Statistical Relationships Between Solar Wind Parameters: Implications for Space Weather Forecasts

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Purpose: Quantify empirical statistical relationships between the solar wind speed and other quantities such as the solar wind density, temperature, magnetic field strength, and the Kp index. Then use multiday solar wind speed forecasts and those empirical relationships to produce multiday forecasts for all of the solar wind, IMF, and Kp index.

Improving Speed Forecast

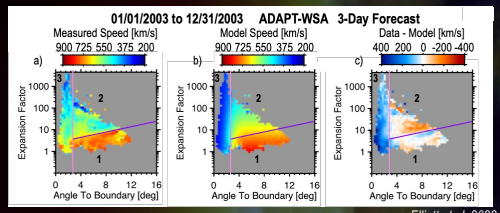
Wang-Sheeley-Arge Speed Formula

$$v_{wsa}(f_p, d; v_0, v_1, \beta, \gamma, w, \delta) = v_0 + \frac{v_1 - v_0}{(1+f_p)^{\alpha}} \cdot \left\{\beta - \gamma \cdot \exp\left[-\left(d / w\right)^{\delta}\right]\right\}^3$$

(Reiss et al., 2019)

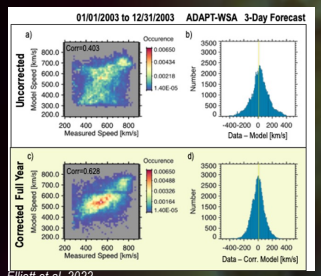
vwsa – speed forecast
fp -expansion factor
d – separation angle to open-closed field line boundary (angle to coronal hole boundary)

- Other quantities are constants parameters



Elliott et al. 2022

Left: Measured speed sorted by expansion factor (fp) and angle to coronal hole boundary (d).
Middle: ADAPT-WSA 3-Day forecast speed vs. fp & d (visual representation of WSA formula).
Right: Residual speed errors (Data-Model) vs. fp and d.



Elliott et al. 2022

Left: The occurrence (color) of given modeled (y-axis) and measured speeds (x-axis).

Right: Histogram of the residual error.

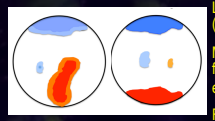
Top Row: Results with no additional corrections.

Bottom Row: Results with corrections applied

The correction reduced the errors overall, and now the errors are nearly symmetric about zero.

Source Properties & Dynamic Interactions

Source Properties

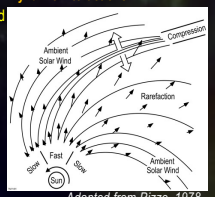


Large polar coronal holes emit very fast wind (650 to 860 km/s).

Moderately fast wind (450-650 km/s) comes from small low latitude holes and/or from edges of larger coronal holes.

Fast wind is hotter & less dense than slow wind

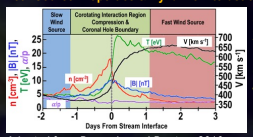
Dynamic Interactions



Adapted from Pizzo, 1978

Dynamic interactions alter solar wind properties en route forming compressions & rarefactions which create correlations

Both Source Properties & Dynamic Interactions

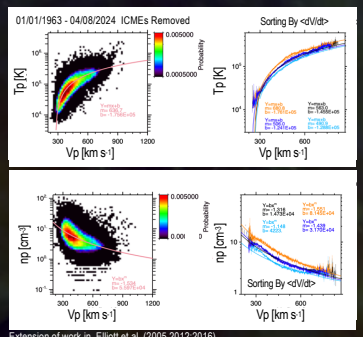


Superposed epoch analysis of 27 CIR compressions.

Correlations between solar wind parameters due to source properties and dynamic interactions.

Adapted from Borovsky and Denton, 2010

Temperature- Speed and Density - Speed Relationships



Top Left: Number of observations color-coded and binned by solar wind temperature and speed.

Top Right: Same observations sorted and binned by the steepness in the 2-day speed-time profile <dV/dt>.

We fit the results with a linear relationship to obtain the temperature formulas.

Bottom Left: Number of observations color-coded and binned by solar wind density and speed.

Bottom Right: Same observations sorted and binned by the steepness in the 2-day speed-time profile <dV/dt>.

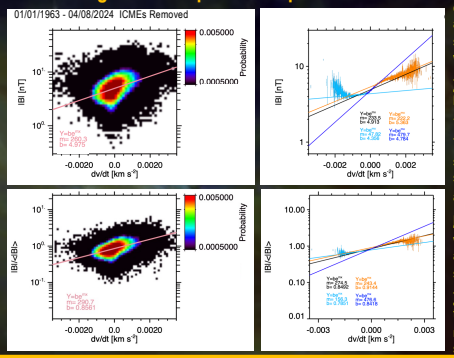
Sorting by the steepness in the speed time profile was developed in Elliott et al. (2005, 2012).

We fit the results with a power law relationship to obtain the density formulas.

- Rising profiles (orange) <dV/dt>2day > 7000km/s/year
- Failing profiles (light blue) <dV/dt>2day < - 7000km/s/year
- Flat profiles (dark blue) |<dV/dt>2day| ≤ 7000km/s/year
- All the data (black)

Extension of work in Elliott et al. (2005,2012;2016).

Field Strength Vs Steepness in Speed -Time Profile



Top Left: Number of observations color-coded in bins of the IMF field strength and average level of steepness in the speed-time profile for 2 day time windows (<dV/dt>2day).

Top Right: Field strength sorted and binned by 2-day speed-time slope <dV/dt>.

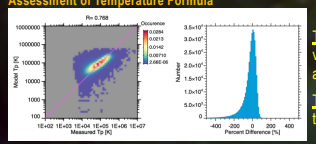
The field strength varies on long time scales. Normalizing by the average field strength from the previous solar rotation accounts for this effect.

Bottom Left: Same format is Top Left with the field strength normalized by the average field strength from the prior solar rotation.

Top Right: Same format and binning as the Top Right, but here the field is normalized by the average field strength from the prior solar rotation.

Test Temperature-Speed and Density – Speed Relationships with <dV/dt> Sorting

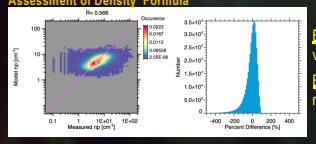
Assessment of Temperature Formula



Top Left: Temperature determined from T-V equations with <dV/dt> sorting plotted versus the measured temperatures. Diagonal pink line indicates perfect agreement.

Top Right: Histogram of the percent difference in the empirical temperatures and the measured ones shown in the Top Left.

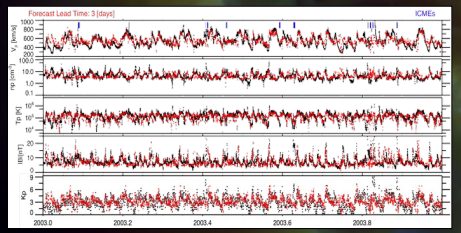
Assessment of Density Formula



Bottom Left: Density determined from n-V equations with <dV/dt> sorting plotted versus the measured densities. Diagonal pink line indicates perfect agreement.

Bottom Right: Histogram of the percent difference in the empirical densities and the measured ones shown in the Bottom Left.

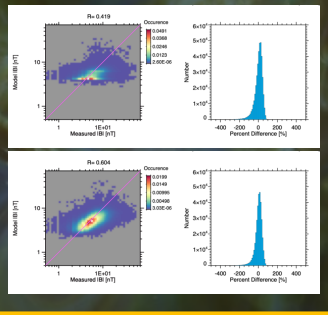
Test Using WSA and Empirical Formulas To Forecast



We chose one realization from a 3-day WSA forecast, corrected the speeds, applied the adapted relationships for density, temperature, field strength, and Kp index.

Most of these formula and WSA work only for the background wind (slow, fast, and CIR); therefore, we show the CMEs as blue bars on the top panel.

Test Field Strength - <dV/dt> Relationships with <dV/dt> Sorting



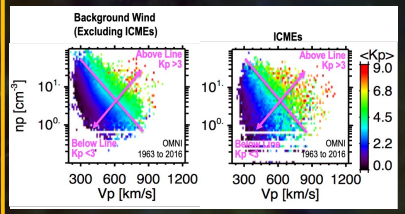
Top Left: Field strength determined from B- <dV/dt> equations with <dV/dt> sorting plotted versus the measured field strength.

Top Right: Histogram of the percent difference in the empirical field strength and the measured ones shown in the Top Left.

Bottom Left: Field strength determined from B/<Bpr>- <dV/dt> equations with <dV/dt> sorting plotted versus the measured field strength.

Bottom Right: Histogram of the percent difference in the empirical field strength and the measured ones shown in the Bottom Left.

Kp Index Vs Solar Wind Speed & Density



The Kp Index varies systematically with on the solar wind speed a density.

The dependence of Kp on speed and density is true for the background wind and ICMEs.

A mission such as PUNCH that can estimate the speed and density of CMEs and CIRs could be used to forecast the Kp index for CMEs and CIRs

Summary and Conclusions

1. Multiday WSA speed forecasts are significantly improved by applying corrections as a function of the expansion factor (bending of the field lines) and the distance to the coronal hole boundary.
2. Multiday forecasts of the scalar solar wind and IMF parameters directly from forecasts of the solar wind speed and the steepness in the solar wind profiles is feasible.

   Empirical Relationships
   - Solar wind density, and temperature directly from the magnitude of the speed.
   - Field strength from the steepness in the speed-time profile.
   - Kp index as a function of density and speed
3. A comprehensive empirical baseline model of the solar wind, IMF and Kp index can be created and coupled to WSA speed forecasts to produce multiday forecasts in real-time for the background (slow, fast, and CIR/SIR) solar wind.