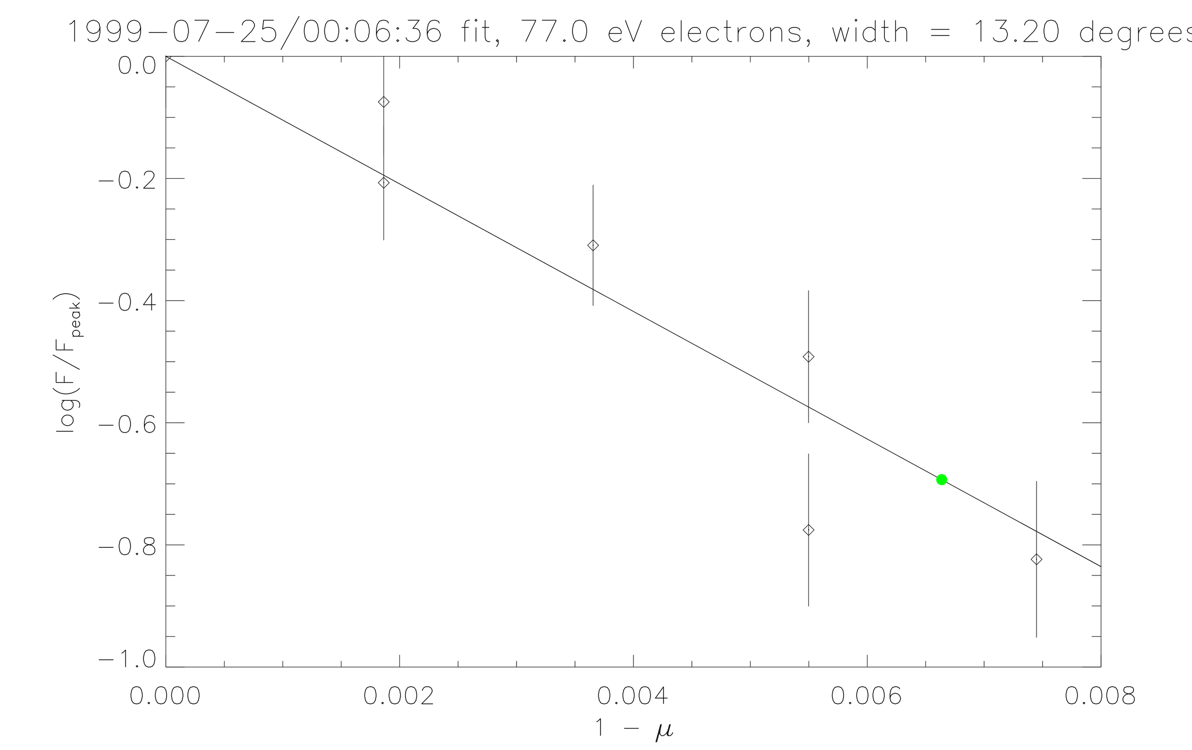

Figure: The full width at half-maximum of the strahl (green) at constant energy is found by fitting the data in the vicinity of the strahl peak to the function $y = mx$, where $x = (1-\mu)$ and $y = \ln(F/F_{peak})$.

Results

Given γ, equation 4 predicts the angular width of the strahl at a fixed energy. The Knudsen number γ is measured separately using SWE electron data to find an "Expected θ_{FWHM}", and then compared with the "Measured θ_{FWHM}" from the strahl sensor.

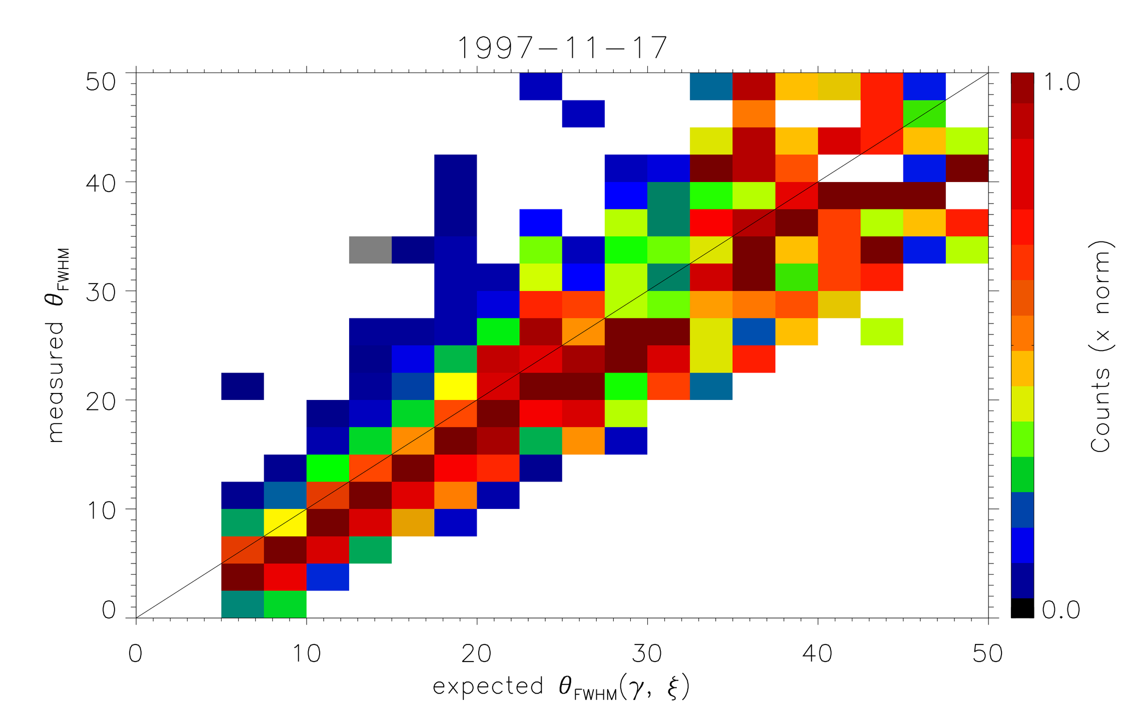

Figure: Expected strahl widths (FWHM, in degrees) from equation 3, plotted versus measured widths. The parameter α', which depends on the density and temperature profiles in the self-similar model, determines the slope of the data above. Setting $\alpha' = -3$ gives very good agreement for this day of data.

Wave-Particle Scattering

Wave-particle scattering is another mechanism that has been proposed to account for the width of the strahl. If for certain regimes of plasma parameters, strahl widths are broader than expected, it may be an indication that wave-particle scattering is also at work.

Conclusions

- The asymptotic solution (3) correctly predicts the angular FWHM of the strahl distribution, for 1 day of data.
- More data is required to test the generality of this result.

References

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Contact Information

- Website: http://home.physics.wisc.edu/~horaites/
- Email: horaites@wisc.edu

SHINE 2016 Conference Santa Fe, NM