WHITE PAPER FOR THE VOYAGE 2050 LONG-TERM PLAN

IN THE ESA SCIENCE PROGRAMME

In situ studies of the solar corona after Parker Solar Probe and Solar Orbiter

Contact scientist : Vladimir Krasnoselskikh

LPC2E

CNRS and University of Orléans

45100 Orléans

France

email : vladimir.krasnosselskikh@cnrs-orleans.fr

Tel. +33 238 25 52 75

Executive Summary

The primary scientific goal of the in situ investigation of the solar corona at low altitudes (as close as 1 solar radius from the photosphere) is to determine how the magnetic field and plasma dynamics in the outer solar atmosphere give rise to the corona, the solar wind and the entire heliosphere. Reaching this goal will be a Rosetta-stone step, with results broadly applicable within the fields of space plasma physics and astrophysics of stars. This investigation will not only advance our understanding of the plasma environment around our Sun, but also of the numerous magnetically active stars with hot plasma coronae. In order to do it we need the first-ever direct in situ measurements of electromagnetic fields, particle acceleration, wave activity, energy distribution and flows directly in the regions where the solar wind emerges from the coronal plasma.

This study should address problems related to regions where both the fast and slow wind are generated; it requires to determine local characteristics of the plasma and provide unique information about the physical processes involved in the creation of the solar wind. Another scientific objective is to carry out unique in situ measurements in the very region where presumably harmful solar energetic particles are energized. This will allow to make fundamental contributions to our ability to monitor and forecast the space radiation environment, with direct relevance for future space exploration, especially for long-term manned space missions.

Although technologically very challenging, a mission that would dive deep in the solar corona is feasible, thanks to recent developments in heat shields, and the experience gained from the Parker Solar Probe mission.

This project is based on the proposal to ESA Call proposal to the European Space Agency (ESA) in response to the "Call for new science ideas in ESA's

ICARUS "Investigation of Coronal AcceleRation and heating Up to the Sun" supported by ICARUS team

Agapitov Oleksiy[1], Balat-Pichelin Marianne[2], Bale Stuart D.[1], Balikhin Michail A.[3], Baumjohann Wolfgang[4], Bruno Roberto[5], Cranmer Steven[19], De Pontieu Bart[6], De Sousa Meneses Domingos[7], Dudok de Wit Thierry[8], Eastwood Jonathan[9], Erdelyi Robertus[10], Ergun Robert[11], Fedun Viktor[3], Ganushkina Natalia[12,13], Greco Antonella[14], Harra Louise[15], Henri Pierre[16], Horbury Timothy[17], Hudson Hugh[18], Kasper Justin[19], Khotyaintsev Yuriy[38], Krucker Sam[20], Kucharek Harald[21], Langevin Yves[22], Lavraud Benoit[23], Lebreton Jean-Pierre[16], Lepri Susan[24], Liemohn Michael[24], Louarn Philippe[25], Maksimovic Milan[26], Moebius Eberhard S.[27], Mozer Forrest[1], Nakamura Rumi[28], Nemecek Zdenek[29], Panasenco Olga[30], Retino Alessandro[31], Safrankova Jana[29], Scudder Jack[32], Servidio Sergio[33], Sorriso-Valvo Luca[34], Soucek Jan[35], Szabo Adam[36], Tagger Michael[16], Tsurutani Bruce T.[37], Vaivads Andris[38], Vekstein Grigory[39], Velli Marco[40], Voros Zoltan[41], Walker Simon[3], Zaqarashvili Teimuraz[42].

I. Introduction

One of the last unexplored regions of the solar system nowadays is that within 0.3 AU of the Sun. The goal of the Solar Probe Plus and Solar Orbiter missions is to study the solar wind inside this distance to 10 solar radii and around it. One of them will approach as close as 9.5 solar radii, another will approach to 0.3 AU but will come out of the ecliptic plane up to latitudes 38 degrees. They will shed light to many questions concerning the solar wind heating and acceleration, however they will pass rather far from several critical regions. Very important region for understanding solar wind heating and acceleration is the region where the maximum solar wind temperature is supposed to be reached close to the one where the maximum energy deposit occurs. Another region of major importance is the region where the transition from subsonic flow to supersonic occurs. Moreover, many observations indicate that the polar wind acceleration occurs at distances smaller than 10 solar radii. Figure 1 represents the dependence of the temperature distribution upon an altitude from the photosphere with the indications of the dominant physical processes.

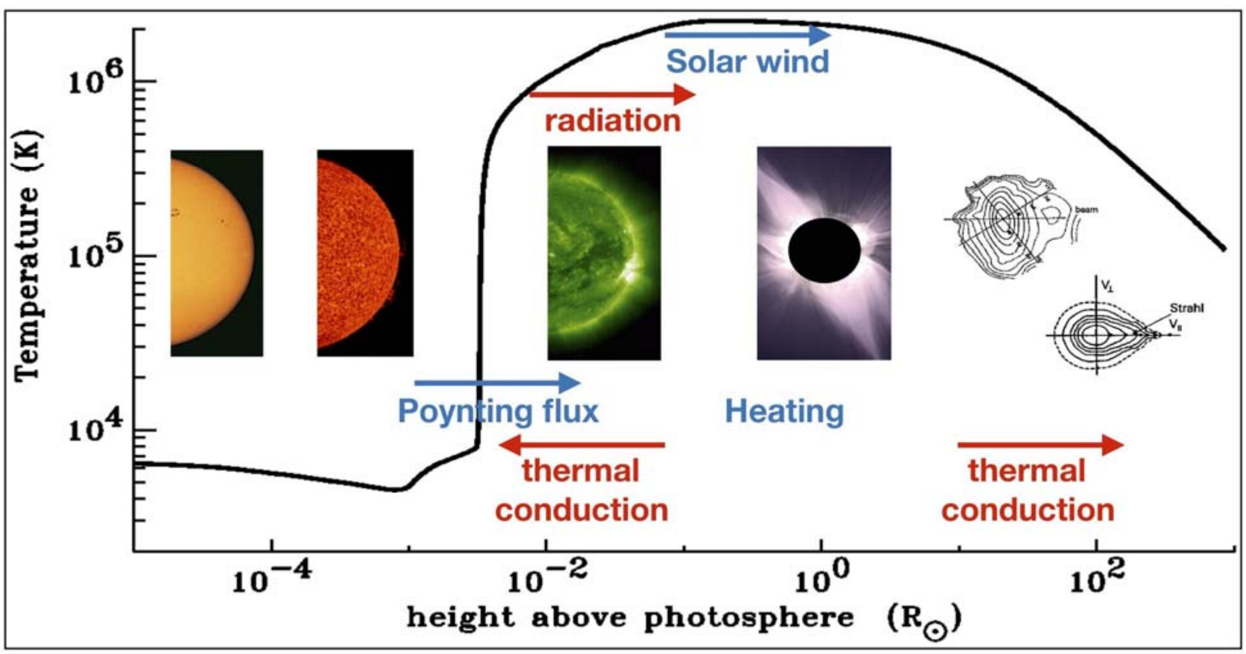

Figure 1. Illustration of the temperature distribution dependence upon an altitude from the photosphere. The temperature maximum is around several solar radii where the major energy deposition occurs. Picture after Velli (2017).

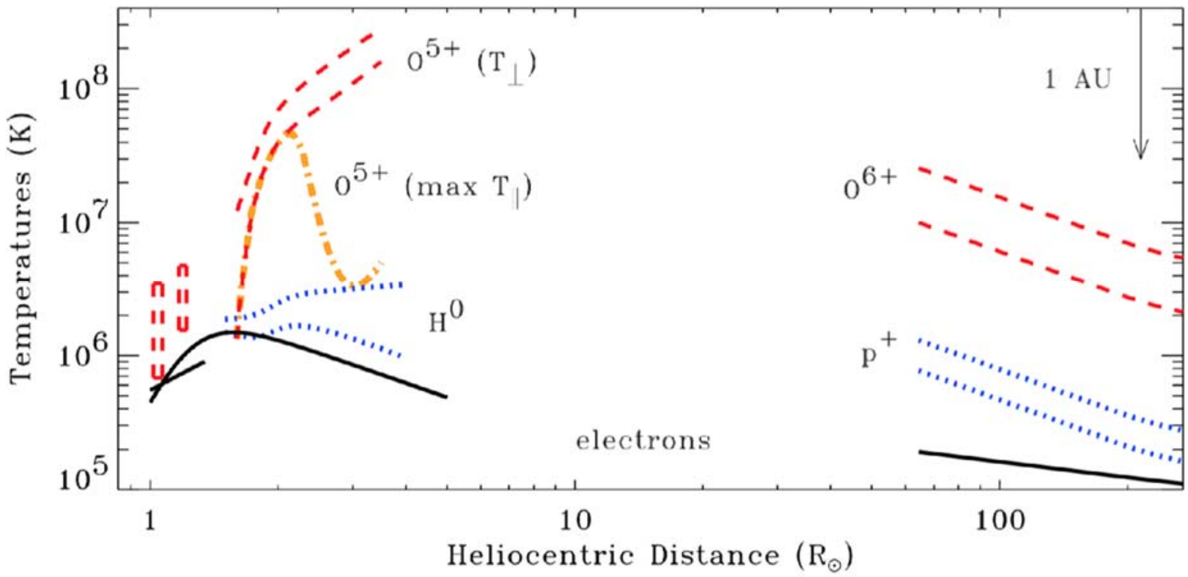

Figure 2: Summary of the radial dependence of temperature in polar coronal holes and the high-speed wind at solar minimum, from both remote-sensing and in situ measurements: electron temperatures (solid lines), neutral hydrogen and proton temperatures (dotted lines), and ionized oxygen temperatures (dashed and dot-dashed lines). Paired sets of curves in the extended corona (1.5 RS < r < 10RS) denote different empirical models derived from UVCS emission line properties; statistical uncertainties are not plotted for clarity. Dashed regions in the low corona (r < 1: RS) correspond to lower and upper limits on the O5+ kinetic temperature from SUMER line widths.

Analysis of eclipse and coronagraph observations

White light (WL) brightness and polarization measurements from solar eclipse observations have been used to determine radial profiles of ne(r), the electron density in the solar corona. Since the hydrostatic H is proportional to the ion temperature, coronal temperatures have been determined at different heliographic latitudes and for all sorts of solar activity conditions. Several different methods were used to determine the maximum temperature. They give comparable estimates of the maximum temperature about 1.1-1.5 MK in the quiet corona. Different methods of evaluation of the altitude of temperature maximum provide quite strong arguments that the most important part of the heating/acceleration
of the solar wind occurs on the distances from the Sun surface between 0.1 RS and 2-4 RS, (Lemaire, 2013) i.e. much closer to the Sun than the closest distance to be achieved by Parker Solar Probe, that is actually operating and Solar Orbiter, presently under preparation.
The physical processes of heating of the solar wind are still poorly understood and are presumably quite complex; one of the mysteries is related to the heating of the minor ions. Measurements of different lines making use of the UV spectroscopy have provided strong arguments that ions such as O5+ may be heated up to temperatures one and a half orders of magnitude higher than the protons, that is the ratio of temperatures may be larger than the mass ratio of ion components (Kohl et al., 2005) (see Fig. 2)

Another set of problems is related to the kinetic physics of the formation of particle distribution functions. It is well established that the electron distribution consists of several components, such as the core, strahl, halo and super-halo. It is certain that the effects of the _filtering (Scudder, 1992), collisions, magnetic field divergence (Landi et al., 2012) and wave activity (Cranmer and van Ballegooijen, 2005) important roles in the dynamics and formation of the different plasma components of the wind. Furthermore, there may be quite intense macroscopic electric fields, that can play an important
role, but present models are too simplified to determine the relative role of these processes and realistic characteristics of the processes even for the case of the quasi stationary wind.
Recent solar imaging spectroscopy by e.g. SOHO, SDO, Hinode, and IRIS reveal the presence of a large number of dynamic features that make the formation of particle distributions even more complicated. The solar corona is very dynamic and intermittent and the relative role of different dynamic features such as spicules, jets, plumes, or active-region flows in the formation is of the slow and fast winds is not in any way clear. Moreover, the physical processes that cause the solar wind formation takes place in the chromosphere, the region that can be studied only by means of remote sensing. These processes are enormously important as one of the stages of the formation of the solar wind. We do not have any direct experimental in situ measurements in the regions where this formation takes place, and the currently planned missions will not directly help us to solve the problems, because the regions where they occur are well inside 9.5 RS.
Another important region occurs at the transition between subsonic and supersonic flow. The flow in this region can be quite unstable. Multiple instabilities modifying the distribution functions may be present in these regions, which lie at the origin of the distribution functions eventually observed in the solar wind. The studies of instabilities in the polar regions of the magnetosphere, where the terrestrial polar wind is formed, present a strong argument that the role of different types of plasma and MHD waves may be quite important. The study of wave-particle interactions and wave activity can uniquely lead to breakthroughs in our understanding of solar and solar wind physics. Figure 3 illustrates an importance of the magnetic field structure for the formation of the fast and slow solar wind.

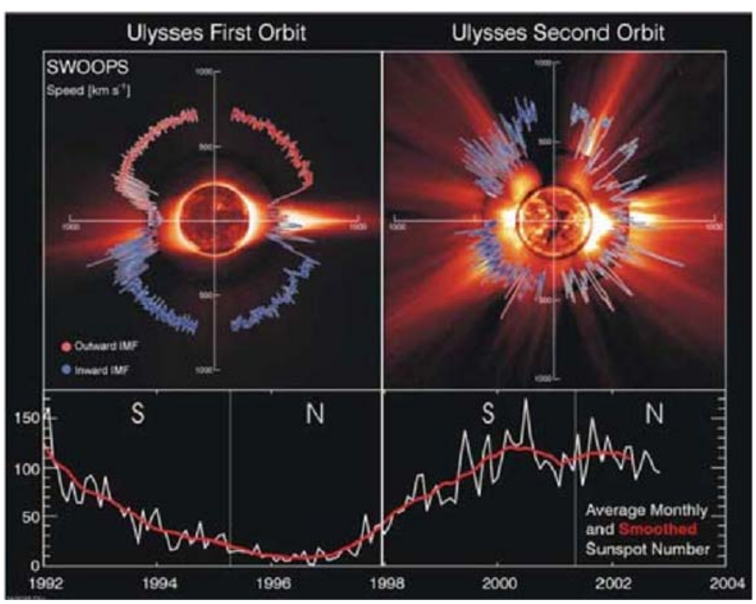

Figure 3: Polar plots of solar wind speed as a function of latitude for Ulysses' first two orbits, superposed on solar images characteristic of solar minimum (8/17/96, left panel) and maximum (12/ 07/00, right panel), EIT , LASCO C2 images from SOHO and Mauna Loa K-coronameter (McComas et al., 2003). These images show how the solar wind characteristics measured in situ depend strongly on the solar coronal magnetic field structure, fast wind emanating from coronal holes and slow wind appearing to originate from the magnetic activity belt.

II. Scientific Objectives

The solar wind flow at solar minimum is subdivided into high and low speed streams, with speeds of around 750 km/s and 400 km/s respectively. Ulysses has shown that the high speed streams come from coronal holes and then via super radial expansion fill in the heliosphere (Hundhausen, 1977; Suess and Nerney, 2001). As the solar cycle progresses, the streamer belt expands in latitude so that, at activity maximum, the corona appears to be nearly uniformly distributed around the solar disk, while high speed wind streams occur over a much smaller volume. This is illustrated by the `dial plot' in Figure 3, (McComas et al. 2003) which depicts solar wind speed measurements as a function of latitude during the first and second Ulysses orbits, near times of solar minimum and maximum activity respectively.
The fast solar wind originates from the coronal holes. This inverse correlation between flow speed and coronal electron temperature where the freezing in of minor ion charge states occurs (Figure 4: This shows that the foundation of the original theory of the solar wind (Parker, 1958), i.e. that high coronal electron temperatures and electron heat conduction drive the solar wind expansion, probably applies only to fast wind from coronal holes. SOHO measurements of the very high temperatures of the coronal ions, together with the persistent positive correlation of in situ wind speed and proton temperature, suggest that other forces, namely magnetic mirror and wave-particle interactions, should also contribute strongly to the expansion of the outer corona. SOHO observations have also made important contributions to our knowledge of the slow solar wind, which is confined to regions emanating from the magnetic activity belt and seems to expand in a bursty, intermittent fashion from the tops of helmet streamers. Hints about this process have come from Yohkoh and Hinode (Sakao et al., 2007).

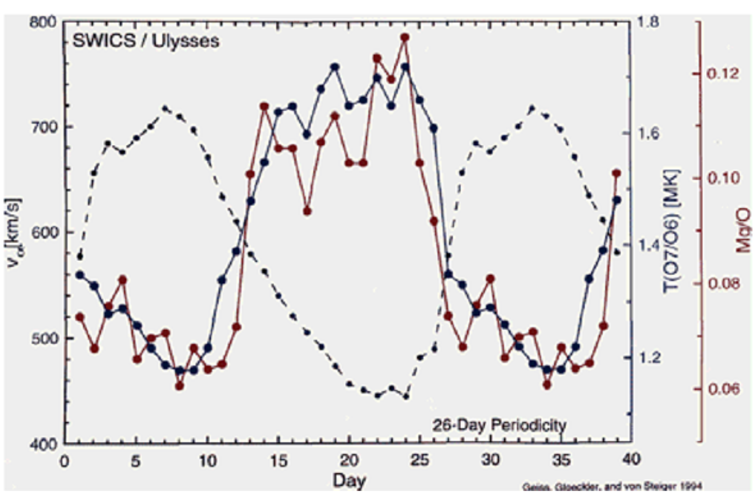

Figure 4: Anti-correlation of solar wind speed (dot-dashed line) with the freezing in temperatures determined from O7 to O6 abundances (blue line), and magnesium to oxygen composition ratios (red line) as a function of time during a low-latitude high-speed low-speed wind crossing period in Ulysses' first orbit.

A third type of flow arises from larger eruptions of coronal magnetic structures, or coronal mass ejections (CMEs), the leading shocks of which lead to acceleration of high-energy particles. The energy that heats the corona and drives the wind must come from photospheric motions and is channeled, stored and dissipated by the magnetic fields that emerge from the photosphere and structure the coronal plasma. Observations by Yohkoh, the Hinode and IRIS reveal dynamic jet-like features in the chromosphere, transition region and low corona. These include \anemone jets" in magnetically isolated active regions and polar jets in intense flux concentrations at high solar latitudes. These have inverted Y-shapes suggesting that they are produced by small-scale reconnection. Even more fine-scale jet-like features appear in sunspot penumbrae; Hinode imaging shows these to have widths as small as 400 kilometers and durations of less than 1 minute. These microjets may possibly be caused by component magnetic reconnection in the complex magnetic configuration in penumbrae and may provide an important contribution to heating of the corona above a sunspot (Katsukawa, 2007).
Several fundamental plasma physical processes -waves and instabilities, magnetic reconnection, velocity filtration, turbulent cascades -operating on a vast range of temporal and spatial scales are believed to play a role in coronal heating and solar wind acceleration. The lack of of measurements of the magnetic field and detailed characteristics of different plasma components in the region inside 70 Rs does not allow for detailed identification at this time; and polar jets in intense flux concentrations at high solar latitudes. Only a mission performing *in situ* measurements at distances around 1 Solar radius to the Sun will be able to explore the critically relevant regions within 9.5 Rs.
Basic unanswered questions concern the storage, transport, exchange and transformation to different forms, and finally, the release of the kinetic energy required for coronal heating; the specific mechanism(s) for the conversion of energy between the magnetic field and thermal and nonthermal particle populations; the dynamics of photospheric and coronal magnetic fields in the source regions of the solar wind; and the sources of high-energy particles and the mechanisms by which they are accelerated.
These questions motivate three broadly distinct but interlinked top-level scientific objectives for the studies we propose. A fourth top-level objective also of an exploratory nature concerns the source, composition, and dynamics of dust in the inner solar system.
In the following sections, these four main objectives are translated into specific scientific questions and basic measurement requirements.

II.1 Explore the fundamental processes underlying coronal heating and solar wind acceleration

The solar corona loses energy in the form of radiation, heat conduction, waves, and due to the change of the kinetic energy of the solar wind flow. This energy must come from mechanical

energy residing in photospheric convection, the solar magnetic field plays a crucial role in redirection, channeling and storing of this energy in the outer atmospheric layers.
However, the mechanisms by which the energy is transferred, redistributed between different components of plasma and dissipated to generate the hot corona, solar wind, and heliosphere throughout the Sun's activity cycle remain one of the fundamental unanswered questions in solar and heliospheric physics. Remote-sensing measurements of the solar corona and in situ measurement of particle distribution functions in the fast and slow solar wind streams have shown that the heating process is correlated with magnetic structure. SOHO/UVCS observations using the Doppler dimming technique (Li et al., 1998; Kohl et al., 1998) (Figure 2.4 and interplanetary scintillation measurements (Grall et al., 1996) indicate that the high speed solar wind is rapidly accelerated near the Sun, reaching speeds of the order of 600 km/s within 10 Rs. Observations of comet C/1996Y1 confirm a most probable speed of about 720 km/s for the solar wind at 6.8 RS (Raymond et al., 1998).
Such rapid acceleration appears to result from the extremely large and anisotropic effective temperatures in the lower corona, moreover, some part of the heating presumably occurs already in the upper chromosphere, which have been measured by SOHO/UVCS in coronal holes, and by IRIS and HINODE, though not directly measured for protons, the main solar wind constituent. These temperatures are supposed to be much higher perpendicular to the magnetic field. The fast solar wind measured in situ shows what may be a relic of this anisotropy, smaller than that inferred from coronal observations, but persisting in the distance range from 0.3 to 5 AU. Proton, alpha-particle, and minor ion distribution functions in the fast wind also present a non-thermal beam-like components whose speed is comparable to the local Alfven speed, and in the upper chromosphere may be even larger. All these properties suggest that Alfven or ion-cyclotron waves may play a major role in coronal heating and solar wind acceleration in high-speed wind. One can mention the observations of the Hinode satellite that provided quite important information about wave activity in the chromosphere. De Pontieu with co-authors (De Pontieu et al., 2012) have pointed out that the observed wave activity of Alfven waves is intense enough to provide the necessary energy source for heating and accelerate the solar wind. Alfven waves have been invoked as a possible mechanism for the heating of the Sun's outer atmosphere, or corona, to millions of degrees and for the acceleration of the solar wind to hundreds of kilometers per second. However, Alfven waves of sufficient strength have not been unambiguously identified in the solar atmosphere. Using the images of high temporal and spatial resolution obtained with the Solar Optical Telescope onboard Hinode satellite led to revealing that the chromosphere, is permeated by Alfven waves with strong amplitudes on the order of 10 to 25 kilometers per second and periods of 100 to 500 seconds. Estimates of the energy flux carried by these waves and comparisons with advanced radiative magnetohydrodynamic simulations indicated that such Alfven waves are energetic enough to accelerate the solar wind and possibly to heat the quiet corona. Measurements close to the sun, within the region where the solar wind becomes supersonic to Alfven waves, are necessary to remove ambiguity due to in situ evolution and obtain direct measurements where the main acceleration is occurring.
The fast solar wind flow is steady, with fluctuations in radial speed of order 50 km/s, and the charge-state distributions indicate a low freezing-in temperature. The slow solar wind is variable, with higher but variable freezing-in temperatures. The composition of the fast and slow wind also differ, Mg and Fe being overabundant with respect to O in the slow wind.
Solar wind protons and ions are however typically hotter in high speed streams than in the slow wind. The difference between the fast and the slow solar wind extends to the shape of the particle

distribution functions as seen on the large distance from the Sun. The fast wind exhibits proton perpendicular temperatures which are slightly higher than the parallel temperatures. Proton distribution functions in the fast wind also present a beam accelerated compared to the main distribution by a speed comparable to the Alfven speed, a feature shared by the alpha particles. Turbulence is also different in fast and slow streams, with fast streams containing fluctuations in transverse velocity and magnetic fields which are more strongly correlated in what is known as Alfvenic turbulence, a well-developed spectrum of quasi-incompressible waves propagating away from the sun. In the slow wind no such preferred sense of propagation is observed, while larger density and magnetic field magnitude fluctuations are present, revealing a much more standard and evolved MHD turbulent state (Grappin et al., 1990).
Anti-correlation of wind speed with coronal (freezing in) electron temperature and the heliospheric distribution of the high speed wind at solar minimum (Figure 5) place the origin of the fast wind in coronal holes.

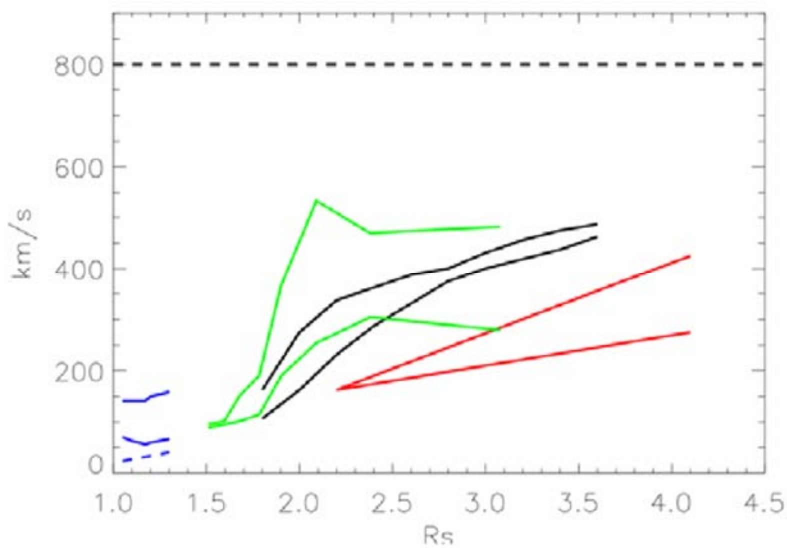

Figure 5: Acceleration profiles of the fast solar wind after SoHO: H0 (red) and O+5 (black) flow velocities from Kohl et al. (1998), O+V I(green) ow velocities from Antonucci et al. (2004); Full-dashed blue lines: plume and interplume flow velocities from Gabriel et al. (2005)

Measurements from the CDS -SUMER experiments aboard SOHO have ascertained that the electron temperature is bounded by 10^6 K (David et al., 1998), in agreement with the brightness temperature based on radio observations of the corona. This presents a discrepancy with the freezing in temperature for different ion charge states measured in situ by the SWOOPS experiment on Ulysses, the most direct interpretation of which requires an electron temperature maximum of about 1.5 10^6 in coronal holes. The discrepancy may be resolved only by admitting strongly non-maxwellian distribution functions for the electrons, or large differential flow speeds between ions of the same charge in the corona, which could have strong implications on the structure of the fast solar wind in the acceleration region. Such ideas have got strong support from observations of intense jets in the chromosphere and low corona onboard IRIS and HINODE satellites. Contrary to proton distributions, observed electron velocity distribution functions (eVDFs) exhibit non-Maxwellian features whatever the type of wind, slow or fast, in which they are observed. The eVDFs permanently exhibit three different components : a thermal core and a supra-thermal halo, which are always present at all pitch angles, and a sharply magnetic field aligned “strahl" which is usually anti sunward-moving (Rosenbauer et al., 1977). Energy transport and dissipation mechanisms strongly depend on the mean free path of particles in the coronal plasma, which varies drastically both with distance from the Sun (from the base of the corona to the supersonic solar wind), as well as across coronal structures (coronal holes to helmet streamers). This dependence suggests that the heating of upper corona is caused by non-thermal tails of particle distribution functions generated between the chromosphere and transition region probably due to magnetic reconnection where the solar atmospheric plasma changes from collisional to collisionless. The higher temperatures and subsequent outflows would then arise naturally through velocity filtration by the Sun's gravitational potential (Scudder, 1994), and may even explain the existence of the fast solar wind (Maksimovic et al., 1997; Zouganelis et al., 2004). The different properties of the low-frequency electromagnetic field and velocity fluctuations observed in the fast and slow solar wind represent further evidence of the role played by turbulence and wave-particle interactions in coronal heating. Fast streams contain stronger fluctuations in transverse velocity and magnetic fields, and display a higher degree of correlation between the velocity and magnetic fluctuations (often described as a well-developed spectrum of quasi-incompressible Alfven waves propagating away from the Sun). In the slow wind, this correlation occurs at a much lower level, while larger density and magnetic field magnitude fluctuations are present, indicating a more evolved MHD turbulent state there. This difference in turbulence state between fast and slow wind streams, together with the fact that slow wind distribution functions are much closer to equilibrium, suggests that the outward propagating wave flux contributes to the heating of the steady fast wind, while the slow wind is heated much more variably. It is not known, however, how the turbulent activity increases toward the Sun, whether it is sufficient to power coronal heating and solar wind acceleration, and how it is driven by time-dependent events in the photosphere, chromosphere, transition region, and low corona (see e.g. Matthaeus et al., 1999).

Whether the solar corona is heated by low-frequency waves resulting from motions naturally arising in the photosphere or whether the dominant energy source resides in the currents stored via slower _eld line motions has been the subject of strong debate.

It is worth noting that combining IRIS observations with observations of the Swedish 1 m Solar Telescope De Pontieu with co-authors have demonstrated that in the solar chromosphere and transition region (TR) there is a prevalence of small-scale twist motions [De Pontieu et al., Science, 2012]. It is supposed that most of the non-thermal energy that powers the solar atmosphere is transformed into heat in the chromosphere and transition region, although the detailed mechanism remains elusive. High-resolution (0.33-arcsec) observations with NASA's Interface Region Imaging Spectrograph (IRIS) reveal that chromosphere and TR are replete with twist or torsional motions on sub-arcsecond scales, occurring in active regions, quiet Sun regions, and coronal holes alike. Coordinated observations with the Swedish 1-m Solar Telescope (SST) allowed one to quantify these twisting motions and their association with rapid heating to at least TR temperatures. This view of the interface region provided new insight into what heats the low solar atmosphere. High level of intense waves observed by IRIS may also presumably originate from reconnection events. Among the MHD waves, only Alfven waves would appear to survive the strong gradients in the chromosphere and transition region, because slow modes steepen into shocks while fast modes suffer total reflection. Transmitted waves propagate at large angles to the radial direction, due to the large Alfven speed, low frequencies and strong structuring of the corona (Velli , 1993). Waves reaching the lower corona should therefore be shear Alfven waves, although discrete coronal structures such as loops and plumes might channel surface waves and propagate energy as global oscillations as well. Simulations show that in a highly stratified atmosphere, the nonlinear interactions of Alfven waves launched from the photosphere are able to generate and sustain an incompressible turbulent cascade, which displays the observed Alfvenicity. The efficiency of turbulence in transporting energy to the dissipative scales is, however, still unclear. The spectral slope at different coronal heights evolves with distance, subject to expansion and driving effects, affecting the radial dependence of dissipation. The initial spectrum of Alfven waves in the photosphere cannot be constrained by in situ data collected in the far solar wind, since local processes contribute to its shaping there (Verdini and Velli , 2007). Only observations in the corona will help in constraining the shape of the Alfvenic spectrum with relevant implications on the role of turbulence in the acceleration of the solar wind and the heating of the corona (Figure 6).

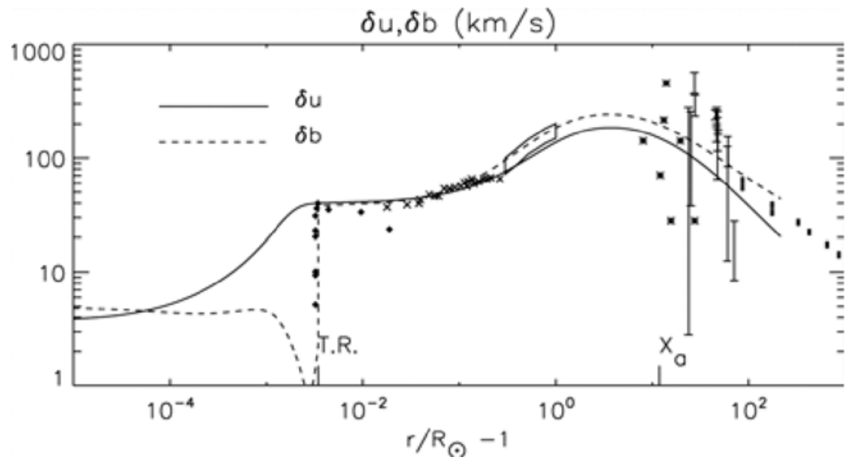

Figure 6: The rms amplitudes u and b (in velocity units) as functions of heliocentric distance for a photospheric Kolmogorov spectrum with u = 40 km /s at the coronal base. Far symbols indicate observational constraints from in situ measurements and interplanetary scintillations, near symbols from remote sensing. We need to study the region inside the fluctuation maximum region, measuring spectra and correlations where the gap in the data is (Verdini and Velli, 2007).

The first in situ studies of distribution functions, waves, turbulence, and electromagnetic fields from 0.3 AU to 1 Rs, and by correlating them with plasma and magnetic field structures, we shall be able to answer the basic questions of how the solar corona is powered, how the energy is channeled into the kinetics of particle distribution functions in the solar corona and wind, and how such processes relate to the turbulence and wave-particle dynamics observed in the heliosphere. The comprehensive measurement of plasma particles distribution functions and electromagnetic fluctuations in the inner solar wind (< 20 RS), will determine how the energy that powers the corona and wind is dissipated and what the dominant dissipative structures are as well as the frequency spectrum of electromagnetic fluctuations. Small-scale magnetic reconnection occupies an important place in current dissipation theories of the coronal plasma (Matthaeus et al., 2003). An important set of investigations required has to be therefore the multi-instrument detection of signatures of small-scale reconnection, such as bi-directional plasma jets, accelerated particles, magnetic field, and velocity gradient correlations along the trajectory. The measurement to be performed of turbulence and nonlinear plasma dynamics in the corona and solar wind will be a watershed for all of astrophysics, where these phenomena are invoked over widely different contexts, from accretion disks to the collisionless shocks occurring in galaxy-cluster formation.

III. Mission profiles

From the previous Section three outstanding science questions can be formulated:

A) How is the solar wind accelerated ?
B) How is the solar wind heated ?
C) What are in situ properties of the solar atmosphere ?

The degree to which these questions can be answered and/or offer a conceptual leap with respect to our present understanding mainly depends on the perihelion of the mission, which is its single most important defining parameter. This can be summarized by the table below, in which we consider mission profiles with different distances from the Sun. The relevance is further reflected by 3-colour code.

distance from the solar surface	**< 1 Rs**	**1-2 Rs**	**2-4 Rs**	**4-10 Rs**
Question A: acceleration	relevant	very relevant	very relevant	relevant
Question B: heating	relevant	very relevant	very relevant	incremental
Question C: probing the atmosphere	very relevant	very relevant	relevant	incremental
Feasibility	not possible	> 1.5 Rs possible	possible	possible

Mission objective	excluded	target objective	backup objective	not relevant

This table reveals a clear optimum of the science objectives versus distance, which occurs between 1 and 2 Rs from the solar surface. Getting closer to the Sun will not give much added value because we move out of the main region in which the solar wind is heated and accelerated. However, the possibility to come that close to the Sun offers fascinating properties such as the in situ study of coronal loops and potentially even an in situ study of the transition region.

In comparison, the solar atmosphere located between 1 and 2 Rs from the surface offers much better prospects for investigating the heating mechanisms of the solar wind, the sources of the solar wind while offering unique conditions for probing the solar atmosphere (include large loops). As we shall see in the next Section, getting that close to the Sun has now become technologically feasible.

As we increase the perihelion, the relevance of all the objectives gradually decreases. Not immediately however. From the preceding Section, we conclude that the region up to approximately 4 Rs still offers a huge potential for ground-breaking science that cannot be addressed by missions such as Parker Solar Probe and Solar Orbiter. The added value rapidly drops beyond 9 Rs, which is the perihelion of Parker Solar Probe.

To summarise

- **the target mission profile, which offer optimal conditions for addressing all three scientific objectives and is technologically feasible, should have a perihelion between 1 and 2 Rs from the photosphere.**
- **a backup profile, of slightly less scientific relevance, with a perihelion below 4 Rs.**
- **missions with a perihelion below 1 Rs are not feasible while those whose perihelion >4 Rs are not recommended.**

IV. Technological issues

Getting as much closer to the Sun than any spacecraft before brings its toll of technological challenges. Such a mission will require cutting-edge technology and push the thermal design to its limits. However, recent developments in material science and the lessons learnt one year after the launch of Parker Solar Probe show that it is now technologically feasible to travel much deeper in the solar corona. Although it is beyond the scope of this white paper to detail these technological issue, we mention here the main ones because of their major impact on the mission profile.

IV.1 Thermal design

The primary technological obstacle is the protection of the spacecraft against the intense radiative flux. Lessons learnt from the PHOIBOS design study and from the Parker Solar Probe and Solar Orbiter missions show that the two key parameters are shape of the heat shield and its material.

The shape of the heat shield needs to be conical with a 15° to 30° half-cone angle and several secondary shields to protect the spacecraft. Radiators are needed to evacuate the heat sideways. The heat shield should be made of one of the three materials envisaged during the NASA STDT/2005 and 2008 studies for Parker Solar Probe (McComas et al., 2008). The most critical choice is that of the coating, for which the two main candidates are Carbon Carbon composite and pyrolytic boron nitride (pBN, also called 'white carbon'). Present studies show that it is possible to remain below 2300 K at 1.5 Rs with a 15°-conical heat shield that is coated with pBN. This is further illustrated below. The final choice will require further physico-chemical studies of these composites at high temperature and with realistic proton and VUV irradiation.

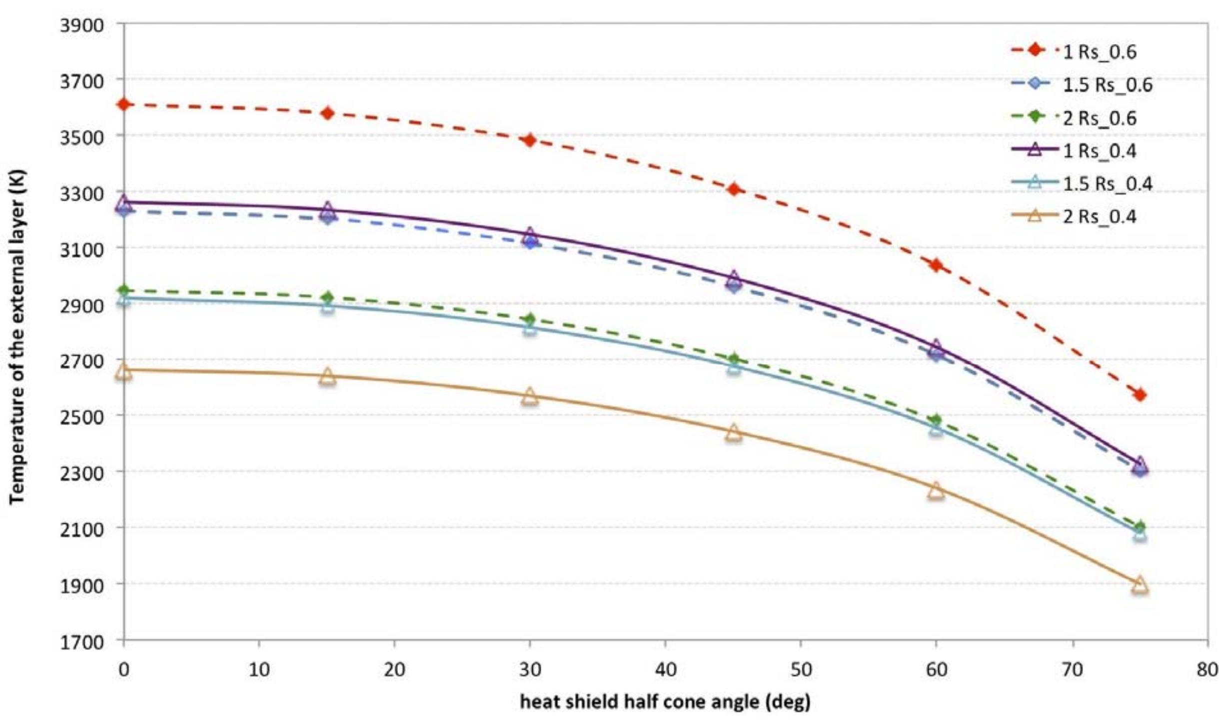

Figure 7: Temperature dependence of the outer part of the heat shield versus half cone angle for two α/ε ratios (0.4 and 0.6) and solar distances ranging from 1 Rs to 2 Rs.

IV.2 Power management and Communication

The challenges and solutions are comparable to those met during the PHOIBOS design study (Maksimovic and Velli, 2009). At perihelion, batteries will be needed to power the instruments. Farther away from the Sun, when solar panels can be deployed, the available power will depend on the size of the solar panels that can be folded behind the thermal shield. This puts severe constraints on the power requirements of the instruments and the spacecraft. For PHOIBOS, a double solution was proposed, with a solar module with small panel, and a transfer module with large surface solar arrays.

Another potential bottleneck is the communication with the Earth because of power requirements and visibility constraints. One may for example consider having two spacecraft: one solar module and one relay spacecraft on a higher orbit. Multiple solutions have already been investigated and the final choice will depend on multiple criteria, foremost on cost.

IV.3 Orbit

The choice of the orbit will primarily be dictated by science objectives. While there is a considerable interest in moving out of the ecliptic to probe the Sun at higher latitudes (ideally, in coronal holes), this adds a number of constraints such as a gravitational pull by Jupiter.

V. Outreach

A mission that dives into the deep solar corona offers a huge potential for communication as it provides an unprecedented combination of technological challenge, outstanding scientific questions (among the major unsolved questions of modern science) and not least, a journey to the most extreme and least well known region of our solar system. Parker Solar Probe has already set a new standard by getting closer to the Sun than ever before and being the fastest human-made object. The mission concept we are describing here would be another major leap forward and thereby offer unique conditions for raising public interest in solar and stellar science. Finally, and not least, some of the scientific questions that will be addressed, such as the acceleration of energetic particles, are of direct societal relevance.

References

Antonucci E, Dodero MA, Giordano S, Krishnakumar V, Noci G. 2004. Spectroscopic measurement of the plasma electron density and outflow velocity in a polar coronal hole. A&A 416: 749–758, DOI:10.1051/0004-6361:20031650.

Brodu E., Balat-Pichelin M., De Sousa Meneses D., Sans J.L., Reducing the temperature of a C/C composite heat shield for solar probe missions with an optically selective semi-transparent pyrolytic boron nitride (pBN) coating, Carbon, 82, (2015), 39-50.

Cranmer, S. R., and A. A. van Ballegooijen (2005), On the generation, propagation, and reflection of Alfven waves from the solar photosphere to the distant heliosphere, Astrophys. J. Suppl., 156, 265.

David, C., et al.• Measurement of the electron temperature gradient in a solar coronalhole, Astron. Astrophys.,336, L90-L94, 1998.?

B. De Pontieu, L. Rouppe van der Voort, S.W. McIntosh, T.M.D. Pereira, M. Carlsson, V. Hansteen, H. Skogsrud, J. Lemen, A. Title1, P. Boerner, N. Hurlburt, T.D. Tarbell, J.P. Wuelser, E.E. De Luca, L. Golub, S. McKillop, K. Reeves, S. Saar, P. Testa, H. Tian, C. Kankelborg, S. Jaeggli, L. Kleint, J. Martinez-Sykora, On the prevalence of small-scale twist in the solar chromosphere and transition region, Science, April, 2016

A.H. Gabriel, L. Abbo, F. Bely-Dubau, A. Llebaria, E. Antonucci, (2005), Solar wind outflow in polar plumes from 1.05 to 2.4 R, Astrophys. J. 635, L185.

Grall, R.R., Coles, W.A. Klinglesmith, M.T., et al., (1996) Rapid acceleration of the polar solar wind, Nature Volume: 379, 6564 p. 429-432.

Grall, R.R., Coles, W.A. Klinglesmith, M.T., (1996) Observations of the solar wind speed near the Sun, SOLAR WIND EIGHT - Proceedings of the Eighth International Solar Wind Conference Book Series: AIP Conference Proceedings, Issue: 382, p. 108-108.

Grappin, R., A. Mangeney, and E. Marsch (1990), On the origin of solar wind MHD turbulence: HELIOS data revisited, J. Geophys. Res., 95, 8197.

Hundhausen, Coronal expansion and Solar Wind, Springer, 1972;

Y.Katsukawa,1* T.E.Berger,2 K.Ichimoto,1 B.W.Lites,3 S.Nagata,4 T.Shimizu,5 R.A.Shine,2 Y.Suematsu,1 T.D.Tarbell,, S.Tsuneta1, Small-Scale Jetlike Features in Penumbral Chromospheres, 7 December 2007 V 318, SCIENCE (2007)

Kohl, J. L., et al. (1998), UVCS/SOHO empirical determinations of the anisotropic velocity distributions in the solar corona, Astrophys. J., 501, L127.

Kohl, J.L., Cranmer, S.R., Gardner, L.D., Lin, J., Raymond, J.C., Strachan, L., (2005), Capabilities of UV coronagraphic spectroscopy for studying the source regions of solar energetic particles and the solar wind, Proceedings of the Conference Solar Wind 11 - SOHO 16: Connecting Sun and Heliosphere Book Series: ESA Special Publications, Volume: 592 Pages: 677-680.

Landi, L. Matteini, and F. Pantellini, On the competition between radial expansion and coulomb collisions in shaping the electron velocity distribution function, The Astrophysical Journal, 760:143 (12pp), 2012 December

Lemaire, Joseph & Stegen, K. (2016). Improved Determination of the Location of the Temperature Maximum in the Corona. Solar Physics. 291. 10.1007/s11207-016-1001-3.

Li, X., et al. (1998), The effect of temperature anisotropy on ob- sevations of Doppler dimming and pumping in the inner corona, Astrophys. J., 501, L133.

MacComas D. J., Acton L. W., Balat-Pichelin et al., Solar Probe Plus: Report of the Science and Technology Definition Team, NASA/TM-2008-214161, July 2008

Maksimovic, M., V. Pierrard, and J. F. Lemaire (1997a), A kinetic model of the solar wind with kappa distribution functions in the corona, Astron. Astrophys., 324, 725– 734.

Maksimovic M., and Velli, M., PHOIBOS: probing heliospheric origins with an inner boundary ob- serving spacecraft, Experimental Astronomy, 23 (2009), 1057–1078.

Matthaeus, W. H., et al. (1999), Coronal heating by magnetohydrodynamic turbulence driven by reflected low-frequency waves, Astrophys. J., 523, L93.

Matthaeus et al., 2004, Geophys. Res. Lett.,.Matthaeus, W.~H. and Minnie, J. and Breech, B. and Parhi, S. and Bieber, J.~W. and Oughton, S., Transport of cross helicity and radial evolution of Alfv{\'e}nicity in the solar wind,   DOI: 10.1029/2004GL019645;

McComas, D. J., et al. (2003), The three-dimensional solar wind around solar maximum, Geophys. Res. Lett., 30(10), 1517, doi:10.1029/2003GL017136

Parker, E. N. (1958), Dynamics of the interplanetary gas and mag- netic fields, Astrophys. J., 128, 644.

Raymond, J. C., et al. (1998), Solar wind at 6.8 solar radii from UVCS observation of comet C/19 96Y1, Astrophys. J., 508, 410.

Rosenbauer, H., Schwenn, R., Marsch, E., et al.\ 1977, Journal of Geophysics Zeitschrift Geophysik, 42, 561

Sakao, Taro, Ryouhei Kano, Noriyuki Narukage, Jun'ichi Kotoku, Takamasa Bando, Edward E. DeLuca, Loraine L. Lundquist, Saku Tsuneta, Louise K. Harra, Yukio Katsukawa, Masahito Kubo, Hirohisa Hara, Keiichi Matsuzaki, Masumi Shimojo, Jay A. Bookbinder, Leon Golub, Kelly E. Korreck, Yingna Su, Kiyoto Shibasaki, Toshifumi Shimizu, and Ichiro Nakatani. "Continuous Plasma Outflows from the Edge of a Solar Active Region as a Possible Source of Solar Wind." Science 318, no. 5856 (2007): 1585-588. http://www.jstor.org.sheffield.idm.oclc.org/stable/20051753.

Scudder, J. D. (1994), Ion and electron suprathermal tail strengths in the transition region: Support for the velocity filtration model of the corona, Astrophys. J., 427, 446.

Suess and Nerney, 2001

Velli, M. (1993). On the propagation of ideal, linear Alfvén waves in radially stratified stellar atmospheres and winds. Astronomy and Astrophysics, 270, 304– 314.

Verdini, A. and Velli, M.(2007) Alfvén Waves and Turbulence in the Solar Atmosphere and Solar Wind, Astrophys J., 662, 669–676, https://doi.org/10.1086/510710.

Zouganelis, I., M. Maksimovic, N. Meyer-Vernet, H. Lamy, and K. Issautier (2004), A transonic collisionless model of the solar wind, Astrophys. J., 606, 542– 554.