Plasma Conditions in Polar Plumes and Interplume Regions in Polar Coronal Holes

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1. Abstract

During times of low solar activity, large polar coronal holes are observed to contain bright raylike **polar plumes** that appear to follow open magnetic field lines. Plumes are believed to be flux tubes that are heated impulsively at their base, which leads to a higher density, a lower outflow speed, and a lower overall temperature in the extended corona, compared to the surrounding interplume regions. Despite years of white light and spectroscopic observations, though, the differences in mass, momentum, and energy flux in plumes and between plumes are not known precisely.

This poster presents an updated survey of data from the **Ultraviolet Coronagraph Spectrometer (UVCS),** aboard *SOHO*, that attempts to sort out the local plume and interplume conditions. These results will be compared with previous analyses that characterized the "mean" plume/interplume coronal hole, averaged over many lines of sight through varying concentrations of plumes. Limits on the relative contributions of plumes and interplume regions to the high-speed solar wind will be determined, with emphasis on the proton outflow speed in the corona and at 1 AU. Implications for theoretical models of coronal heating and solar wind acceleration will be discussed.

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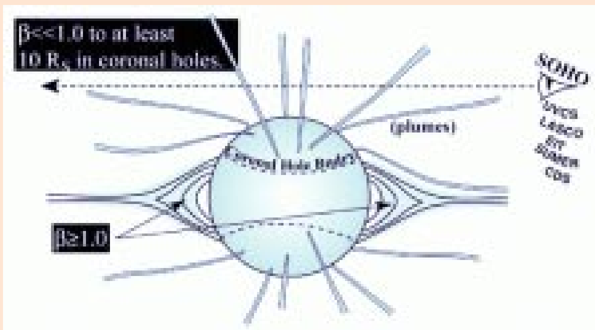
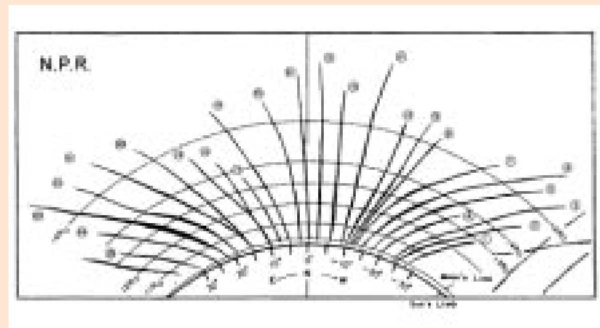
The above image of the Rosette Nebula was taken by T. A. Rector, B. Wolpa, and M. Hanna (AURA/NOAO/NSF).

2. Introduction

★ Polar plumes are dense, open-field flux tubes that permeate the large coronal holes observed over the north & south poles at solar minimum.



(Suess 1999)

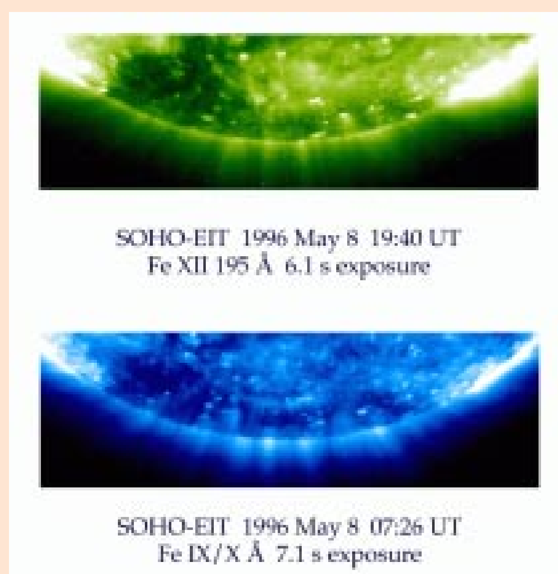


(Saito 1965)

★ The relative contribution of plumes and the lower-density "interplume" corona to the **high-speed solar wind** is uncertain. Both plumes (Walker et al. 1993) and interplume regions (e.g., Wilhelm et al. 1998) have been suggested as the primary source of solar wind mass flux.

★ Plumes have been observed in visible and ultraviolet light for several decades, but *SOHO* has provided a new window on these inhomogeneities.

(see, e.g., DeForest et al. 1997)

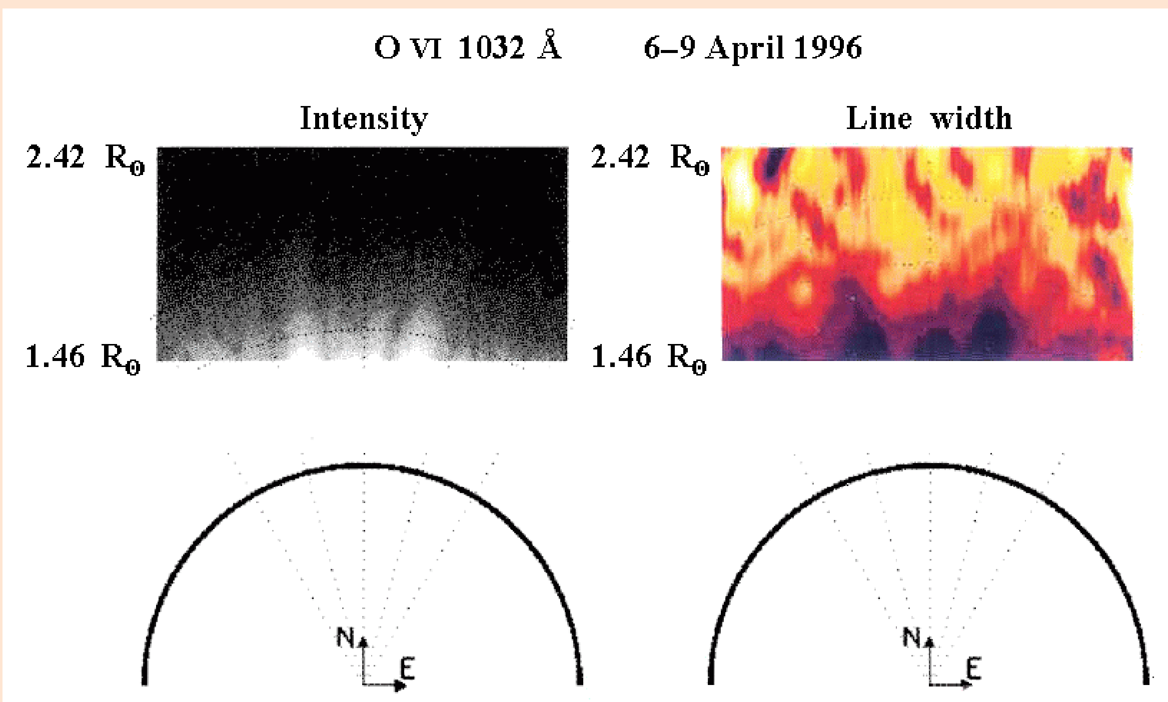


Properties of Polar Plumes (1)

- ⋆ Plumes originate on the solar disk in small (1000–4000 km) magnetic flux concentrations along network cell boundaries. Plumes expand outward to angular diameters of 2° to 4°, measured from Sun center.

- ⋆ Most plumes have **lifetimes** of order 1 day, but plumes tend to "refill" the same flux tube several times over a solar rotation (Lamy et al. 1997). The shortest-lived plumes cross over into the domain of impulsive *polar jets* (see poster **SH41B–09**).

- ⋆ Plumes appear **denser** than interplume plasma and have **lower** outflow speeds (e.g., Giordano et al. 2000). Close to the limb, plumes may have **higher** temperatures than the interplume corona (Walker et al. 1993), but above 1.1–1.3 $R_\odot$ they seem to have **lower** temperatures (Kohl et al. 1997; Hassler et al. 1997).



(Giordano et al. 1997)

Properties of Polar Plumes (2)

- ⋆ The contrast between plume and interplume plasma **disappears in interplanetary space.**

  However:

  ⟹ Thieme et al. (1990) found weak periodicities (in *Helios* data between 0.3 and 1 AU) in gas vs. magnetic pressure variations at 2° to 5° spatial scales.

  ⟹ Reisenfeld et al. (1999) found a weak correlation (in *Ulysses* data between 2 and 4 AU) between plasma β ($P_{\rm gas}/P_{\rm mag}$) and helium abundance, indicating some degree of flux tube coherence.

  Thus, significant cross-flux-tube **mixing** of both mass and momentum seems to be required between about 20 and 60 $R_\odot$ in order to smooth out the plume/interplume density contrast (e.g., Parhi et al. 2000; Andries et al. 2000).

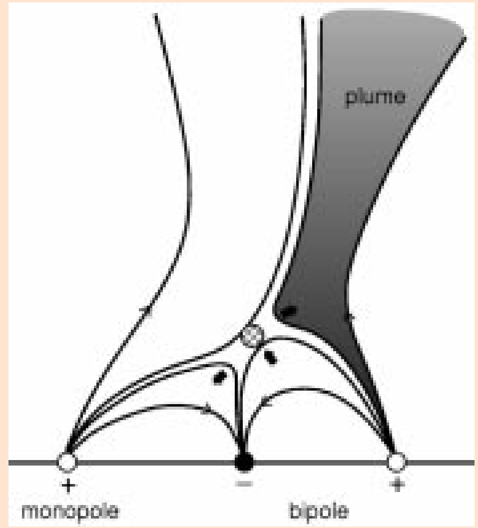
- ⋆ **Compressive MHD waves,** observed as propagating intensity fluctuations, seem to be channeled in polar plumes (DeForest & Gurman 1998; Ofman et al. 1999, 2000), and if the oscillations are slow magnetosonic waves they should steepen into shocks at relatively low coronal heights (Cuntz & Suess 2001).

- ⋆ High-latitude extensions of coronal **streamers** are often observed in projection against coronal holes, but these so-called "polar rays" often are clearly distinguishable from true coronal hole structure (Li et al. 2000).

Polar Plume Formation

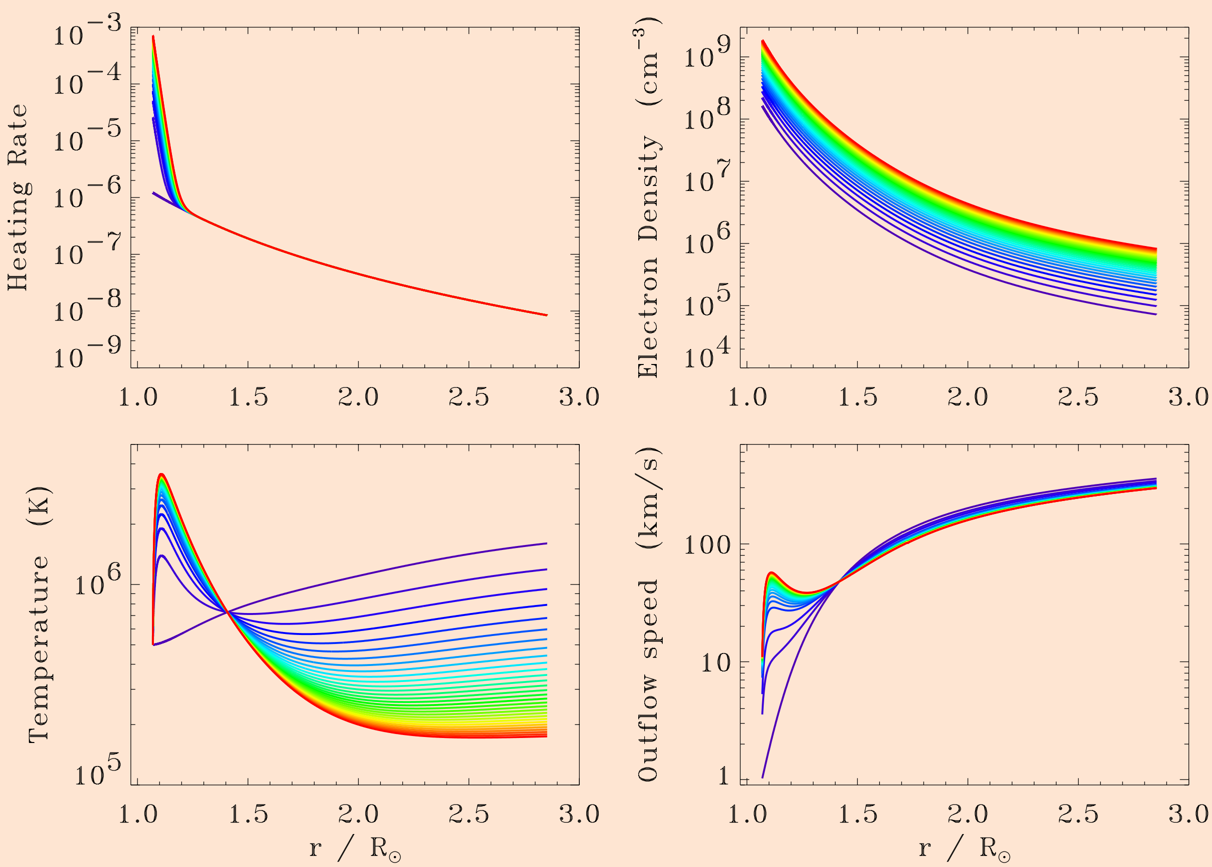
- ⋆ Wang (1994, 1998) suggested that small-scale magnetic reconnection at the coronal base gives rise to polar plumes.

- ⋆ Basal heat input is balanced by conductive losses to produce a **larger plume density.**



- ⋆ The heating rate in the extended corona is ∼unaffected, but the larger density implies less heating *per particle,* which leads to lower temperatures (and a lower ∇P force) at larger heights.

- ⋆ A simple implementation of Wang's basal heat input scenario:



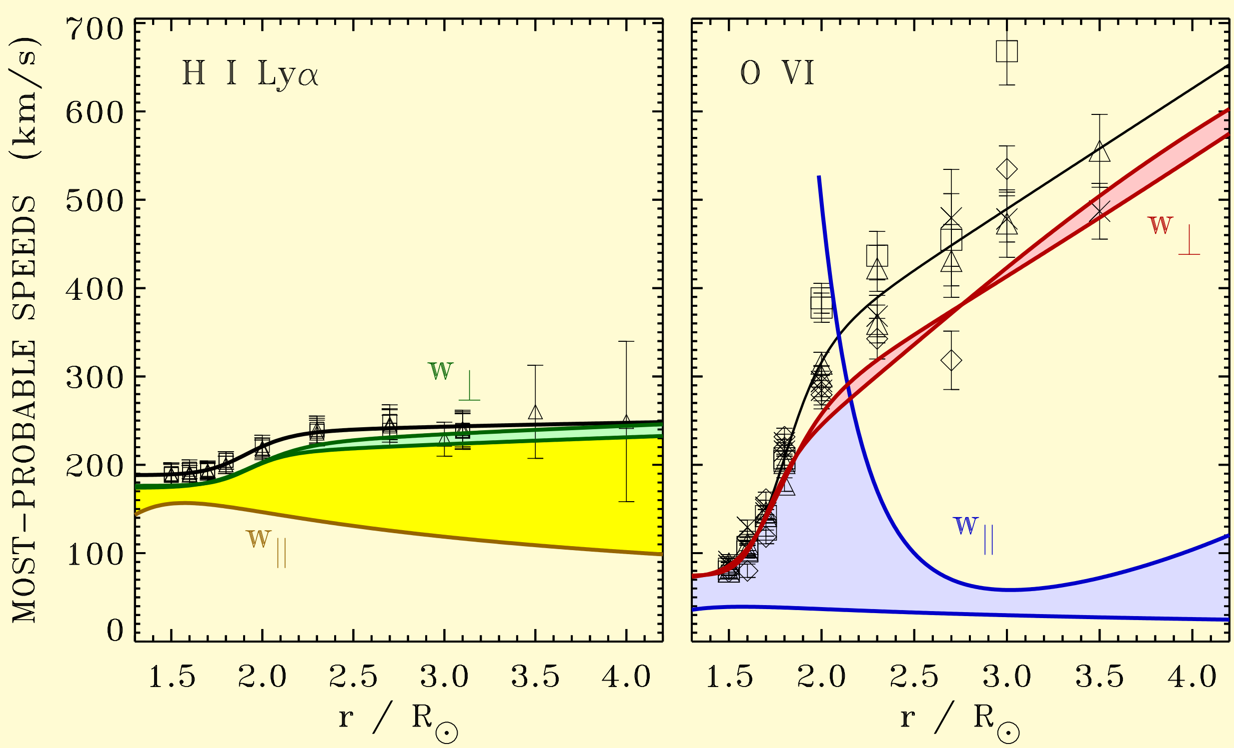
3. Empirical Models

⋆ Kohl et al. (1998) and Cranmer et al. (1999) constructed "empirical models" of the mean plasma properties in polar coronal holes during 1996–1997, from UVCS/*SOHO* observations.

⋆ *These empirical models do* ***not*** *specify the physical processes that maintain the corona in its assumed steady state.*

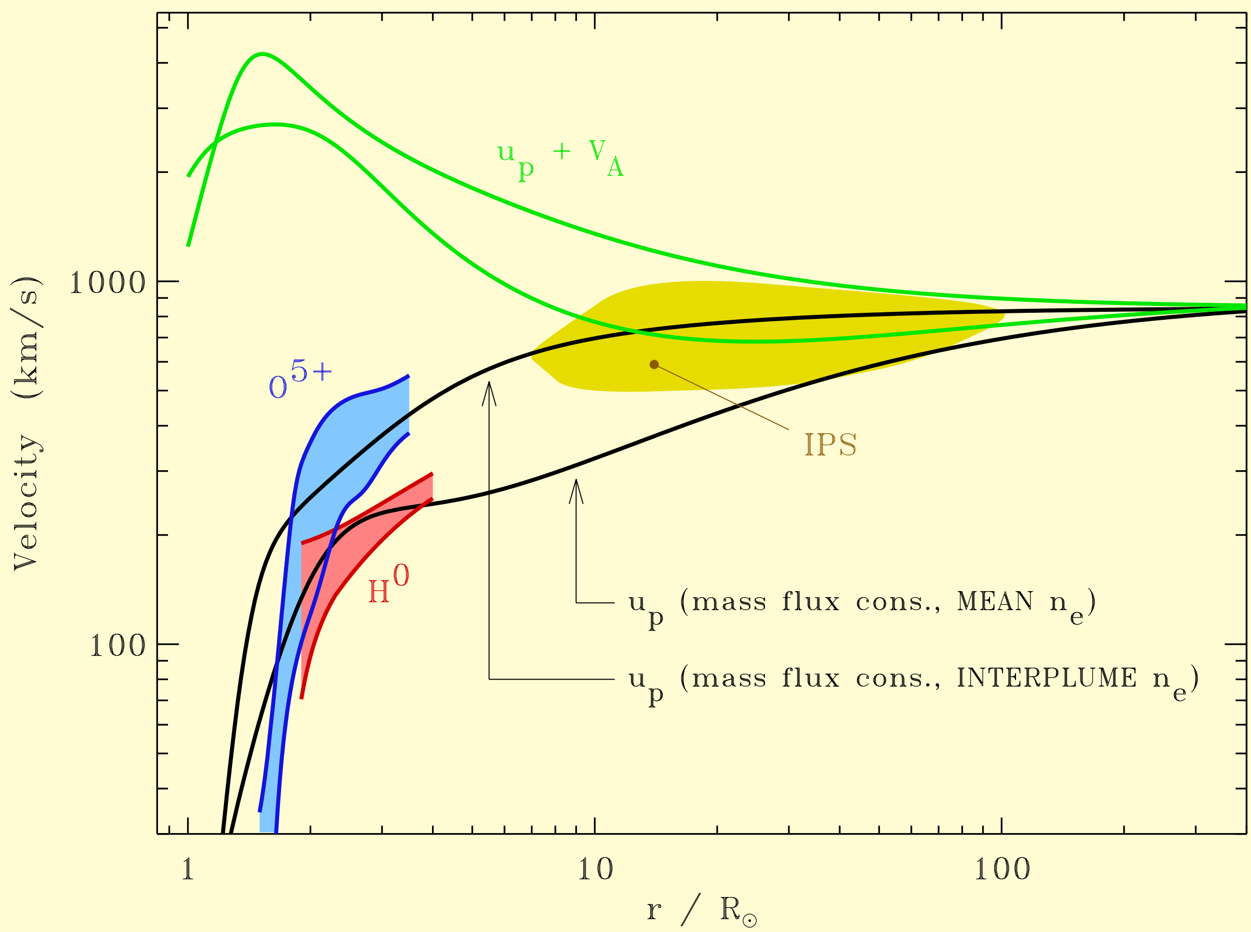
⋆ Mean electron densities determined from UVCS White Light Channel pB's fell between the minimum and maximum (i.e., "interplume" and "plume") limits of Fisher & Guhathakurta (1995).

⋆ Mean ion kinetic temperatures and anisotropies have been discussed elsewhere as strong constraints on models of solar wind heating and acceleration (e.g., Hollweg 1999; Esser et al. 1999; Cranmer 2000, 2001; Tu & Marsch 2001):



Summary of Empirical Outflow Speeds

- ⋆ Coronal observations can be compared with *in situ* measurements to produce strong constraints on theoretical models:



- ⋆ Mass flux conservation from n_e (*upper:* Fisher & Guhathakurta 1995; *lower:* Guhathakurta & Holzer 1994) and flux tube area (Banaszkiewicz et al. 1998). **Range of IPS speeds** from Grall et al. (1996); **H^0** and **O^{5+}** speeds from Cranmer et al. (1999).

- ⋆ Note that the UVCS empirical models were constructed with all inputs being **mean quantities,** averaged over spatial dimensions subtending many plumes and interplume regions.

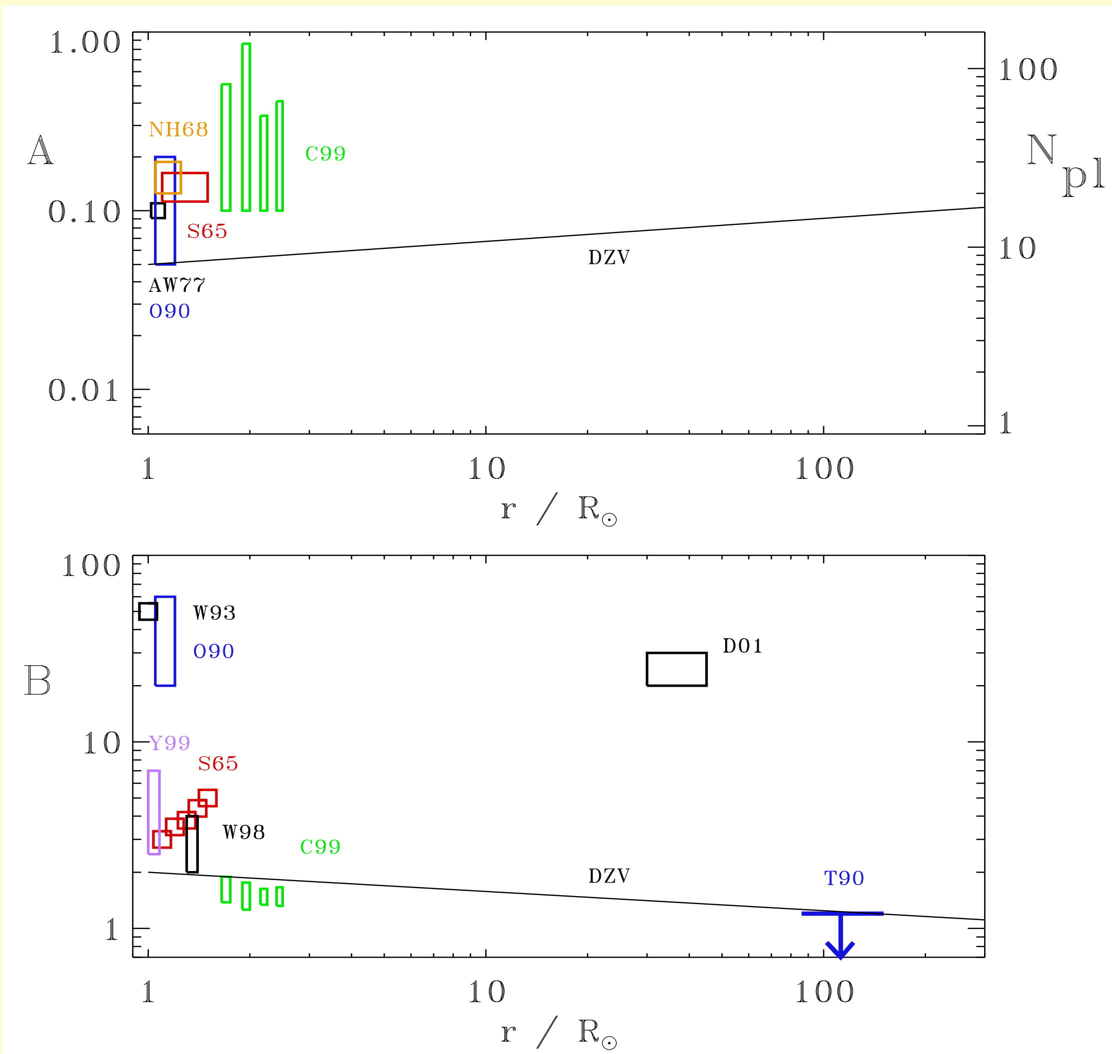
- ⋆ **The remainder of this poster is an attempt to begin deriving the properties of plumes and interplume regions as separate entities.**

Plume Densities and Filling Factors

★ There have been many attempts to determine the following intrinsic quantities from observations:

$$A \equiv \left\{ \begin{array}{c} \text{volume} \\ \text{filling factor} \\ \text{of plumes} \end{array} \right\} \propto \left\{ \begin{array}{c} \text{number of plumes} \\ \text{in a coronal hole} \end{array} \right\}$$

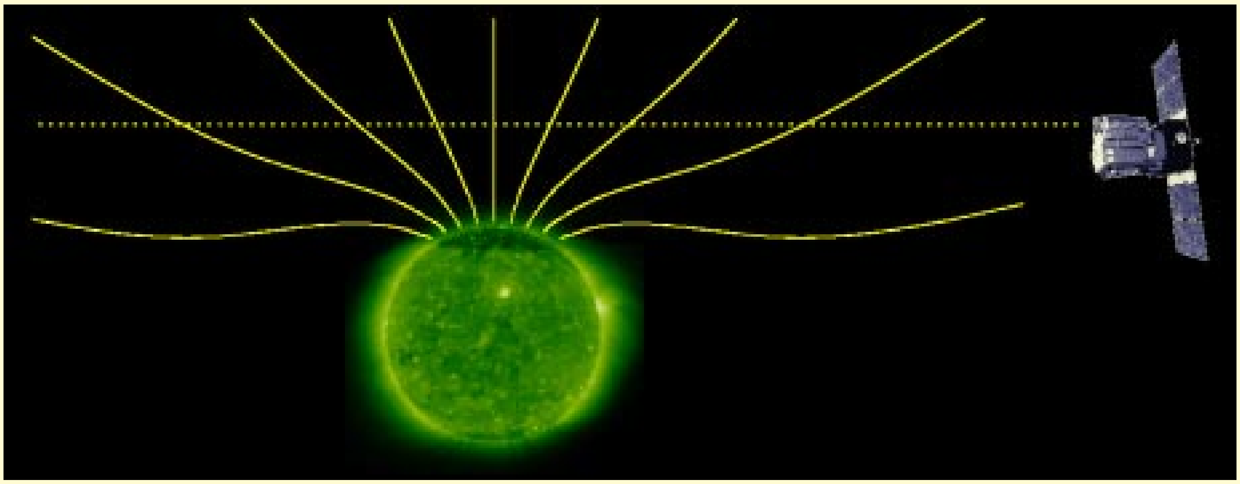
$$B \equiv \left\{ \frac{\text{plume density}}{\text{interplume density}} \right\}$$



AW77: Ahmad & Withbroe (1977), C99: Cranmer et al. (1999), D01: DeForest et al. (2001), DZV: Del Zanna & Velli (1999), NH68: Newkirk & Harvey (1968), O90: Orrall et al. (1990), S65: Saito (1965), T90: Thieme et al. (1990), W93: Walker et al. (1993), W98: Wilhelm et al. (1998), Y99: Young et al. (1999)

Difficulties in Determining Plume Properties

- ⋆ Integration over the optically thin line of sight represents a nontrivial loss of spatial information.



- ⋆ Coronal hole plasma is probably not a strict two-phase (i.e., plume & interplume) medium. A continuous distribution of plasma parameters probably exists, and time variability cannot be ignored (see, e.g., Feldman et al. 1974, 1997).

- ⋆ Both above difficulties make it hard to measure (or even properly *define*) the filling factor A by simple counting of plumes.

- ⋆ Absolute photometric calibrations are required to determine the numerators and denominators of B individually.

- ⋆ Line of sight effects (both the unknown distribution along the line of sight and the locations of plumes in or out of the plane of the sky) also make measurements of B less certain.

We require other methods of constraining the properties of polar plumes.

4. Plume Statistics

- ⋆ The long time base of *SOHO* allows many **repeated measurements** in coronal holes, once per day over the span of several months to years.

- ⋆ Because plumes come and go on 1-day time scales, *and* because solar rotation brings new flux tubes into a specified line of sight, such repeated observations provide a **quasi-random sampling** of the plume-filled coronal holes.

- ⋆ Plume properties can be extracted from the distributions of, e.g., observed visible light polarization brightness (pB) and ultraviolet line intensities.

- ⋆ Absolute calibration issues can be avoided, in part, by computing **dimensionless moments of the distributions:**

$$\boldsymbol{M_1} \equiv \frac{<\boldsymbol{pB}>}{\min(\boldsymbol{pB})} \qquad \boldsymbol{M_2} \equiv \frac{(<\boldsymbol{pB}^2> - <\boldsymbol{pB}>^2)^{1/2}}{<\boldsymbol{pB}>}$$

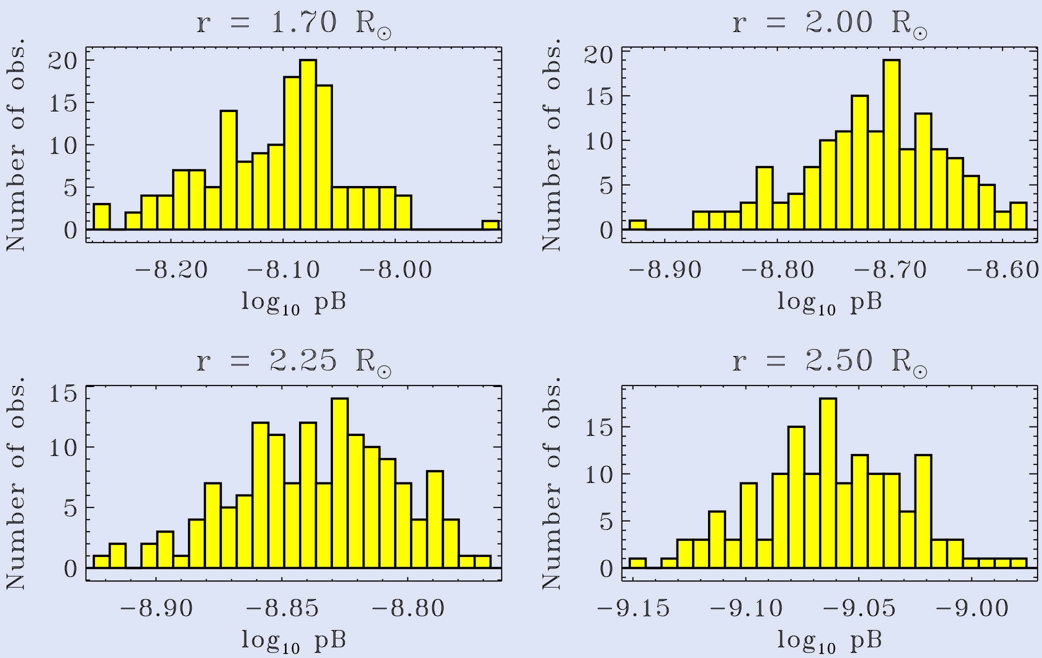
- ⋆ Observed $\boldsymbol{M_1}$ is a lower limit on the true value of $\boldsymbol{M_1}$ because we may have not sampled the (“pure interplume”) line of sight with the minimum possible $\boldsymbol{pB}$.

- ⋆ Observed $\boldsymbol{M_2}$ is corrected by subtracting out the standard deviation in $\boldsymbol{pB}$ due to pointing jitter ($\lesssim$10 arcsec; no more than a 5% effect). Other uncertainties are minimized because each observation was carried out in the exact same manner.

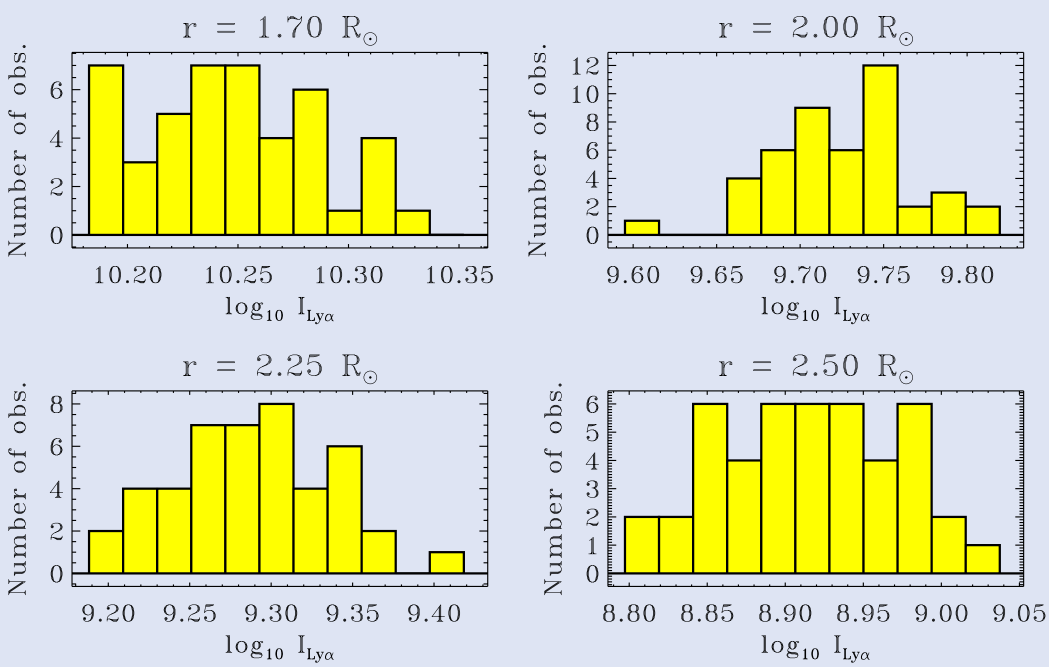
UVCS Plume/Interplume Distributions

- ⋆ From Nov 1996 to Jan 1997, we assembled a database of identical synoptic observations of N and S polar coronal holes, at 4 heights.

- ⋆ Visible light pB distributions: (153 observations per height)



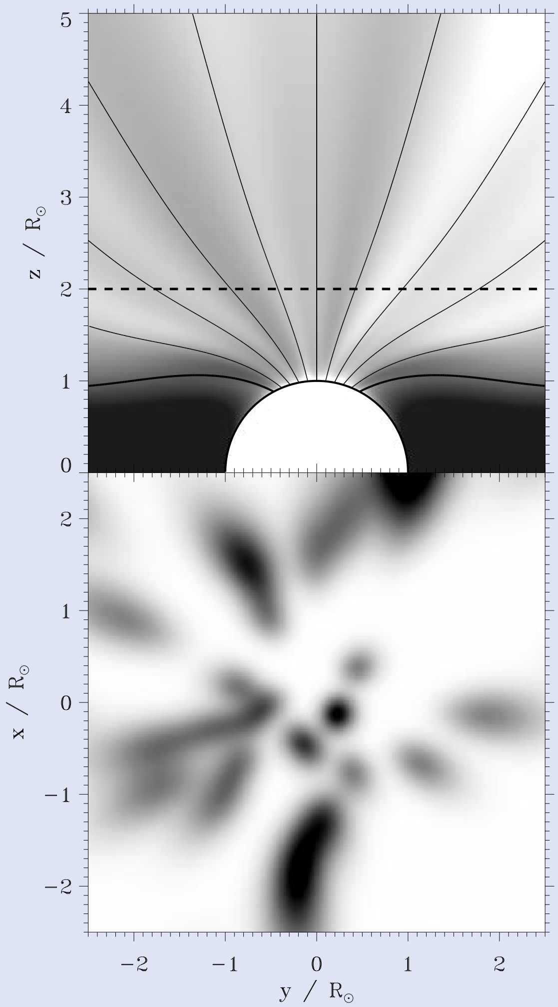
- ⋆ H I Lyα intensity distributions: (46 observations per height)



3D Statistical Plume Model

- ⋆ The observed pB and $I_{\rm Lya}$ distributions must be compared with **simulated distributions** with known input plume and interplume properties.

- ⋆ Wang & Sheeley (1995) and Cranmer et al. (1999) modeled a plume-filled coronal hole by placing $\boldsymbol{N_{\rm pl}}$ identical plumes randomly between the pole and the edge of the coronal hole (colatitude $\boldsymbol{\theta_0}$).



- ⋆ The model plumes have a Gaussian lateral density enhancement, with basal half-width $\boldsymbol{\beta}$ of 30,000 km (e.g., Ahmad & Withbroe 1977), and expand superradially, following the solar minimum flux tubes of Banaszkiewicz et al. (1998).

- ⋆ **Free parameters:** $\boldsymbol{A}$ and $\boldsymbol{B}$, as defined above, with

$$\boldsymbol{A} = \frac{\boldsymbol{N_{\rm pl}}\,(\boldsymbol{\pi^2\beta^2}/4)}{2\boldsymbol{\pi R_\odot^2}\,(1-\cos\boldsymbol{\theta_0})}$$

- ⋆ Total number of models: $\boldsymbol{N_{\rm A}} \times \boldsymbol{N_{\rm B}} \times \boldsymbol{N_{\rm trials}}$

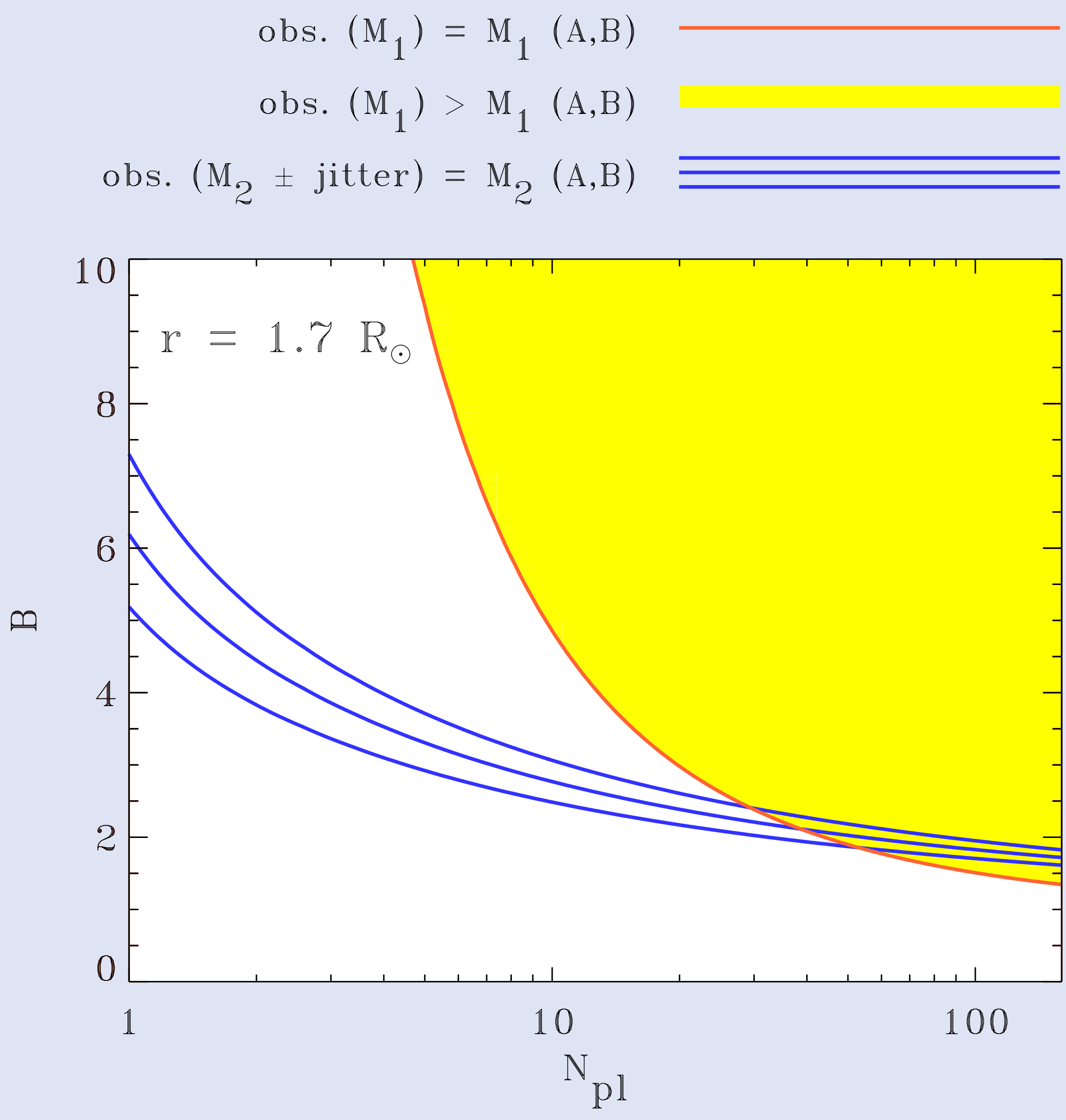
$\boldsymbol{N_{\rm A}}$ = 30 (with $\boldsymbol{N_{\rm pl}}$ varying between 1 and 80)

$\boldsymbol{N_{\rm B}}$ = 30 (with $\boldsymbol{B}$ varying between 1.01 and 50)

$\boldsymbol{N_{\rm trials}}$ = 5000 (for each set of $\boldsymbol{A}, \boldsymbol{B}$)

Statistical Model Results

- Observed values of moments M_1 and M_2 correspond to loci of points (i.e., curves) in the 2D grid of modeled $M_1(A, B)$ and $M_2(A, B)$ values:



- At $r = 1.7\,R_\odot$, this analysis suggests

$$A \approx 0.25 \quad , \qquad N_{pl} \approx 40 \quad , \qquad B \approx 2$$

- Formal uncertainty analysis and an extension to other heights in the corona are subjects for future work.

H I Lyα Doppler Dimming in Plumes

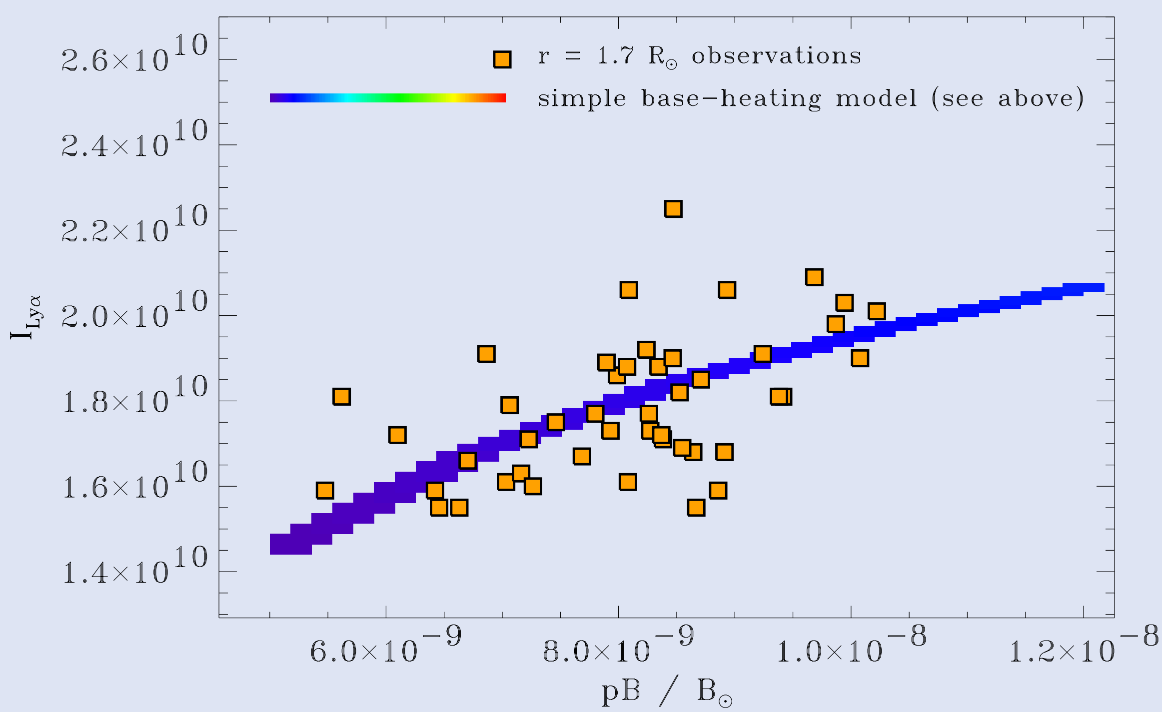
- ⋆ Denser (plume) lines of sight are also brighter in H I Lyα . . . but not with a 1:1 correlation between intensity and pB.

- ⋆ According to Wang's (1994) model, denser lines of sight would have lower outflow speeds $\boldsymbol{u}$ and lower most-probable speeds $\boldsymbol{w}$. The Lyα total intensity ratio for two lines of sight (i and j) is approximately given by

$$\frac{I_{\mathrm{Ly}\alpha}(i)}{I_{\mathrm{Ly}\alpha}(j)} \approx \frac{n_{e,i}\ \exp(-u_i^2/w_i^2)\sqrt{w_j^2 + w_\odot^2}}{n_{e,j}\ \exp(-u_j^2/w_j^2)\sqrt{w_i^2 + w_\odot^2}}$$

(Assumed: 90° scattering; disk profile width of $w_\odot \approx$ 75 km/s; constant ionization rate in $\boldsymbol{i}$ and $\boldsymbol{j}$)

- ⋆ If the dominant variation is in $\boldsymbol{n_e}$ and $\boldsymbol{w}$, the scaling based on the simple models above agrees roughly with the observed intensity-$\boldsymbol{pB}$ correlation:



Preliminary Conclusions

- ⋆ Polar plumes supply a non-negligible fraction of mass to the high-speed solar wind. Existing (mean corona) empirical models therefore provide *intermediate* values between “pure” plume and interplume states.
- ⋆ Future work will further constrain the *radial dependence* of plume contributions to the mass and momentum flux in the wind.

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