THE SOLAR PROBE MISSION: A SEARCH FOR THE ORIGIN OF THE SOLAR WIND AND AN UNPRECEDENTED VIEW OF THE SOLAR SURFACE

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ABSTRACT

Despite significant advances in space exploration, in particular with the recent observations from Ulysses and SOHO, the basic questions of solar wind origin and solar surface topology over the poles can only be resolved with a near-Sun Solar Probe mission. Flying along a trajectory perpendicular to the Earth-Sun line during its perihelion passage, Solar Probe will use in-situ and imaging measurements to provide the first three-dimensional view of the corona, direct high spatial and temporal resolution observations of solar polar regions and magnetic fields, and local sampling of the near Sun environment down to 3 R_s from the solar surface. The trajectory will enable the first helioseismic measurements over the poles. The high sampling rate will enable the resolution of fine magnetic structures at all latitudes starting from the pole, through imaging and plasma and field in situ measurements. The NASA Solar Probe is an approved mission to be launched in 2007 with a first perihelion pass at solar maximum in 2010 and a second perihelion pass in 2014 at solar minimum. This review summarizes the latest observations and measurements of the solar wind. It describes the baseline NASA Solar Probe mission, its prime objectives, and its science core payload.

Key words: space missions; solar wind; solar surface.

1. INTRODUCTION

We have flown by many planets. *Galileo* is now orbiting Jupiter, and *Cassini* will soon circle Saturn. We are exploring the high latitude heliosphere with *Ulysses* and the remote regions of the solar system with *Voyagers* which are soon expected to reach and report on the distant boundary of the heliosphere. From the orbit of earth we are imaging the Sun far better than ever before, yet with the limitations of being in the ecliptic plane.

However, we have never encountered the Sun. This last frontier, the inner heliosphere from a few to 60 solar radii has yet to be explored. The inner boundary of our solar system, the polar photosphere and the solar corona remain essentially unknown. We do not know how the Sun creates its energetic and pervasive wind which affects the earth, all the planets, modulates the penetration of cosmic rays from the galaxy into the solar system and onto earth, and interacts with the local interstellar cloud.

Solar Probe is a mission of exploration, comprehension and discovery. Flying from pole to pole through the solar atmosphere, as close as three solar radii above its 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 images of the solar atmosphere over the poles 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. Solar Probe will determine the origin and acceleration of the solar wind which engulfs the entire solar system, controlling interplanetary space from the Sun to the local interstellar medium far beyond the outermost planets.

2. RECENT ADVANCES IN THE EXPLORATION OF THE SOLAR WIND

Our current understanding of the *terminal* and *initial* solar wind have been significantly enriched by the completion of the pole to pole trajectory by *Ulysses* (e.g., McComas et al. 1997) and recent in-situ measurements from SOHO (e.g. reviews in Fleck and Svetska 1997). In addition, radio occultation measurements are playing a critical role in bridging coronal and interplanetary observations, and have raised new questions regarding the origin of the solar wind (Woo and Habbal 1997, Habbal et al. 1997).

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That there exists primarily two types of solar wind, readily distinguishable by their speed, with the fast wind exceeding 750 km/s at Earth's orbit, and the slow wind coasting at 300 km/s at 1 AU, was firmly established by *Helios* (e.g. reviews in Schwenn and Marsch 1991). *Ulysses* observations in a plane perpendicular to the ecliptic verified the existence of these two solar wind states, and the remarkable fact that the fast solar wind dominated the heliosphere (Phillips et al. 1995) (Fig. 1). The slow wind was found to be limited to $\approx \pm 30^\circ$ about the equator over a period starting from solar maximum in 1992, into solar minimum in late 1996. During its extended mission, *Ulysses* is currently covering the rise in activity. In addition to differences in speeds, the slow and fast wind are clearly distinguishable by their chemical and isotopic compositions (Figs. 2 and 3). The marked temperature anisotropy in the fast solar wind is depicted in the measured skewness of the velocity distribution function, with a temperature perpendicular to the magnetic field larger than that parallel to it (see Marsch 1991). The ions are flowing faster than the protons by a local Alfvén speed and have higher temperatures. The transition from fast to slow solar wind also shows up as a rather sharp transition in the in situ measurements (see Fig. 1).

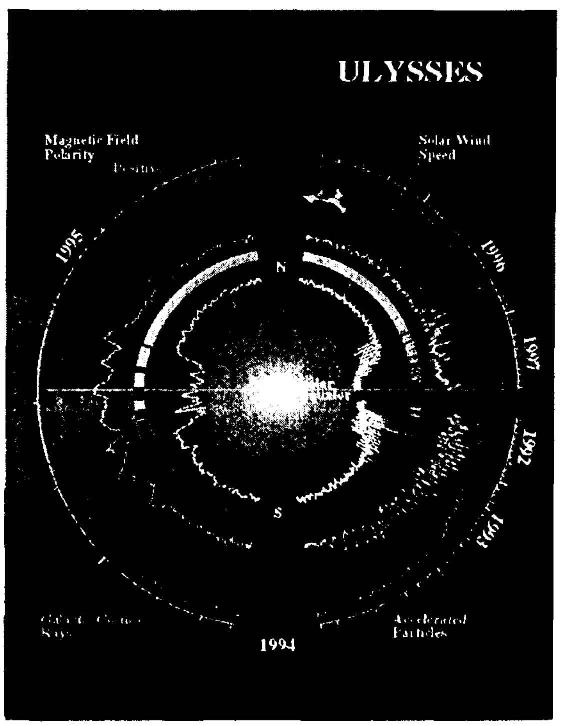

Figure 1. Polar plot of the solar wind velocity, magnetic field polarity, accelerated particles and galactic cosmic rays, as measured by Ulysses from 1992 to 1997.

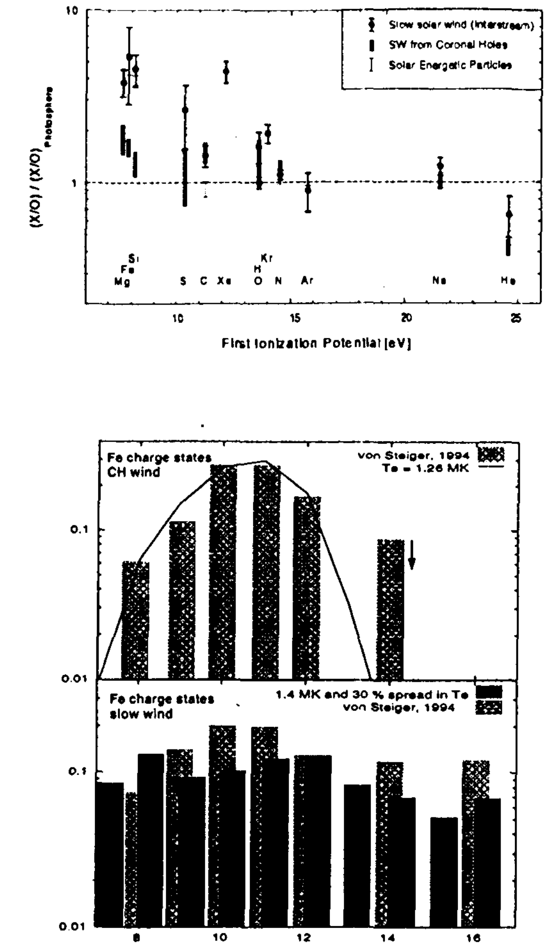

Figure 2. Top: Composition in the slow, fast solar wind and energetic particles versus first ionization potential (FIP). Adapted from von Steiger (1996). Bottom: Iron (Fe) charge state composition measured in a few days interval in the fast and slow solar wind. Adapted from von Steiger (199?).

Our knowledge of the *initial* solar wind, i.e. its status in the first few solar radii above the solar surface, has been significantly enriched by SOHO observations. It is now clear that the basic state of the terminal fast solar wind is established within a few solar radii from the solar surface. The temperature anisotropy develops within 1.5 R_s (Kohl et al. 1997, 1998). The temperature of the ions can reach 10^8 K in that region, while the protons seem to be heated to 3-4 10^6 K (Figure 3). Furthermore, ions accelerate past the protons by 3 R_s (Li et al. 1998). While polar coronal holes still remain the source of the fastest solar wind,

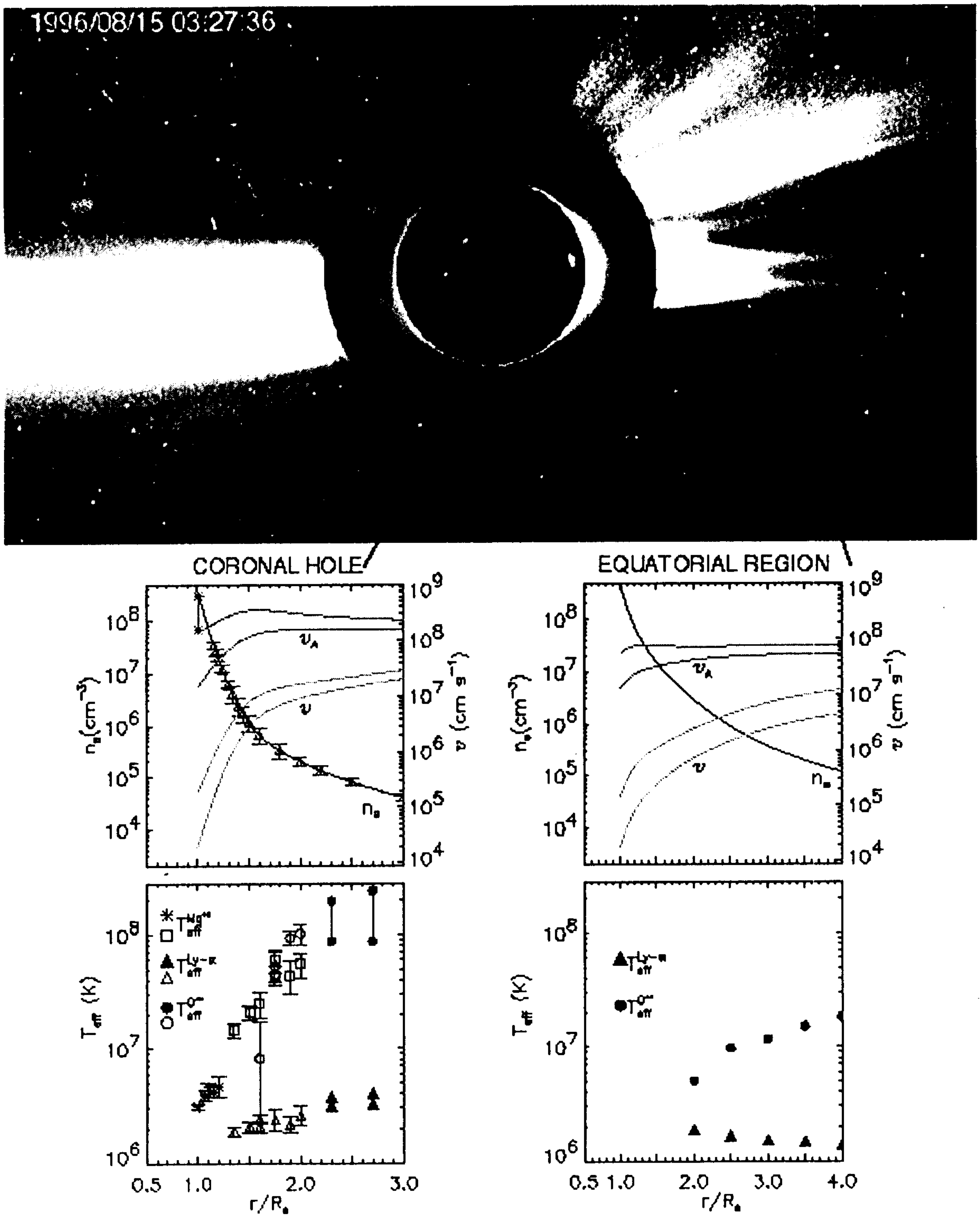

Figure 3. Top: composite image of the corona in x-rays from Yohkoh, polarized brightness from HAO Mk III coronagraph (1-2 R_s) and white light intensity from SOHO/LASCO C2 coronagraph (2-6 R_s). Lower panels: solar wind parameters as inferred from observations. Densities are from Fisher and Guhathakurta (1995) for the coronal hole and from Saito (1970) for the equatorial region. Effective temperatures are from Esser et al. (1998) and Kohl et al. (1997). Velocity and Alfvén speed are derived from mass and magnetic flux conservations, using the densities given here, and in situ measurements of magnetic field and particle flux, with the two limits of 1 and 7 for the expansion of flow tubes beyond radial. From Esser and Habbal (1998).

there is evidence that the quiet Sun (i.e. the solar surface excluding coronal holes and active regions) is also the source of the fast solar wind (Woo and Habbal 1997, Habbal et al. 1997). The transition from fast to slow solar wind occurs sharply at the boundary of the extension of streamers (Fig. 4), within 10° – 15° of their narrowing down into stalks occupying 1° – 2° where the slowest wind occurs (Woo and Martin 1997). White light images of the corona (Fig. 4), and radio occultation measurements have shown that the corona is highly filamentary with structures reaching down to a few kilometers at the Sun (Woo 1996).

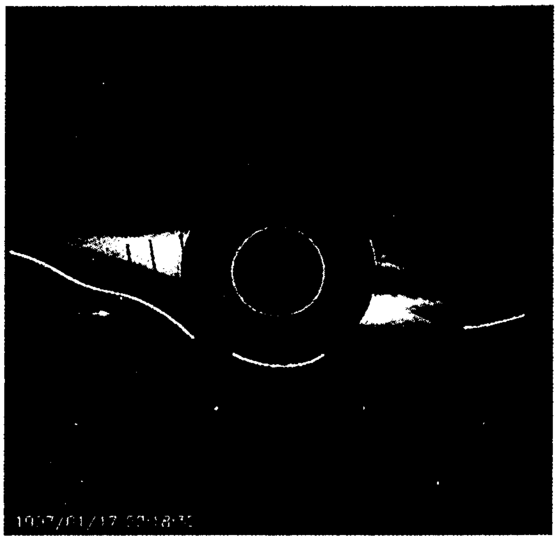

Figure 4. White light image of the corona taken with the SOHO/LASCO C2 coronagraph. The field of view spans 2 - 6 R_s. The black straight lines are the slit positions of the SOHO/UVCS instrument. The white lines mark the location of the 94 km/s flow speed inferred from the UVCS measurements of the O^{+5} *doublets. From Habbal et al. (1997).*

These recent results have not resolved fundamental issues such as: the source origin of the solar wind at the Sun, the magnetic field topology over the poles and how it differs from low latitudes, the filling factor of the solar wind plasma, the wave/turbulence spectra in the inner corona, the transition from fast to slow solar wind, and the magnitude of the polar coronal magnetic field at all latitudes. These questions are the basis for a Solar Probe mission.

3. SOLAR PROBE: THE FIRST CLOSE ENCOUNTER WITH THE SUN

The Solar Probe Science Definition team has categorized the prime objectives of the mission as follows: (A) core objectives to be fulfilled with a baseline mission, (B) and (C) objectives to be fulfilled if the requirements for the baseline mission can be technologically exceeded. The basic requirements for the mission consist of complementary in situ and remote sensing measurements with a high sampling rate. Described next are the prime scientific objectives, the current NASA baseline mission, the NASA strawman payload and the launch schedule as presently set.

3.1. Prime Scientific Objectives

3.1.1. Objectives A

- Determine the acceleration processes and find the source regions of the fast and slow solar wind at *maximum* and *minimum* solar activity
- 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 photospheric and coronal magnetic field at all latitudes
- Identify the acceleration mechanisms and locate the source regions of energetic particles, and determine the role of plasma turbulence in the production of the solar wind and energetic particles

3.1.2. Objectives B

- 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 observations at 1 AU and plasma structures near the Sun

3.1.3. Objectives C

- Determine the role of X-ray microflares in the dynamics of the corona
- Probe nuclear processes near the solar surface from measurements of solar gamma-rays and slow neutrons

3.2. The Baseline Mission

Using Jupiter for gravity assist, the Solar Probe will have a polar orbit, perpendicular to the Sun-Earth line at perihelion. The closest flyby will be at 3 R_s above the photosphere at the equator. As shown in Figure 5, the critical phase of the science acquisition will occur between - 24 hrs to + 14 hrs from perihelion at 0 hrs. In addition, this phase will be preceded by plasma observations starting at - 10 days prior to perihelion when the spacecraft is at 104 R_s, and helioseismology observations around - 4 days.

3.3. Science Core Payload

The strawman payload based on the science objectives A is given in Table 1. As originally defined in the Report of the Minimum Solar Mission Science Definition Team by Axford et al. (1995), the payload consists of a complement of in situ and imaging instruments (Fig. 6). The parabolic shield which will protect the instruments will also serve as an antenna. Unique to the current configuration is the side mounted shield for the nadir viewing plasma spectrometer (Fig. 7). Other new elements include the baffle tubes that pass vertically from the bus and penetrate the shield. These tubes accommodate the visible and XUV instruments for disk observations (Fig. 8). Other recent design concepts include the high temperature solar arrays which will be stowed within the umbra at perihelion. The shield carbon-carbon material has undergone significant testing. Recent estimates from Lockeed-Martin/General Atomic tests indicate the mass loss rate to be 310^{-3} mg/s.

The prime mission will be 3.6 years. If launched in 2007 (Fig. 9) it will reach the Sun at solar maximum in 2011. This will be followed by a second perihelion pass at solar minimum in 2015.

The payload shown in Fig. 6 is a strawman payload with the primary goal to have a complement of in situ and imaging instruments to fulfill the prime science objectives of the mission. The final selection which depends on instruments proposed to the AO may in fact be substantially different.

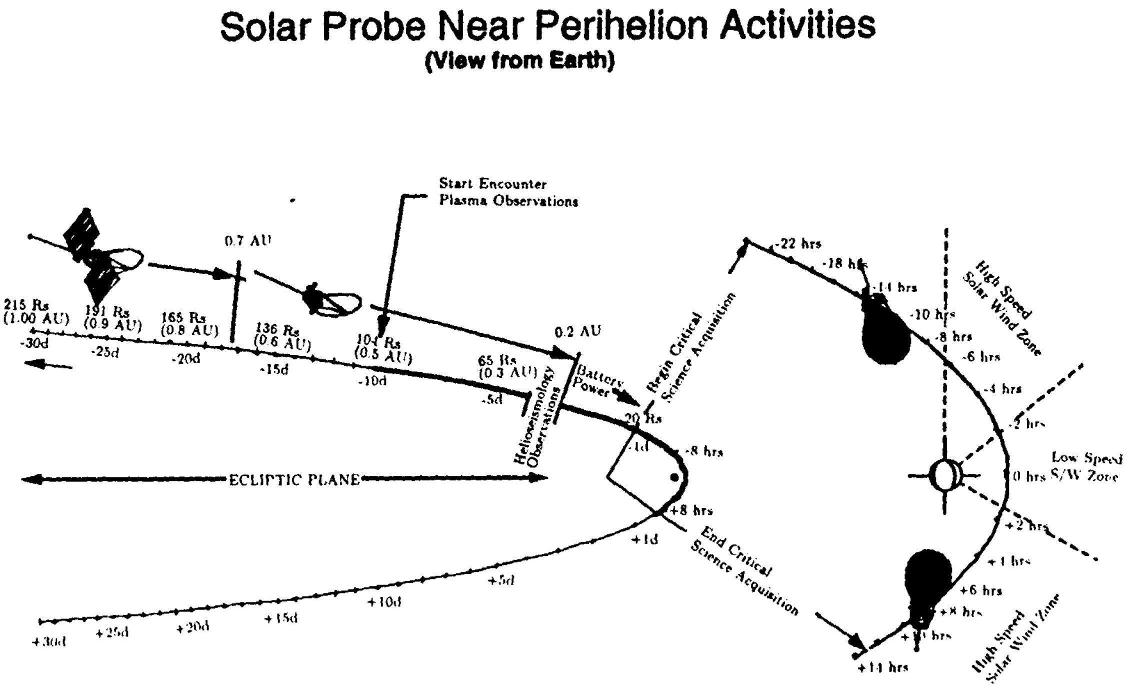

Figure 5. The Solar Probe trajectory as seen from Earth at ± 30 days from perihelion. An enlarged view of the critical science acquisition phase is also shown for ± 1 day.

Table 1. Solar Probe science core payload.

In-situ instruments	*weight (kg)*	*Power (W)*	*Data rate (kbps)*	*spatial resolution (km)*
Magnetometer (including boom cables)	0.8	0.5	1.2	1
Solar wind composition spectrometer	4.4	4.4	15.6	100
Energetic particle composition spectrometer	0.7	0.6	4.8	100
Plasma wave sensor (including boom cables)	2.5	2.5	9.6	1
Fast solar wind proton - electron detector	1.0	1.5	19.2	1
Remote sensing instruments				
Visible Magnetograph-Helioseismograph	3.0	0.2	30	30-75
XUV imager	3.0	0.2	30	30-75
All-sky, 3D coronagraph imager	2.5	2.0	2.0	300

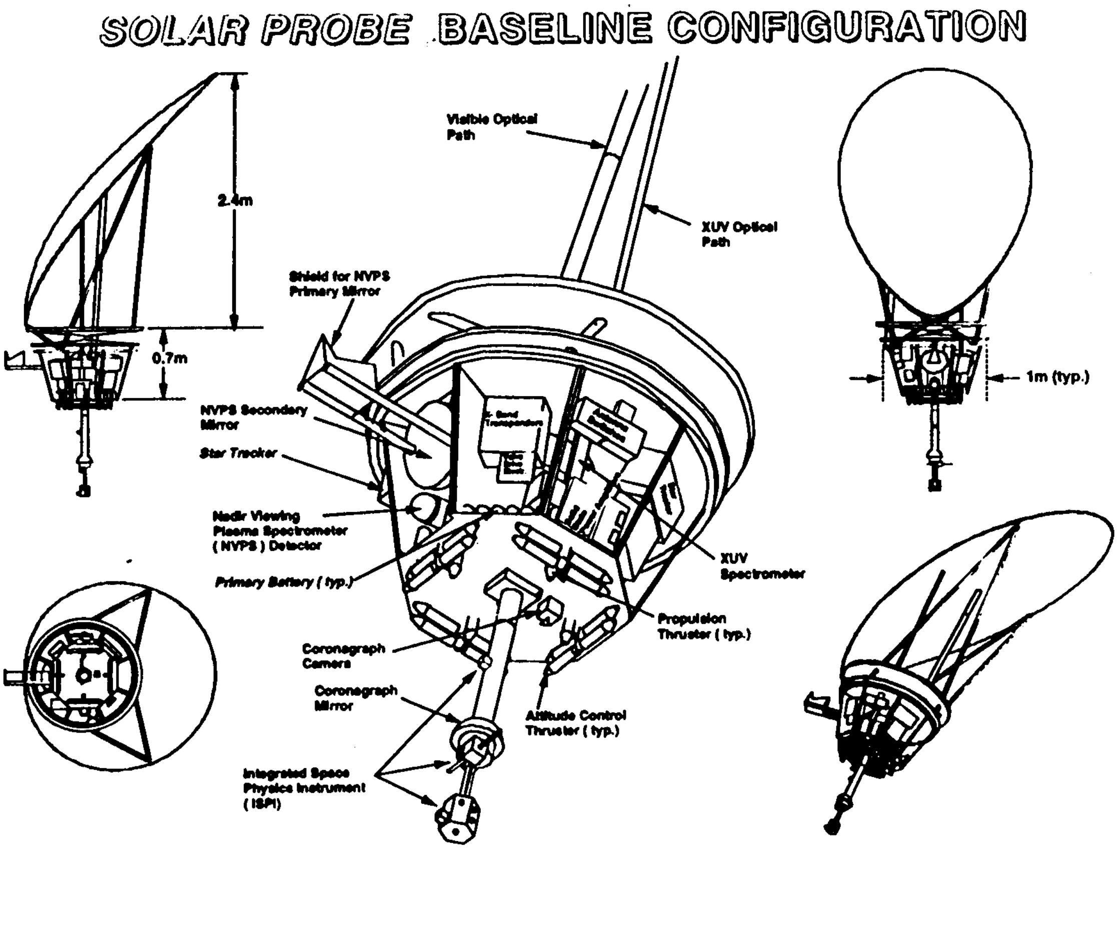

Figure 6. A Solar Probe concept baseline configuration. The center view identifies the various instruments and components. The remaining four views show the Probe from different perspectives.

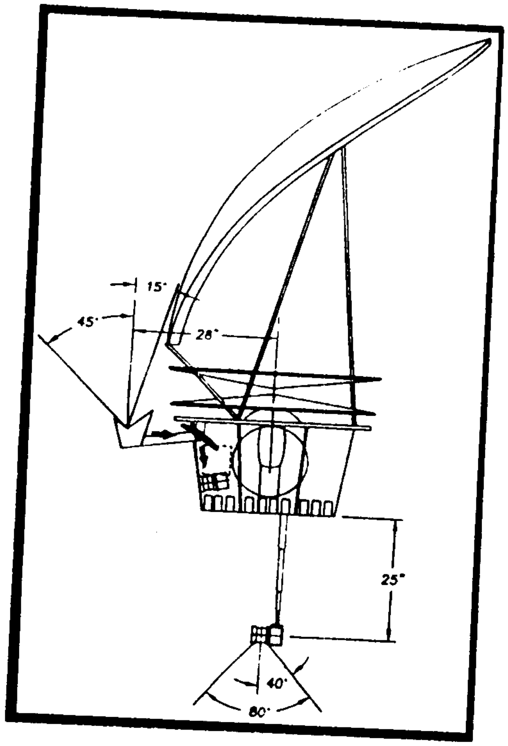

Figure 7. The field of view covered by the dual plasma spectrometers as positioned on the instrument platform. Relative to the spacecraft orientation, the Sun will be in the upward direction and the Earth will be toward the right. From E. Sittler.

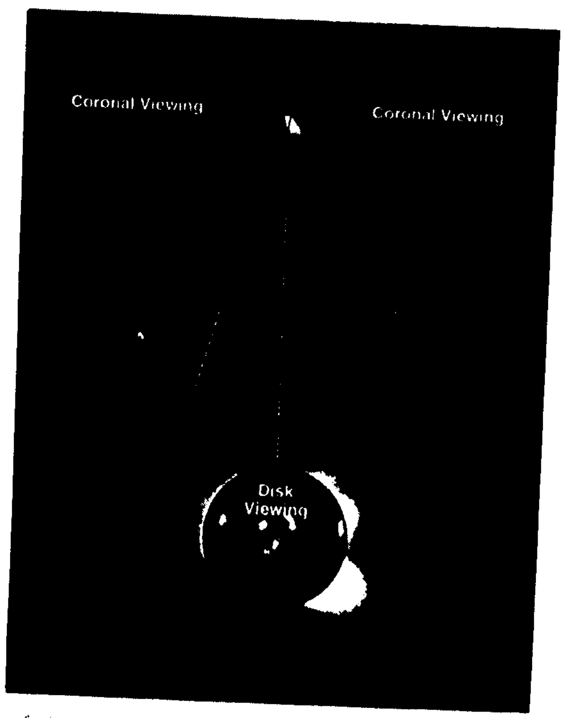

Figure 8. Fields of view of the white light coronal and XUV disk imagers. From A. Title.

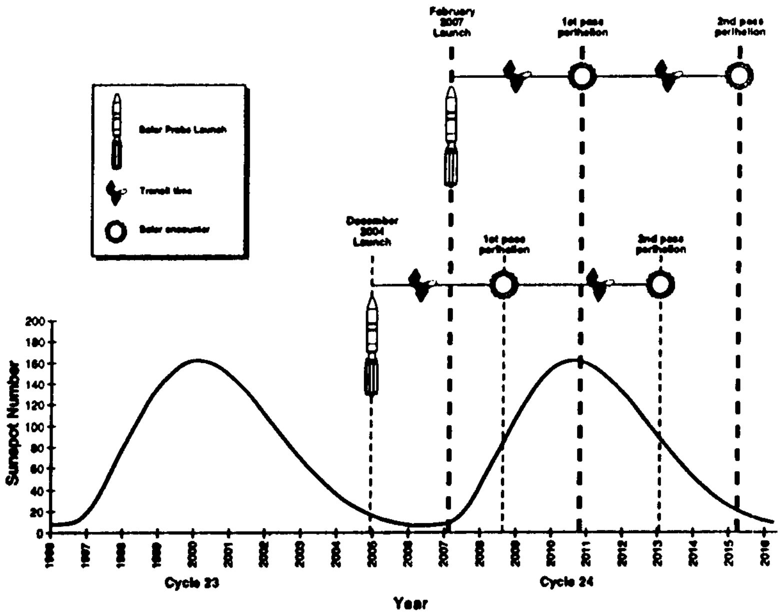

Figure 9. Potential launch, travel and perihelion dates in the context of the solar cycle.

4. SUMMARY

Solar Probe is a mission of exploration, comprehension and discovery, investigating the last uncharted regions of the Sun and the solar system. Its main objective is to find the origin of the solar wind and, for the first time, map the polar surface of the Sun and the longitudinal structure of its inner corona. Solar Probe is now technologically mature and ready.

Our progress in trying to understand the origin of the solar wind and the dynamics of the Sun (including its long term solar cycle variability) is impeded without the critical measurements in the solar wind acceleration region and over the poles.

Solar Probe is an *approved* NASA mission currently scheduled for a 2007 launch, with a second perihelion pass approved for observations at solar minimum. The AO will be ready in October 1998.

REFERENCES

Axford, W. I. et al. 1995, Close Encounter with the Sun, Report of the Minimum Solar Mission Science Definition Team, JPL D-12850

Esser, R., et al. 1998, ApJ Lett, in press

Fisher, R.R., Guhathakurta, M. 1995, ApJ, 447, L139

Habbal, S.R. et al. 1997, ApJ, 489, L103

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

Kohl, J. L. et al. 1998, ApJ Lett., 501

Li, X., Habbal, S. R., Kohl, J.L., Noci, G. 1998, ApJ Lett., 501

Marsch, E. 1991, in Physics of the Inner Heliosphere 2: Particles, Waves and Turbulence, R. Schwenn & E. Marsch (eds.) Springer-Verlag, 45.

McComas, D. J., et al. 1998, Geophys. Res. Lett., 25, 1

Phillips, J. L., et al. 1995, Geophys. Res. Lett., 22, 3301

Schwenn, R. 1990, Physics of the inner heliosphere: 1. Large-Scale Phenomena, R. Schwenn and E. Marsch (Eds.), Springer-Verlag

Woo, R. 1996, Nature, 379, 321

Woo, R. & Habbal, S. R. 1997, Geophys. Res. Lett., 24, 1159

Woo, R. & Martin, J. 1997, Geophys. Res. Lett., 24, 2535