Structure and Evolution of the Three Dimensional Solar Wind

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The Solar Origin of the Solar Wind
Parker’s Isothermal Solar Wind Model

**FIGURE 1** E. N. Parker’s original solutions for solar wind flow speed as a function of heliocentric distance for different coronal temperatures. Subsequent work has demonstrated that the simple relationship between coronal temperature and solar wind speed illustrated here is incorrect. [From E. N. Parker (1963), “Interplanetary Dynamical Processes.” Interscience, New York. Copyright © 1963. Reprinted with permission of John Wiley & Sons, Inc.]
Parker’s Model of the Heliospheric Magnetic Field

Axes are heliocentric distance in units of AU.
### Table 1. Statistical Properties of the Solar Wind at 1 AU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>STD</th>
<th>Most Probable</th>
<th>Median</th>
<th>5-95% Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (/cm³)</td>
<td>8.7</td>
<td>6.6</td>
<td>5.0</td>
<td>6.9</td>
<td>3.0 – 20.0</td>
</tr>
<tr>
<td>$V_{sw}$ (km/s)</td>
<td>468</td>
<td>116</td>
<td>375</td>
<td>442</td>
<td>320 – 710</td>
</tr>
<tr>
<td>B (nT)</td>
<td>6.2</td>
<td>2.9</td>
<td>5.1</td>
<td>5.6</td>
<td>2.2 – 9.9</td>
</tr>
<tr>
<td>A(He)</td>
<td>0.047</td>
<td>0.019</td>
<td>0.048</td>
<td>0.047</td>
<td>0.017 – 0.078</td>
</tr>
<tr>
<td>$T_p$ ($10^5$K)</td>
<td>1.2</td>
<td>0.9</td>
<td>0.5</td>
<td>0.95</td>
<td>0.1 – 3.0</td>
</tr>
<tr>
<td>$T_e$ ($10^5$K)</td>
<td>1.4</td>
<td>0.4</td>
<td>1.2</td>
<td>1.33</td>
<td>0.9 – 2.0</td>
</tr>
<tr>
<td>$T_\alpha$ ($10^5$K)</td>
<td>5.8</td>
<td>5.0</td>
<td>1.2</td>
<td>4.5</td>
<td>0.6 – 15.5</td>
</tr>
<tr>
<td>$T_e/T_p$</td>
<td>1.9</td>
<td>1.6</td>
<td>0.7</td>
<td>1.5</td>
<td>0.37 – 5.0</td>
</tr>
<tr>
<td>$T_\alpha/T_p$</td>
<td>4.9</td>
<td>1.8</td>
<td>4.8</td>
<td>4.7</td>
<td>2.3 – 7.5</td>
</tr>
<tr>
<td>$nV_{sw}$ ($10^8$/cm²s)</td>
<td>3.8</td>
<td>2.4</td>
<td>2.6</td>
<td>3.1</td>
<td>1.5 – 7.8</td>
</tr>
<tr>
<td>$C_s$ (km/s)</td>
<td>63</td>
<td>15</td>
<td>59</td>
<td>61</td>
<td>41 – 91</td>
</tr>
<tr>
<td>$C_A$ (km/s)</td>
<td>50</td>
<td>24</td>
<td>50</td>
<td>46</td>
<td>30 - 100</td>
</tr>
</tbody>
</table>

$n$ is proton density, $V_{sw}$ is solar wind speed, $B$ is magnetic field strength, $A$(He) is He$^{++}$/H$^+$ ratio, $T_p$ is proton temperature, $T_e$ is electron temperature, $T_\alpha$ is alpha particle temperature, $C_s$ is sound speed, $C_A$ is Alfven speed.
Commonly Observed Ionization States in the Solar Wind

He$^{2+}$

C$^{5+}$, C$^{6+}$

O$^{6+}$ to O$^{8+}$

Si$^{7+}$ to Si$^{10+}$

Fe$^{8+}$ to Fe$^{14+}$

Unusual ionization states in portions of ICMEs:

He$^+$ and Fe$^{16+}$
Coronal and Solar Wind Stream Structure
The Heliospheric Current Sheet and the Solar Dipole
Solar Latitude and Solar Cycle Effects: Ulysses
Characteristics of Solar Wind Stream Structure

1-hr averaged data

Np (cm\(^{-3}\))
Tp (K)
P (dyne cm\(^{-2}\))
V (km s\(^{-1}\))
Phi (Deg)
Br (nT)
|B| (nT)
Evolution of Stream Structure with Heliocentric Distance

1-D Compressible Fluid Simulation
Damped High-Speed Streams in the Outer Heliosphere

Voyager 2 data obtained at ~18 AU
Stream Evolution in Two Dimensions
Flow Deflections in CIRs Observed by Ulysses in the Opposite Solar HemispHERes

Flow Angles Relative to Radial

Ulysses 5.1 AU 19.5° S
F. Shock
R. Shock

Ulysses 4.4 AU 25.3° N
F. Shock
R. Shock

Pressure (nPa)

10^{-6}
10^{-5}
10^{-4}
10^{-3}

Flow Speed (km s^{-1})

1
2
3
4
5
6
7

November 1992

29
30
1
2
3
4
5

September/October 1996
Forward and Reverse Shocks Observed by Ulysses During its First Solar Orbit
Corotating Interaction Regions in 3D
A Meridional Cut Through Stream Structure at a Fixed Longitude
Solar Wind Electrons

Integrated over all look directions

Suprathermal Pitch Angle Distribution

ACE
1/10/99
22:54 UT

$T = 13.39 \text{ eV}$

Thermal Population

Suprathermal Population

ACE
1/10/99
2254 UT

272 eV

Strahl

Halo

$0 \quad 30 \quad 60 \quad 90 \quad 120 \quad 150 \quad 180$

Pitch Angle (Degrees)

$10^{-34}$

$10^{-32}$

$10^{-30}$

$10^{-28}$

$10^{-26}$

$f(V) \; (s^{-3} \text{cm}^{-6})$

Electron Energy (eV)

$10^{0}$

$10^{1}$

$10^{2}$

$10^{3}$

$10^{4}$
Coronal Mass Ejections and Transient Solar Wind Disturbances
A Simple 1D Fluid Simulation of a Solar Wind Disturbance Driven by a Fast CME

Shown at time when leading edge of disturbance reaches 1 AU.
3D Simulation of CME-Driven Disturbances in a Simply Structured, Tilted Dipole Solar Wind

Colors indicate the CME material injected into the simulations.
List 1. Characteristics of Interplanetary Coronal Mass Ejections (ICMEs) at 1 AU

Common signatures:
- Counterstreaming (along the field) suprathermal electrons (energy > 70 eV)
- Counterstreaming (along the field) energetic (energy > 20 keV) protons
- Helium abundance enhancement
- Anomalously low proton and electron temperatures
- Strong magnetic field
- Low plasma beta
- Low magnetic field strength variance
- Anomalous field rotation (flux rope)
- Anomalous ionic composition (for example, Fe^{16+}, He^+)
- Cosmic ray depression

Average radial thickness: 0.2 AU
Range of speeds: 300 - 2000 km/s
Single point occurrence frequency:
  - ~72 events/yr at solar activity maximum
  - ~8 events/yr at solar activity minimum

Magnetic field topology: Predominantly closed magnetic loops rooted in Sun
Fraction of events driving shocks: ~1/3
Fraction of earthward-directed events producing large geomagnetic storms: ~1/6
The Magnetic Field Topology of CMEs and the Problem of Magnetic Flux Balance

3D magnetic reconnection within the magnetic legs of a CME

Possible mixture of resulting field topologies
Sketch Illustrating Effect of Suddenly Decreasing the Speed of the Solar Outflow on a Particular Field Line

This sketch ignores dynamic effects associated with the rarefaction produced by a sudden drop in speed.
Field Lines Resulting From a Combination of Differential Rotation and a Rigidly Rotating Dipole

HMF lines originating from 70° S in Fisk’s model (a) and Parker’s model (b).
Variation of Solar Rotation-Averaged Magnetic Field Strength Over 4 Solar Activity Cycles
Comparison of Solar Wind Between Cycles 22 (red) and 23 (blue) as Function of Heliolatitude

Ulysses Data
Lower Particle Density and Dynamic Pressure Near Most Recent Solar Minimum
THE END