HERE COMES SOLAR PROBE!

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ABSTRACT

Despite recent advances, fundamental questions remain about the nature of the solar corona and the solar wind: 1) What produces the corona and accelerates the solar wind? 2) Where in the corona do different types of solar wind originate? 3) Where and how are energetic particles produced and transported near the Sun? 4) What role do plasma turbulence and waves play in the corona and solar wind production? 5) What is the nature of the magnetic field and photospheric structures near the solar poles? Flying a trajectory perpendicular to the Earth-Sun line during its perihelion passage, Solar Probe will use in-situ and imaging instruments to provide the first three dimensional viewing of the corona, direct observations of solar polar regions, and local sampling of the solar environment. These primary observations are complemented by context-setting cruise measurements and Earth-based observations. Solar Probe is currently scheduled for launch in February 2007 as the third in the new Outer Planets/Solar Probe mission line of NASA and will arrive at the Sun in 2010 under solar maximum conditions with a second closest approach near solar minimum in 2015.

INTRODUCTION

One of the last unexplored regions of the solar system is the innermost portion of the heliosphere, where the solar wind emerges from the solar atmosphere. Almost all of the planets have been visited by spacecraft, the Voyagers are soon expected to reach and report on the distant boundary of the solar system, and even the high latitude regions of the solar wind are being explored by Ulysses, but a visit of the key region from close to the Sun's surface up to the orbit of Mercury (≈ 0.3 AU) has remained a dream over the past 20 years. From its 1 AU orbit SOHO is imaging the Sun far better than ever before, but the polar photosphere remains essentially unknown. The composition of the solar wind and of solar energetic particles are measured in greater detail and with greater precision than ever before with Wind, SOHO and ACE. Yet their source, the solar corona and its heating, remain relatively little understood. We do not understand how the Sun creates its pervasive solar wind which affects the earth, all the planets and interacts with the local interstellar cloud outside the solar system.

To close this gap in understanding there is only one way, namely to sample for the first time this unexplored region from a few to $\approx 100\ R_s$ with a well-instrumented spacecraft. Such a mission is a Solar Probe, as has been proposed and studied in various incarnations since the 1970's. Because of the hostile environment near the Sun the mission concept has always been complex, challenging and huge in demand of resources. However, the challenge of the new paradigm for smaller more cost-effective missions was taken on by concentrating on key objectives, and combining two major components of the spacecraft into one, the heat shield and the main antenna dish. This idea of a Minimum Solar Probe Mission kept the idea alive, until Solar Probe found its home as the third mission in NASA's new Outer Planets/Solar Probe Program. Solar Probe will determine the origin and acceleration of the solar wind which engulfs the entire solar system, modulates the penetrating cosmic rays from the galaxy, and controls interplanetary space from the Sun to the local interstellar medium.

CURRENT KNOWLEDGE OF THE SOLAR WIND, OF THE CORONA AND OF THE SOLAR SURFACE

Recent measurements with state-of-the-art instruments on Ulysses, SOHO, Wind and ACE have advanced our current understanding of the initial and terminal solar wind and of the characteristics of the solar surface. We will now briefly review some of the new results and discuss related unresolved questions.

Fast and Slow Solar Wind. Ulysses with its near polar 1.4 by 5.4 AU orbit has shown quite clearly that the solar wind comes in two distinct states. The fast wind, with speed of ≈ 800 km/s and a simple structure flows at latitudes higher than ≈30°, while the slow wind with a typical speed of ≈400 km/s and much greater variability, is confined to the region near the ecliptic plane (Fig. 1). Around solar minimum the fast wind dominates the heliosphere. Composition measurements with SWICS on Ulysses reveal that the fast wind resembles most closely the elemental composition of the photosphere and that the overabundance of low FIP (first ionization potential) elements is at most weak (Geiss et al., 1995). The charge state distribution is characterized by a single, low freezing-in coronal temperature for each element (Geiss et al., 1995). In contrast, the slow wind is highly variable in speed (Fig. 1), its charge states can no longer be characterized by a single freezing in temperature (von Steiger et al., 1997), and the FIP effect is far more pronounced. In addition, the $^3He/^4He$ ratio is both higher and more variable in the slow wind compared to the fast wind (Gloeckler and Geiss, 1998). Using solar wind composition the boundary between the slow and fast wind appears to be sharp, with a step transition in the freezing-in temperature (from O^{6+}/O^{7+}) and FIP strength (from Mg/O). These results (Geiss et al., 1995), indicate that a sharp boundary extends even into the lower solar atmosphere.

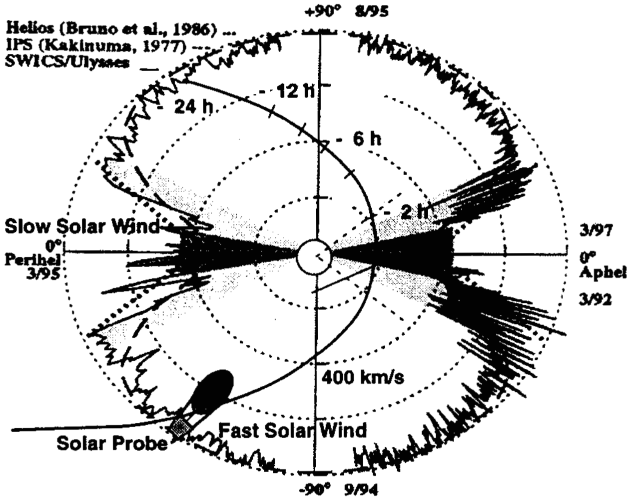

Fig. 1. Polar plot of solar wind speed with heliographic latitude from Woch et al. (1997). A Solar Probe trajectory is overlaid.

Initial Solar Wind. The SOHO/UVCS results based on Doppler-dimming observations of the corona below 10 R_s (e.g. Kohl et al., 1997) show that the coronal hole wind reaches its terminal speed of 800 km/s at 10 R_s and is still being accelerated at 4 R_s. The temperature of heavy ions is much larger than that of protons. The proton temperature at 3 R_S in the coronal hole is a factor of two to three higher than the electron temperature inferred from charge states in the terminal wind. The proton temperature in the equatorial regions, however, seems to be lower than the inferred electron temperature.

Solar Photosphere. SOHO measurements, especially from MDI, have revealed some remarkable features of the equatorial photosphere and have provided some indications of conditions at the polar photosphere which cannot be viewed effectively by SOHO. The magnetic flux in the equatorial regions is replaced very rapidly, about every 40 h, and there are indications for meridional flows a factor of more than two higher than previously estimated. The rotation rate at higher latitudes is ≈10% - 20% lower than expected. Helioseismic observations of the polar region, though limited by the observation angle, show an indication of circumpolar jet streams within 15° of the pole. They also provide some evidence for a polar vortex that may extend to the bottom of the convection zone. Polar plumes were observed with SOHO EIT, that are associated with strong unipolar fields, are ≈2°-3° wide, get replenished with plasma every few days, and extend to ≈15 R_s from the Sun.

Energetic Particles. Solar energetic particle events have been subdivided into two main classes. Impulsive events are enriched in heavy ions, most prominently in Fe, and often in ^3He, while gradual events resemble more closely the photospheric composition (e.g. Reames 1992). While gradual events are believed to be associated with CME-driven shocks, acceleration in impulsive events is thought to occur in the flare site with resonant wave absorption probably responsible for the drastic ^3He enrichment. In addition, there is ample evidence for very small solar flares, coined microflares, that occur at a high rate (e.g. Lin et al., 1991). These events may also produce energetic particles, but probably below the sensitivity of sensors at 1 AU.

Unresolved Questions. Many fundamental questions regarding solar wind origin and acceleration, coronal heating and energy flow from the solar surface to the corona are still unresolved. We have no direct information on the nature of wave turbulence and wave plasma interactions in the acceleration region, against which current models could be tested. The debate where and how energetic particles are produced has not been resolved, nor have the highly selective processes that lead to drastic changes in the composition been identified. Ulysses results indicate that the fast wind originates in the cool, open field regions of the polar coronal holes and reaches the lower latitudes by superradial expansion. It is not clear, however, whether the fast wind comes from the newly discovered solar plumes or the interplume regions of the coronal holes, or even from quiet non-active regions outside coronal holes (Habbal et al., 1997). The slow wind appears to come from regions outside the coronal hole. However, to isolate individual source various regions will not be possible using remote observations because of the strong mixing of the flows at 1 AU (Gloeckler et al, 1998).

We do not know the magnetic field topology, the surface and subsurface flow patterns in the polar regions nor how they differ from those at lower latitudes. We do not know how far into the corona these structures dominate the energy transfer and the outflow pattern. For example, the polar plumes do not spread with distance from the Sun in a way that is consistent with any current model of these structures.

THE SOLAR PROBE MISSION AND PAYLOAD CONCEPT

The Solar Probe Science Definition Team (W. Feldman, G. Gloeckler, Chair, S. Habbal, C. Korendyke, P. Liewer, R. McNutt, E. Möbius, T. Moore, J. Randolph, R. Rosner, J. Slavin, B. Tsurutani) was charged with providing the prime scientific objectives for the Solar Probe Mission and a core strawman payload. The science objectives were further prioritized into three categories: (A) irreducible core objectives to be fulfilled with the baseline instruments payload, (B) objectives that require only minor enhancement, and (C) objectives that could be addressed with additions to the core payload. The two primary categories are listed below:

Category A Objectives

- Acceleration processes and source regions of the fast and slow solar wind at solar maximum and minimum
- Locate the source and trace the flow of energy that heats the corona
- Construct the three-dimensional density configuration from pole to pole, and determine the subsurface flow pattern, the structure of the polar magnetic field and its relationship with the overlying corona
- Identify the acceleration mechanisms and locate the source regions of energetic particles, and determine the role of plasma turbulence in the production of solar wind and energetic particles

Category B Objectives

- Investigate dust rings and particulates in the near-sun environment
- Determine the outflow of atoms from the Sun and their relationship to the solar wind
- Establish the relationship between remote sensing, near-earth and in-situ observations near the Sun

Science Core Payload. The strawman payload consists of five in-situ and three remote-sensing miniaturized instruments. The measurements required to address the Category A science objectives are listed for each of these instrument in Table 1. In order to be able to scan the core solar wind distribution at all times it was found necessary to provide nadir viewing capability for the Solar Wind Ion Composition Spectrometer. Therefore, some allowance for a nadir viewing deflector was included in the resources. The most economical use of the spacecraft resources is achieved by two instrument packages - Remote Sensing and In-Situ - each with its own common data processing unit, which brings the total mass and power under 20 kg and 20 W. The data rate at closest approach is over 112 kbits/s, roughly half transmitted in real time and the rest stored on board.

Table 1 Solar Probe Strawman Instruments: Measurement Requirements

Strawman Instruments	Quantity(ies) Measured	*Dynamic Range*	Spec. Range, *Resolution*	Ang. Range, *Resolution*	Time or Spat. *Resolution**
Remote Sensing Instrument Package					
Visible Magnetograph - Helioseismograph	Magnetic Field, Line-of-Sight Velocity Field,	*10-3000* G *10-4000* m/s 1% *1-400* %	3 Å Visible *70* mÅ	1024 arc sec *2* arc sec	2 sec 32 km
XUV Imager	Intensity @ Entrance aperture	100 ergs/cm²sr *100-40,400* ergs/cm²sr	EUV Band Coronal Imaging, *8*Å	2560 arc sec *5* arc sec	< 1 sec
All-sky, 3 - D Coronagraph Imager	White light	Signal to Noise > 100, > *1000*	400-700 nm	< *1*°, 20-180° S/C-Sun line	< 1 min
In-Situ Instrument Package					
Solar Wind Ion Composition and Electron Spectrometer	Dist. fncs of main Q of H, He, C, O, Ne, Si and Fe; e	10^5/cm^{2}s *2•10⁷*	0.05 < E < 50 keV/e *ΔE/E < 0.07*	Nadir and 135° x 300° *10° x 10°*	1 sec H, He, e⁻; 10 sec Z>2
Energetic Particle Composition Spectrometer	Diff. fluxes of H, ^{3}He, ^{4}He, C, O, Si, Fe, and e	10/cm^{2}s-sr keV *10⁷*	i: 0.02-2 MeV/n e⁻: 0.02-1 MeV *ΔE/E < 0.07*	135° x 300° *20° x 20°*	1 sec for e⁻; 5 sec for H 30 sec Z > 1
Fast Solar Wind Ion Detector	Dist. fcn of ions	10^6/cm^{2}s *10⁶*	0.02-50 keV/e *ΔE/E < 0.07*	90° x 300°	1 ms
Magnetometer	Vector DC Magnetic Field	±0.05 nT *10³*	---	---	10 ms 3 km
Plasma Wave Sensor	AC Electric and Magnetic Fields	10^{-5} V/m 10^{-9} nT/Hz, *10⁶*	0.05 - 150 kHz *Δω/ω = 0.05*	---	1 ms (wave cap) 1 sec (spectral)

Solar Probe Spacecraft. The unique feature of the Solar Probe spacecraft is the large but low mass carbon-carbon parabolic heat shield which provides thermal protection for payload and spacecraft (Fig. 2) and serves as the high-gain antenna. Tests of the carbon-carbon material for the heat shield show mass loss rates that are insignificant. Nadir viewing for the visible and XUV imagers is accomplished with carbon-carbon tubes that penetrate the heat shield and spacecraft bus. An electrostatic deflector provides the nadir viewing for the ion made from carbon-carbon structure that protrudes from the umbra instrument. It is recognized that the baseline mission with two perihelion passes requires an Advanced Radiọisotope Power Source (ARPS). An ARPS is baselined the other two missions (Europa and Pluto) in the Outer Solar System/Solar Probe Program.

Baseline Mission. The Solar Probe trajectory is oriented such that at perihelion the orbital plane is perpendicular to the Sun-Earth line which permits use of the unique parabolic, side mounted heat shield as the high gain antenna for real time transmission. This orientation allows a unique scan of both the fast and slow solar wind regions (Fig. 1) and context-setting observation of the corona from Earth in an ideal geometry. According to the current plan Solar Probe will be launched by a Delta III in February 2007 on a direct trajectory to Jupiter to minimize flight time and to use gravity assist into a highly elliptic polar orbit. Closest approach at 4 R_s takes place in late 2010. As the first encounter is at solar maximum, precluding observations of the well-structured Sun at solar minimum, a second perihelion pass is baselined for early 2015. This time the orbital plane will not be exactly perpendicular to the Sun-Earth line. Therefore, the main science data will have to be recorded and relayed after closest approach. For each of the two passes encounter measurements start 10 days before closest approach and end 10 days after perihelion passage. During this twenty day period, the inner heliosphere (at < 0.5 AU) will be observed in-situ for the first time. Helioseismology observations begin at -4 days (0.2 AU) from closest approach. The most intense observations are made in the two-day period at < 20 R_s, when Solar Probe will make high time resolution in-situ measurements in the inner corona, high spatial resolution pole to pole observations of the solar surface, and 3-D pictures of the solar corona.

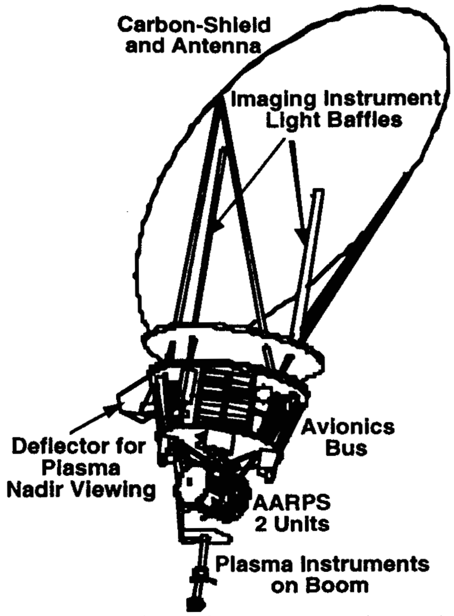

Fig. 2. Side view of a possible Solar Probe with instruments on the sides, inside the bus and on the boom, constrained by the umbra of the heat shield. Nadir viewing for the plasma instrument is achieved by means of an ion deflection system.

SUMMARY

Solar Probe, one of the first 3 missions in the Outer Solar System/Solar Probe Program of NASA, is scheduled to be launched in February 2007. It is a mission of exploration, of discovery and of comprehension. Flying from pole to pole through the solar atmosphere, as close as 3 R_s above the solar surface, Solar Probe will perform the first close-up exploration of the Sun, the only star accessible to humankind. This pioneering mission will sample directly the solar wind in the acceleration region and will take high resolution images of the solar atmosphere, especially of the polar regions of the Sun. This missing "ground truth" picture will link the wealth of existing solar and coronal observations to the actual physical state and dynamics of the solar corona.

ACKNOWLEDGMENTS

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REFERENCES

Bruno, R., et al., *Solar Physics*, **104**, 431, 1986.

Geiss, J., G. et al., *Science*, **268**, 1033-1036, 1995.

Gloeckler, G. and J. Geiss, *Space Sc. Rev.* **84**, in press, 1998.

Gloeckler, G., et al., *Geophys. Res. Lett*, submitted, Aug. 1998.

Habbal, S. R., et al., *Ap. J.*, **489**, L103, 1997.

Kakinuma, T., in *Study of traveling interplanetary phenomena*, ed. M. A. Shea et al., D. Reidel Publishing, 101, 1977.

Kohl, J. L., et al., *Solar Phys.*, **175**, 613, 1997.

Lin, R.P., et al., *Solar Phys.*, **135**, 57, 1991.

Reames, D.V., in: Particle Acceleration in Cosmic Plasmas, G.P. Zank, T.K. Gaisser eds., *AIP Conf. Proc.* **264**, 213, 1992.

von Steiger, R., J. Geiss, and G. Gloeckler, in *Cosmic Winds and the Heliosphere*, (eds. J. R. Jokipii, C. P. Sonnett, and M. S. Giampapa), University of Arizona Press, 581, 1997.

Woch, J., et al., *Geophys. Res. Lett.* **24**, 2885, 1997.

FIGURE CAPTIONS

Fig. 1. Polar plot of solar wind speed with heliographic latitude from Woch et al. (1997). A Solar Probe trajectory is overlaid.

Fig. 2. Side view of a possible Solar Probe with instruments on the sides, inside the bus and on the boom, constrained by the umbra of the heat shield. Nadir viewing for the plasma instrument is achieved by means of an ion deflection system.