SOLAR WIND PHYSICS WITH SOLAR PROBE:

How will our first mission to the nearest star contribute to our understanding of coronal heating and the acceleration of the high-speed solar wind?

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3 December 1999

These unpublished notes have been written to assist the definition of science goals for the *in situ* instrumentation that is being designed for NASA's *Solar Probe* mission. They contain only the opinions of one researcher in 1999, and are not representative of any larger group or community. These notes can be distributed freely, provided they remain unmodified and original authorship is retained. Although most of the information below has been summarized from the refereed literature, references to this document can be made in the following way:

Cranmer, S. R.: 1999, "Solar Wind Physics with Solar Probe," unpublished notes,
URL: http://cfa-www.harvard.edu/∼scranmer/Preprints/cranmer_probe.pdf

1. Introduction

The theoretical questions and problems discussed in this document concern primarily the high-speed (low-density and steady-state) component of the solar wind that dominates over the heliographic poles at solar minimum. Familiarity with existing observational data is assumed, but some references are provided here for background information about the following types of diagnostics: *in situ* particle and field measurements (Neugebauer 1975, 1982; Dobrowolny and Moreno 1977; Smith and Wolfe 1979; Marsch 1991; Gosling 1996; Goldstein *et al.* 1996; Feldman and Marsch 1997; Ogilvie and Desch 1997; Richardson *et al.* 1999), spectroscopy and polarimetry of the extended solar corona (Withbroe *et al.* 1982; Kohl *et al.* 1997; Esser and Habbal 1997; Cranmer *et al.* 1998; Wilhelm *et al.* 1998; Sittler and Guhathakurta 1999), radio sounding measurements through solar wind plasma (Bird and Edenhofer 1990; Yakovlev and Mullan 1996), remote sensing measurements of backscattered solar radiation by interstellar atoms (Fahr 1974; Bertaux *et al.* 1996), and inferences about the solar wind from its interaction with comets (e.g., Brandt *et al.* 1972; Ip and Axford 1982; Raymond *et al.* 1998).

Two of the primary benefits of the *Solar Probe* mission are (1) that the spacecraft covers a huge dynamic range of heliocentric distance: 4 to 1000 $R_\odot$ (assuming a Jupiter gravity assist), and (2) that in the corona, the *Probe* measurements can verify and help calibrate remote sensing measurements, as well as provide small-scale details that are smeared out in the remote sensing data. This mission will entail a direct sampling of the region of the solar wind where the bulk of its acceleration takes place.

This document is organized by the *in situ* diagnostics that *Solar Probe* should measure: particle velocity distributions (§ 2) and field fluctuations and waves (§ 3). Important problems and issues are scattered throughout, and the main organization is into 20 specific questions that *Probe* can help to resolve.

2. Particle Velocity Distributions

First, there are five questions that apply to all particles in the high-speed solar wind. These are followed by sections specifically devoted to protons (§ 2.1), electrons (§ 2.2), and heavy minor ions (§ 2.3).

1. *Where does the wind acceleration take place?* In other words, what is the detailed velocity law $u(r)$, and how do neighboring flux tubes vary in their acceleration? There is some controversy whether there is *any* acceleration at distances greater than 4 $R_\odot$ in the fast wind; some theories suggest the wind is essentially finished accelerating by this distance (e.g., McKenzie *et al.* 1997), but there is some evidence that the wind keeps gaining kinetic energy significantly beyond 4 $R_\odot$ (Raymond *et al.* 1998).
2. *Does the fast wind come from plumes as well as interplume plasma?* There is evidence for both extremes as well as for a middle ground (i.e., that the wind is all plume, all interplume, or a mixture of the two). Theories of plume/interplume mixing are still in early stages of development (e.g., Parhi *et al.* 1999). Figure 1 shows that steady-state mass flux conservation can be used to derive the wind speed, but very different answers are found when the densities are assumed to be all interplume (e.g., the minimum values of Fisher and Guhathakurta 1995) or a mean "mixed" state (e.g., the average coronal hole values of Guhathakurta and Holzer 1994). Consistency with UVCS/*SOHO* Doppler dimming H^0 speeds (Kohl *et al.* 1998; Cranmer *et al.* 1999) seems to demand the mean state, but many theoretical models produce velocities more consistent with the pure interplume state (e.g., McKenzie *et al.* 1997; Hollweg 1999b). *Solar Probe* can measure outflow along individual flux tubes to help determine the overall contribution of different structures.
3. *What are the high IPS speeds?* Radio interplanetary scintillation (IPS) has been used to measure speeds approaching 1000 km s^{-1} at 7–10 $R_\odot$ over the solar poles (Grall *et al.* 1996; Esser *et al.* 1997), but it is unclear whether these represent bulk plasma speeds or the phase or group speeds of fluctuations propagating in the wind. Figure 1 indicates that either may be the case, and *Solar Probe* would help determine exactly what types of motions are dominant at these speeds.

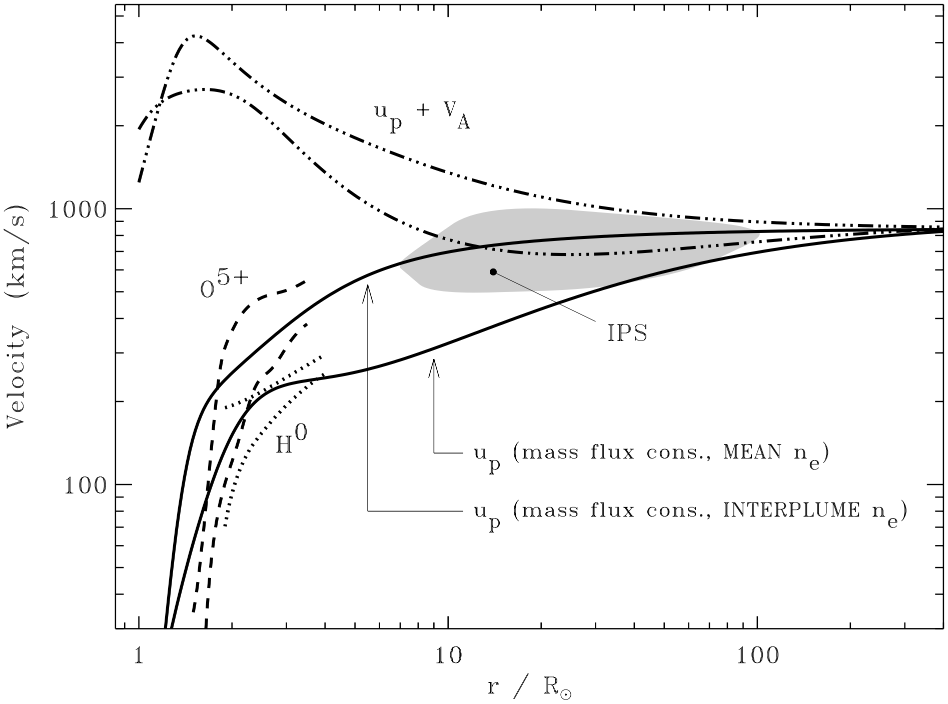

Figure 1. Summary plot of empirically derived wind speeds: proton velocities u_p derived from mass flux conservation (solid lines), UVCS hydrogen (dotted) and oxygen (dashed) Doppler dimming velocities, and the summed $(u_p + V_A)$ "surfing" speeds (dash-triple-dot). The gray region denotes the range of polar IPS speeds reported by Grall *et al.* (1996).

4. *Are coronal velocity distributions suprathermal?* Since Scudder's (1992a,b) suggestion that coronal heating may be a simple kinetic "velocity filtration" of suprathermal particles, researchers have sought a way to determine conclusively if this mechanism is operating in the corona. Suprathermal distributions are common in low-density space plasmas, but it is not known if coronal plasmas can support these departures from thermal equilibrium.[*] *Solar Probe* should be able to measure suprathermal tails in coronal particle distributions—as well as how the energy in the tails evolves with distance—to finally determine the validity of coronal heating mechanisms that depend on their presence.
5. *How does the wind maintain its quasi-fluid character?* Above 2–5 $R_\odot$, Coulomb collisions become negligible in determining ion distribution properties in the high-speed wind. However, *in situ* distributions are far closer to isotropic Maxwellian distributions than pure collisionless kinetic theory would predict. Some source of non-collisional particle isotropization must exist, but the dominant mechanisms are not yet clear (see, e.g., Dum 1983; Meister 1992).

[*] However, Scudder (1998) has shown that in the presence of a sufficiently strong heat flux gradient, a suprathermal distribution may in fact be the equilibrium distribution.

Although no single *in situ* diagnostic can be predicted to determine this process, the *Solar Probe* data as a whole will help constrain theoretical models.

2.1. PROTON DISTRIBUTIONS

6. *How does the proton anisotropy evolve?* The *Helios* spacecraft detected a strong anisotropy in the cores of proton velocity distributions, with temperatures higher in the direction perpendicular to the magnetic field than parallel to the field (see Marsch 1991). UVCS/*SOHO* observations of H^0 (which is coupled to protons by charge transfer below heights of 3–4 $R_\odot$) indicate a similar mild anisotropy in the extended corona (Kohl *et al.* 1998). The anisotropy ratio $T_\perp / T_\parallel$ is a strong probe of coronal heating mechanisms and wave-particle instabilities, and it is expected to vary in regions of different density, flow speed, and magnetic field strength. *Solar Probe's* database of $T_\perp / T_\parallel$ versus r, n, and u will be extremely valuable in sorting out the heating mechanisms present in various types of solar wind.
7. *How does the proton magnetic moment depart from adiabaticity?* In an adiabatic plasma the magnetic moment μ (proportional to $T_\perp / B$) is constant along flux tubes, but *Helios* observed a steep rise in this parameter between 0.3 and 1 AU (Schwartz and Marsch 1983). This indicates a net deposition of heat in the far solar wind, and *Solar Probe* can continue to measure this heating rate over a much larger range of distances than ever before possible. The exact form of the radial dependence of μ will put firm constraints on candidate physical processes for proton heating.
8. *Do proton distributions follow resonant shells?* The dissipation of high-frequency (10 to 10,000 Hz) ion cyclotron resonant waves is a leading candidate for ion heating and acceleration (e.g., Hollweg and Turner 1978; Marsch *et al.* 1982a; Isenberg and Hollweg 1983; Tu and Marsch 1997; Cranmer *et al.* 1999a, 2000a; Li *et al.* 1999; Hollweg 1999a,b,c). In this theory, the waves produce an effective diffusion in velocity space that produces filled circular "shells" centered at a high parallel velocity ($V_A \approx$ 1000–5000 km s^{-1} in the corona). Figure 2 shows a set of numerical solutions to the resonant diffusion equation for coronal conditions (see also Isenberg *et al.* 1999; Cranmer 2000b), and the gradual filling of these shells produces the commonly seen anisotropy ($T_\perp > T_\parallel$). If *Solar Probe* measures these shell distributions directly it would be a precise confirmation of the ion cyclotron theory.
9. *Where and how to proton beams develop?* Proton distributions in the high-speed wind often exhibit field-aligned enhancements of particles propagating ahead of the core distribution by about the local Alfvén speed V_A (see Figure 2). Such a forwardly beamed distribution can be created by Coulomb collision runaway (even in a weakly collisional plasma; see Livi and Marsch 1987) or possibly by wave-particle interactions (e.g., Tam and Chang 1999). *Solar Probe* measurements of the initial development of this beam at distances less

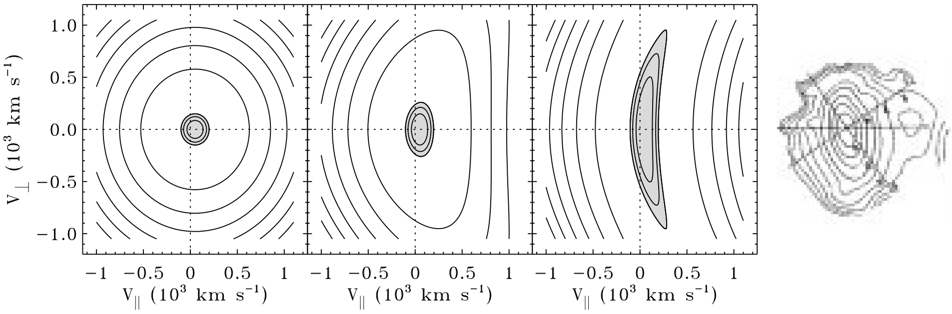

Figure 2. The left panels show numerical velocity distributions after 0, 5, and 80 minutes of ion cyclotron diffusion, with wave power levels set by the models of Cranmer *et al.* (1999a). The gray regions denote the most populated "cores" of the distributions, having greater than $1/e$ of the peak phase space density. The right panel shows a representative fast-wind *Helios* proton distribution at 0.3 AU (Marsch 1991), not to scale.

than 0.3 AU will be needed to distinguish between the different proposed mechanisms. Possible departures between the beam's relative speed and V_A would be important constraints on models.

2.2. ELECTRON DISTRIBUTIONS

10. *What are the core electron temperatures in the corona?* Remote sensing measurements of the electron temperature T_e (which reflects the core of the velocity distribution function) are currently not in agreement with one another between about 1.1 and 1.5 $R_\odot$. The solid lines in Figure 3 highlight this discrepancy: CDS and SUMER line ratios suggest T_e rapidly decreases to about 300,000 K by 1.3–1.4 $R_\odot$ (e.g., David *et al.* 1998), whereas models of the freezing in of *in situ* ionization states suggest that T_e continues to increase to about 1.5×10^6 K by 1.5 $R_\odot$ before beginning to decrease (Ko *et al.* 1997). Although *Solar Probe* will not sample plasma this close to the Sun, its measurements of T_e for $r > 4\,R_\odot$ will guide the interpretation of the remote sensing data. (Perhaps the "multi-thermal" nature of the transition region and low corona continues into the extended corona, and a continuous distribution of temperatures is present on very small scales in the flux tubes that make up the fast solar wind; see, e.g., Feldman 1998.)
11. *How do the core and halo electrons compare?* Electron velocity distributions typically exhibit a cold, nearly isotropic "core" and a higher energy "halo" superimposed at nearly the same streaming velocity (see, e.g., Feldman and Marsch 1997). The temperature ratio between the two is a measure of the strength of Coulomb collisions (Scudder and Olbert 1979a,b), and the energy of the break point between the two components is sensitive to the local electrostatic potential (e.g., McComas *et al.* 1992). These two parameters are roughly

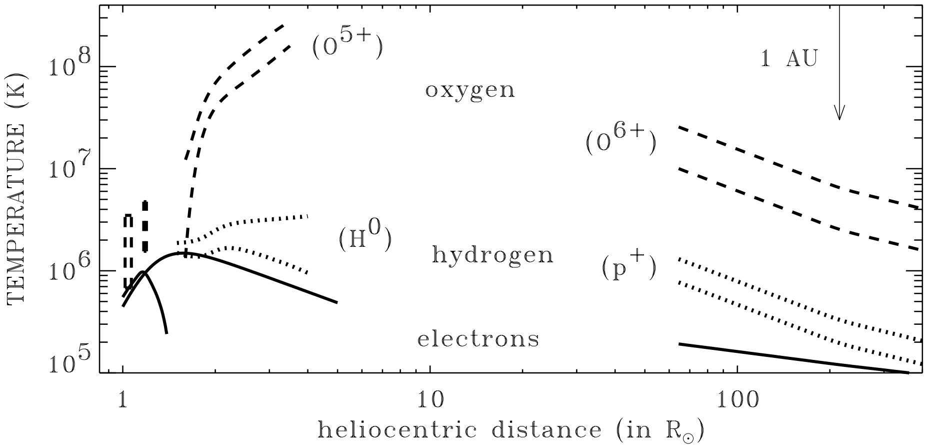

Figure 3. Summary plot of empirically derived coronal and wind temperatures: electron (solid), hydrogen (dotted), and oxygen (dashed) temperatures, with neutral hydrogen and O^{5+} in the corona (UVCS/*SOHO,* SUMER/*SOHO*), and protons and O^{6+} in the far solar wind (*Helios, Ulysses, Voyager*).

constant between 1 and 4 AU, but their deviation from constancy in the innermost solar wind will be a strong constraint on models of fast-wind electron kinetics. Also, the weak "super-halo" (Lin *et al.* 1997) that was discovered by the *Wind* spacecraft needs to be probed at a range of distances to see if it has any dynamical impact on the wind as a whole.

12. *Is the strahl a remnant of coronal electrons?* In the high-speed wind, electron distributions are strongly enhanced along the forward field-aligned direction, and this narrow beam is referred to as a "strahl." The temperatures along strahls often approach 10^6 K, and they have been interpreted as the collisionless extension of hot coronal electrons into interplanetary space. Feldman and Marsch (1997) discuss several suggested mechanisms for the production and evolution of electron strahls, and detailed measurements of their development with *Solar Probe* (especially how their widths in pitch angle evolve with energy) will help identify the dominant physical processes.

2.3. HEAVY ION DISTRIBUTIONS

13. *Does the alpha-proton velocity difference deviate from V_A?* He^{2+} and several other ions have been observed to flow faster than protons by about a local Alfvén speed at $r > 0.3$ AU (Marsch *et al.* 1982b; Hefti *et al.* 1998). UVCS/*SOHO* has also measured flow speeds of O^{5+} ions that may be as much as double the local proton speeds at 2–3 $R_\odot$ (Cranmer *et al.* 1999b). However, in the innermost corona Coulomb friction would tend to drag out all species at nearly the same speed. Thus, there must be a range of heliocentric distances where the ions accelerate ahead of the primary proton-electron plasma, and this range

may vary from ion to ion. Ion cyclotron wave damping has been suggested as a probable mechanism to produce this preferential acceleration (see McKenzie and Marsch 1982; Hollweg 1999b), but the details are not yet clear. *Solar Probe* measurements of how the velocity difference ($u_{\text{ion}} - u_p$) evolves with distance, and how it compares with V_A, will put firm constraints on theories. Fine tuning of specific models can be performed if the relative velocities of a large number of ion species are measured.

14. *How do ion temperature anisotropies develop and differ?* There are indications of strong temperature anisotropies of minor ions in the fast wind, but nothing approaching a comprehensive picture of their kinetic properties exists. UVCS/*SOHO* has found evidence that O^{5+} has $T_\perp \approx$ (10–100)$T_\parallel$ at 2–3 $R_\odot$ (Kohl *et al.* 1997, 1998). For He^{2+}, *Helios* determined that $T_\parallel$ was greater than $T_\perp$ by about 10–30% in the highest-speed flows near 0.3 AU (Marsch *et al.* 1982b). The ion cyclotron wave dissipation theory predicts that helium should reverse this anisotropy (i.e., have $T_\perp > T_\parallel$) at smaller heliocentric distances, and *Solar Probe* should be able to confirm or deny this easily. *Probe* can also evaluate whether the extreme anisotropies deduced from spectroscopy persist in the wind above 4 $R_\odot$ or if plasma instabilities and the magnetic mirror force drive the distributions back toward isotropy.
15. *How does the deviation from mass-proportional heating depend on distance and wind speed?* The most-probable speeds of ions ($w = [2kT/m_{\text{ion}}]^{1/2}$) are approximately constant in the high-speed wind, implying $T \propto m_{\text{ion}}$ (Ryan and Axford 1975). However, in the fastest streams observed with $u > 700$ km s^{-1}, heavier ions have temperatures exceeding simple mass proportionality (see, e.g., Collier *et al.* 1996). This property is a unique feature of the ion cyclotron wave dissipation theory. *Solar Probe's* comparative measurements of ion temperatures as a function of heliocentric distance and wind speed will provide strong constraints on models of heat deposition in the fast wind, and may lead to specific predictions for the shape of the high-frequency (10–10,000 Hz) Alfvén wave spectrum.
16. *Are polar plume characteristics preserved in helium abundance and plasma beta?* Reisenfeld *et al.* (1999) found strong correlations in *Ulysses* data between fluctuations in helium abundance and the plasma beta ratio β. The correlation was moderately strong at 1 AU and decreased almost to zero by 4.5 AU; presumably *Solar Probe* can detect even stronger correlations of this type closer to the Sun. *Probe* can determine if these fluctuations have their origin in polar plumes, because it will pass directly through the plumes themselves where $\beta \ll 1$, as well as witness their disruption (and the possible evolution of plume remnants into pressure balance structures) where the wind speed exceeds the Alfvén speed.
17. *Are ion properties steady-state or jet-driven?* Although several theoretical mechanisms have been proposed that maintain the extended solar corona in a steady-state manner, it is certain that time variability exists in most coronal

and wind structures. Feldman *et al.* (1993, 1997) proposed that the bulk of the corona is composed of a large number of transient expanding jets, and that heavy ions are accelerated and heated episodically only in the presence of these energetic streams. *Solar Probe* measurements of "intermittency" in the ion plasma properties would confirm the basic premise of this idea—as would the detection of cooler, infalling ions in the *absence* of jets. However, if the measurements indicate that both heavy ions and the bulk proton-electron plasma are reasonably steady-state in their heating and acceleration, the contribution of impulsive structures would be concluded to be negligible.

3. Field Fluctuations and Waves

18. *How does interplanetary turbulence develop?* The heliosphere has been observed to be a highly turbulent plasma, with fluctuations in magnetic field strength, velocity, and density measured on time scales ranging from 0.1 second to years (e.g., Goldstein *et al.* 1995; Tu and Marsch 1995). A fully developed inertial range is observed at 0.3 AU, but the turbulence is dominated by outwardly propagating structures; at 1 AU and beyond the outward and inward motions are comparable. It is thought that the turbulence arises from nonlinear interactions among waves that originate in the corona, and *Solar Probe* will view this process directly. Observing the initial development of the inwardly propagating component (arising from, e.g., wave reflection or nonlinear steepening) is key to the understanding of how the turbulence is produced and maintained.
19. *Are there ion cyclotron waves in the extended corona?* Although a considerable amount of circumstantial evidence exists for the presence of parallel-propagating gyroresonant waves in the corona, these high-frequency fluctuations have not been detected directly. *Solar Probe* should be able to detect Alfvénic fluctuations up to the local proton cyclotron frequencies during its perehelion pass. Knowing the full three-dimensional power spectrum of these oscillations (i.e., the wave amplitudes vs. wavenumber and propagation direction) will help clear up existing uncertainties about how MHD turbulence is damped at high frequencies—and thus how much of the wind's kinetic energy is produced by this process. For example, if a power law spectrum is discovered to exist for parallel-propagating waves (i.e., $P \propto k_{\|}^{-\eta}$), then turbulence theories that predict only perpendicular cascade need to be revised (see, e.g., Matthaeus *et al.* 1994; Roberts *et al.* 1999).
20. *Is dissipation-range turbulence enhanced in the "supercorona?"* Between 10 and 30 $R_{\odot}$, interplanetary scintillation (IPS) measurements have detected strong enhancements in fluctuation power at ion inertial length scales (e.g., Lotova 1988; Coles *et al.* 1991). This region has been called the "supercorona," the "transitional region," or the "transsonic region" (mainly in the Russian literature) because it was suspected that the wind flow there undergoes a rapid

acceleration to become supersonic. *Solar Probe* will be able to determine exactly what types of motions are dominant in this region, and thus determine the major modes of energy transfer between fluctuations, the bulk flow, and random microscopic motions. These measurements will also provide useful context for the interpretation of the multi-decade database of radio sounding observations (see also Yakovlev and Mullan 1996).

4. Conclusions

Below there is a large bibliography (mostly taken from an upcoming review paper; Cranmer 2000b) that may prove helpful in surveying the ongoing progress in the field of solar wind acceleration and coronal heating.

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