

Solar Wind Variation Throughout the Heliosphere

Instructor Notes and Comments

Audience and Goals:

The target audience is early and mid-career graduate students studying solar and space physics. More advanced participants may find some of the activity a little pedestrian but will be able to use it as a jumping off point for their own explorations. Undergraduates should be able to follow the steps but will need more context to connect the activities to their course work.

In addition to the direct goals stated in the lab introduction, participants will become familiar with aspects of the solar wind simulations - variables involved, the shape of the simulation volume - and the accepted methods for displaying those results.

Pre-activity questions

Here are some questions

The major misconception that students can have is that the solar wind flows along magnetic field lines rather than flowing essentially radially outward from the Sun. Students may also think that the solar wind slows down as it moves away from the Sun. These questions are good to give at the beginning of the activity and then to review at the end.

- 1) As a parcel of solar wind that is moves away from the Sun in interplanetary space, how does its density change?
 - a. The density increases as it moves away from the Sun.
 - b. The density is constant as it moves away from the Sun.
 - c. The density decreases as the inverse of distance from the Sun.
 - d. **The density decreases as $1/r^2$.**
 - e. The density can increase or decrease depending on the circumstances.
- 2) As a parcel of solar wind moves further away from the Sun in interplanetary space, how does its velocity change?
 - a. The velocity increases as it moves away from the Sun.
 - b. **The velocity is constant as it moves away from the Sun.**
 - c. The velocity decreases as the inverse of distance from the Sun.
 - d. The velocity decreases as $1/r^2$.
 - e. The velocity can increase or decrease depending on the circumstances.

The first two questions are linked primarily by the continuity equation. For the velocity question, many will choose one of the decreasing answers, often as a hold of from a mechanics misconception that things must be slowing down due to drag. Some may argue that "e" is the correct choice since the there is spacial variation in the velocity along a line out from the Sun. The point to be made here is that after parcel of solar wind leaves the Sun, there is very little force acting on it and so its velocity is more or less constant. Therefore the density must be decreasing as the gas expands into a larger volume of space.

- 3) At 1 AU (Earth's Orbit), during a solar "quiet" period, what is the direction of the solar wind magnetic field?
- Primarily in the radial direction.
 - Primarily North or South.
 - Primarily East or West.
 - At about 45 degrees from the radial direction with some small Northward or Southward variations.
- 4) At 1 AU (Earth's Orbit), during a solar "quiet" period, what is the direction of the solar wind velocity?
- Primarily in the radial direction.
 - Primarily North or South.
 - Primarily East or West.
 - At about 45 degrees from the radial direction with some small Northward or Southward variations.

Another typical misconception is that the solar wind flows along the direction of the magnetic field lines in the "Parker Spiral".

Question Goal

The goal of the above questions and the question in the lab manual are to elicit discussion among the students and between the students and instructor.

Response to Question from the "Introduction"

- *What solar wind variables are you viewing in the iSWA layout? What range of values do they take?*

- The left panel shows the plasma density [in particles per cc] scaled with the square of the distance from the Sun [in AU's]. Notice then that at Earth's orbit [1 AU] this variable is just the plasma density.**
- The right panel shows the magnitude of the plasma velocity.**

- *What other features are represented in the plots?*

- Magnetic field lines are traced from points of interest (planets or the position of spacecraft).**
- The intersection between the ecliptic plane and the current sheet.**

- *What other variables might you expect from the Enlil model?*

- The Enlil model can provide all the of the plasma variables: density, velocity components, magnetic field components, pressure and temperature. Electric field and current components can be derived from these.**

- *What other information would you like from the model?*

- This is an open ended question which the students can discuss.**

Students should take the time to understand the plots and think about what the results should look like.

Cut Planes

- *On your groups shared pad, sketch the 3-D simulation volume showing*

Students often have trouble orienting the cut planes, particularly the R=1AU surface.

the cut planes.

- *Can you describe the volume?*
- a) **It is a spherical volume to about 2 AU, with an inner boundary at 30 Solar Radii, and the polar cones above 60 degrees latitude removed.**
- *Why do you think this volume was chosen by the model developers?*
- a) **The inner surface is set at the outer surface of the coronal model driving the solar wind simulation.**
- b) **The polar regions are cut out limit the computational work. These regions are of limited interest, and are not regularly incorporated in the simulations. That said, an important mission to study the high latitude solar wind was the ULYSSES mission (<http://ulysses.jpl.nasa.gov/index.html>) which explored the variation in and structure of the solar wind with latitude. (<http://solarscience.msfc.nasa.gov/SolarWind.shtml>)**

Each cut plane is painted with a variable that is derived from the simulation results.

- *What is the scale (range) of the velocity variable?*
- a) **The scale is given on the plot. Typical solar wind ranges are between 300 and 700 km per second**
- *How is the “density” plotted? What simulation results are used to calculate it?*
- a) **The density is scaled by multiplying by r^2 - the square of the distance from the Sun measured in AU's. This factor accounts for the variation due to the expansion of the solar wind into space and leaves only the variation due to changes in the source of the solar wind at the solar corona.**
- *What is it's range? What is the expected density at 1 AU (Earth's orbit)?*
- a) **The scale is given on the plot. Typical densities at Earth are 5 - 10 particles per cc. Notice that since the distance is in AU, then all all particle densities are given relative to what they would be at 1 AU.**

Variation in Density and Velocity

- *Describe how density and velocity vary with distance from the Sun.*
- a) **The intent of this question is for participants to understand the gross variation, in the density and velocity with distance from the Sun. As the solar wind expands out into interplanetary space the overall velocity stays roughly constant while the density falls off as $1/r^2$.**
- *Can you explain these results in terms of fundamental physics?*
- a) **At the most fundamental level this can be answered using Newton's 1st Law and conservation of mass. If you consider a parcel of solar wind plasma, it only interacts with the plasma ahead and behind, which is more or less moving at the same speed. With no force acting on it, the speed must be constant. If the speed is the same, then that plasma flux must pass through a greater area as it moves out from the Sun. Since the total plasma flux must be conserved and the area increases at r^2 , the plasma density must decrease by that factor.**
- b) **One thing to consider is the gravitational PE due to the Sun. To show that it is small as compared to the KE of the solar wind, have students calculate the change in PE (per unit mass) from about 30 solar radii to 1 AU and compare that to the kinetic energy (per unit mass).**

Consider just the velocity cygnet.

- *What is the direction of the velocity (say relative to the radial direction) as you move away from the Sun? Does the direction change further from the Sun? Why?*
 - *What simulation results would you want to look at to answer these questions?*
- a) As stated above, there is a persistent misconception that the solar wind flows along the Parker Spiral. So according to this misconception the velocity would be at an angle to the radial line which increases as the solar wind travels further from the sun.**
- b) There is nothing in the results presented so far that would dispel this misconception. The second question is to get students to think about what they should look at. Ideally they will want to look at the components of the plasma velocity, but they may come up with other ideas that could be explored.**

Part II: A Second Look

In this second part, procedural instructions are in a slightly different font from concept questions. The instructor may want to make that distinction.

Variation in Density

- *Where is this line in the equatorial plane that you plotted previously? Sketch it on your shared workspace.*
 - *Compare the variation in the magnetic field to the density. Are they related? Why?*
 - *Can you tell how the density varies with distance from the Sun? What would help?*
- a) The line plot is a plot of the chosen variables along a radial line from the Sun.**
- b) The principle of “frozen in flux” tells us that the magnetic field and density should match each other. These variations are difficult to see but is apparent when the plotted on a semi-log axis.**
- c) The density falls off as a power law. The log plot shows this better though the power law would only be evident on a log-log plot.**

Rescaled Density

- *How would you describe this plot? How does it vary with distance from the Sun?*
 - *What general conclusions can you draw about how the density varies with distance from the Sun?*
- a) Once the density is rescaled with the R^2 , the plot appears flat punctuated by spikes that represent the co-rotating interaction regions.**
- b) Since, after rescaling, the background solar wind is roughly flat, the density generally falls off as $1/r^2$.**

A Second Look at Variation in Velocity

Look at the components of velocity.

- Over what range do each of the components vary?
 - Range for V_r **250 Km/s - 600 Km/s**
 - Range for V_{lat} **-30 Km/s - 25 Km/s**
 - Range for V_{lon} **-20 Km/s - 15 Km/s**

- What does this say about the general direction of the solar wind velocity?
- How does the solar wind vary with distance from the Sun?

- a) **The solar wind velocity is primarily in the radial direction**
- b) **The solar wind velocity has no particular variation with distance.**

Finally let's look at the correlation between the solar wind velocity and plasma density.

- Are the velocity and density correlated? When the velocity is high what happens to the density? When the velocity is low? During the transition from high to low?

- a) **The sharp spikes in density correspond to sharp decreases in velocity. This is an indication of a shock that develops when fast solar wind piles up behind parcels of slow solar wind.**

- Describe the structure that you see of the region closest to the Sun.
- Describe how the structure changes as it moves out from the Sun.
- How far from the Sun is the CIR when it develops into a Shock?

- a) **The plots below show what the students would be looking at. This plots are line cuts through the simulation volume at a fixed time. Notice that as the longitudinal angle changes, similar structures appear further from the Sun and are more compressed. Note that this is only indicative of the time evolution and do not actual show the time evolution since this particular model supplies a static result. We can infer the since the similar solar wind structures were generated by the same regions on the inner boundary of the simulation.**



