SOLAR PROBE: THE RAMSES PROPOSAL

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ABSTRACT

After several years of intensive studies carried out with remote sensing instrument, located at, or near 1 AU, the process(es) that accelerate(s) the solar wind remain(s) a matter of debate. A new strategy involving a close fly-by of the sun is now credible. It will completely renew our knowledge of the corona and of its relation to the chromosphere. Thanks to a suite of instruments especially designed to carry out both in-situ measurements in the corona and high resolution remote sensing of the corona and of the underlying chromosphere, it will be possible to decide upon which mechanism(s) is responsible for this acceleration. In view of recent findings, in particular from SOHO, ULYSSES and WIND it is explained why a solar probe is the next step toward understanding the solar corona heating and solar/stellar wind acceleration. A solar probe will also be a unique opportunity to establish the link between the magnetic field in the corona and the chromospheric network, via a combination of in situ measurements, EUV and white light imaging. A solar probe will, for the first time, allow the assessment of the nature/role of the filamentation of the coronal plasma, and its link to plasma acceleration. The non thermal characteristics of the distribution functions and their relation to micro and meso-scale structures will be investigated, directly via in situ measurements and indirectly via white light imaging of the surrounding corona. The importance of a solar probe mission has been acknowledged for long, in particular in the H-2000 prospective document. Yet it is challenging mission. We describe recent studies made in France and in the US to resolve the technical difficulties associated with flying a probe close to the sun. The results presented here are based upon a study made by a group of French scientists, with the technical support of CNES, to solve the question raised by the H-2000+ survey committee. The outcome of the group is described in a document called the RAMSES proposal, which was recently submitted to CNES, in the context of a prospective meeting, held in Arcachon, France (beginning of March 1998). We describe the main results of this study, in particular the new simulation and test facility (MEDIASE) built at Odeillo to characterize the C-C materials that would be used to build the thermal shield of the probe and the corresponding instrumentation.

I. INTRODUCTION

Stars are not isolated systems. Besides photons, they exchange matter and energy with the interstellar medium through stellar winds and/or accretion flows, with an efficiency that strongly depends on their mass, their age, their current evolution phase, and on the parameters of the surrounding media.

![Figure 1: Schematics of the Hertzsprung-Russell diagram, indicating expected characteristics of stellar winds (electronic temperature, terminal velocity)](image)

For stars having masses of the order of that of the Sun, one observes either dense and cold winds or very hot coronae associated with thin but very fast winds. Thus from an astrophysical viewpoint, the study of the solar wind, of the processes that lead to its generation and to its main characteristics are important to the
understanding of how the mass is lost for a large class of stars, for which, in spite of their luminosity, the radiation pressure is not sufficient to blow up substantially the surrounding gas.

Recent mission such as ULYSSES and SOHO, both have greatly increased our knowledge about the phenomenology and the physics of the processes that are likely to be responsible for the solar mass and energy losses. These results suggest that small scale processes, occurring besides 10 Rs from the Sun, play a critical role for accelerating the wind. Since its becomes super-Alfvénic and super-sonic in this region, the information about the exact nature of the acceleration(s) process(es) is lost in the outer corona. For example, we discuss the potential role of small scale processes, in particular the possible role of High-Frequency Alfvén waves. Should these HF Alfvén wave be involved in the acceleration of the wind, then these waves, which do not escape from the corona, should be measured inside the corona.

II. SCIENTIFIC OBJECTIVES

II.1. Origin and acceleration of the solar wind(s)

ULYSSES data have definitely shown that solar wind exhibits two regimes. During solar minimum, a slow solar wind, with bulk velocities ranging around 200 kms\(^{-1}\) at 10 Rs originates from the magnetic equatorial regions of the Sun. A fast wind (700-800 kms\(^{-1}\)) mainly flows from the coronal holes appearing in polar regions, at magnetic latitudes higher than 45°. Even if it seems that the equatorial flow of the sun could well be a superposition of the two regimes, as suggested by UVS observations. The solar wind(s) acceleration is also known to mainly take place in regions lying very close to the Sun (say below 10 Rs), and apparently closer for the fast wind than for the slow wind.

The simple pressure gradient forces that were thought to be responsible for the wind expansion have been shown to be insufficient to explain the fast wind acceleration. The role of Alfvénic wave pressure and/or cyclotron heating by higher frequency waves are now considered as necessary ingredients of the whole story. The near-Sun corona is not in thermodynamical equilibrium, with decoupling of relatively cold electrons and various ionic species whose temperatures seem to increase with the ion masses. The broadening of the ionic EUV lines at about 3 Rs indicate strong and selective wave-particle interactions leading to anisotropic distribution functions \((T_e > T_i)\). The role of the exospheric electric field linked to the relative motions of the ions and electrons has also to be stressed. Non-thermal, - maybe run away - electronic populations are likely to be produced, resulting in non local heat transport. It could be generally said that the behavior of the near-Sun plasma is now thought as being intrinsically kinetic, such that the link between electrons and ions occurs mainly through the presence of electric fields and that collisional processes only affect the less energetic electrons constituting the core of their velocity distribution. The interplay between these electric fields and the mirror forces due to the inhomogeneous magnetic fields has to produce very complex distribution function for the non-thermal electrons, including beams, trapped populations, etc... exhibiting very strong non-thermal features that are able to produce a complex phenomenology of plasma and electromagnetic waves.

Denser, slower and intermittent winds flow out the equatorial streamer belt. Do the closed coronal archs observed in these regions be responsible for stopping the plasma flow or do the corresponding magnetic surfaces be patchy, such that the plasma is allowed to reach the magnetically open regions? SOHO observations show rapid motions of the plasma with very hard transition between slow and fast winds. In these regions, brightened localized regions are observed to flow at velocities of the order of a few hundred kilometer by second. Do they are true « flux tubes » or « plasmoids », indicating that the matter is also ejected at such velocities, due to reconnection events within thin current sheets, or « phase velocity features », linked to plasma concentration due to low frequency waves propagation? The nature of these irregularities of the flow, the role they play in the processes occurring in the slow solar wind, as well as their link to local altitude phenomena can only be reached by in situ measurements together with simultaneous high angular resolution imaging.

Generally speaking, remote sensing of the near-Sun corona is clearly insufficient for studying the non-collisional drags of the various species of ions by waves whose frequencies are likely to locally match the species' gyro frequencies. Similarly it is important to measure the fine characteristics of the electronic and ionic distribution functions that would reveal the complex interplay between particles populations and waves. In situ exploration of this region is necessary to get an insight of the physics of plasma acceleration, and to determine if the main part of this phenomenon is due to weak turbulent wave particle interaction or to strongly turbulent wave structures, as observed, for instance, throughout the terrestrial auroral zone.

II.2. Coronal structure and dynamics and their link to chromospheric counterparts

Remote sensing at optical frequencies and soft X-rays already have shown that even the near-sun corona is a very structured magnetized medium that strongly varies with both space and time. Observations of cold jets generated by explosive events, macrospicules, hot jets linked to chromospheric bright points, striations or plumes linked to the supergranulation network, etc... strongly suggest that coronal structures are related to the very dynamical chromospheric network. Radio observations also clearly indicate that corona is a very fibrous and time dependant medium.
Models of the solar wind expansion that make the assumption of radial symmetry of the flow are likely to be strongly modified to take into account the intrinsic non-stationarity of the medium and/or the non-radial gradients of the plasma parameters. Such features indeed could play an important role in the dynamics of the solar outflow and in the local energization of the plasma. For example, in the terrestrial auroral zones that are also fed by low \( \beta \) plasma and that by many aspect could exhibit physical processes similar to those occurring in the near-Sun corona, the observed non radial density gradients mark off the regions where the dissipation of electromagnetic energy preferentially takes place.

New models, such as those of the « solar furnace », point out the particular role that could be played by the magnetic field concentrations occurring at the chromospheric level either for heating the plasma or for accelerating the flow. A fundamental result from SOHO\(^\text{10}\) is the evidence for the temporal variability of the chromospheric network. The extrapolation of the measured radiative losses due to structures observed at large spatial dimension (10\(^4\) km) strongly encourage to increase the spatial resolution to get the heating power due to the variability of structures occurring at smaller scales.

Only in situ measurements can definitely confirm the filamentary nature of the near-sun corona and the role likely played by the gradients and the associated turbulence. In order to study the link between the coronal structures and the chromospheric features it is essential that such measurements will be accompanied by very high resolution imaging of the solar disk region where the field lines passing through the probing experiment are anchored.

II.3 Non thermal electrons and their implications for coronal phenomena

As yet superthermal particles produced in the vicinity of the sun have been detected either due to their interaction with the solar atmosphere, where they produce radio, X and gamma emissions or by in situ measurements in solar wind, at distances from the Sun ranging from 0.3 to 1 AU. Inversion of X and gamma rays spectra are difficult, whereas recent data from the satellite WIND, performed at 1 AU, revealed the existence of an electronic « super halo » at energies ranging up to 100 KeV\(^\text{11}\).

The origin of these non-thermal particles seems to be closely linked to the heating of the high altitudes layers of the solar atmosphere by dissipation of numerous, small-scale, low intensity eruptive events. This motivated various studies about active phenomena either at X-ray energies or at radio wavelengths. Eruptive bright points have been shown to be associated with the production of non-thermal electrons\(^\text{12}\). « Nano flares », likely linked to small scale magnetic activity, are present during solar maxima and minima as well and could explain the coronal heating by magnetic energy dissipation due to reconnection processes.

It also has to be kept in mind that the initial charge states of minor ions produced within the ionization layer occurring at small distance of the sun are mainly influenced by the non-Maxwellian tail of the electron distribution and not by its « core » temperature\(^\text{15}\). Thus, the precise study of the « return heat flow » due to non-Maxwellian electrons could be a clue for determining the initial ionisation of the various species of ions as observed farther away in the solar wind.

The main production of energetic electrons could be possibly related to the disruption of a great amount of small scale current sheets occurring in the near-sun region. These electrons likely play an important role both for the heating of corona and for the determination of its ionic composition. It is therefore important to study their precise distribution function within the near-Sun corona where they are expected to be produced. The presence of localized current sheets could also easily be studied by local magnetic field measurements together with in pro xime imaging of the corona by a white light telescope probing the Thomson emissivity of the plasma and thus giving a tomographic view of its density irregularities. With respect to the remote sensing of the same region this would have the great advantage to increase the angular resolution to the necessary value and to allow to disentangle the expected features from the integration of the optical signal along the line of sight.

III THE RAMSES PROPOSAL

Since the beginning of the seventies, plasma and solar physicists have dreamed to make in situ measurements into the plasma that closely surrounds our own star. Early proposals like VULCAN, in Europa, or STARPROBE, in the US, were considered as out of possibility for both budgetary and technological reasons. Since this time, many studies have been performed to overcome the technical difficulties and to decrease the cost of such a mission. In the past few years, the Minimal Solar Mission (MSM) have been funded by NASA as one among three deep space missions likely to be launched during the first years of the next century, whereas Solar Probes proposals have been made to ESA in the context of the european Horizon 2000 and Horizon 2000+ programs. Taking into account the recommendations performed by the selection panels, new studies, supported by CNRS and CNES, have been performed that leads to the RAMSES (Son of the Sun) proposal, that was put, in France, to the highest priority by the astrophysical community, during the prospective meeting held in Arcachon in March 1998.

III.1 General presentation

The RAMSES mission profile closely follows those that have been studied in the US during the recent years.
Like MSM, it follows a 4 AU-4 Rs orbit that use the gravity assist of Jupiter to allow a close approach of the Sun and to incline the orbital plane in order to be able to explore the high magnetic latitudes of this star and to study the fast solar wind generation region. This nevertheless impose to leave the earth with a high relative velocity (V, of the order of 10-11 km/s), thus necessitating that the launch should be provided by an ARIANE 5, a Delta II rocket with a supplementary thruster (STAC 30 C), or any other launcher of this class.

The near-Sun part of the orbit (distance to Sun less than 20 Rs) for which the instrumentation will be optimized, should have a duration of 48 hours, and a cruise science phase will be possible from 0.3 AU.

The technical studies performed in view of the RAMSES proposal allow to increase the flexibility of the mission operations as compared with the needs indicated in the MSM proposal. First of all, retractable solar pannel have been chosen for the onboard power supply, together with dried batteries (Li) : a peak power of 70 W is necessary in the sun vicinity and a average power of about 25 W for the whole mission. The data recorded during the near-Sun phase of the mission will be stored onboard the probe and transmitted afterward to the ground. Unlike MSM, the thermal shield will not be used as a TM antenna, which simplifies its design. These overall technical concepts allow for making two or three passage at the perihelion, thus increasing the scientific return of the mission.

Optionally, it would be possible to use a simple solar sail during the inbound leg of the first travel towards Sun (about 45 months from Earth to Sun), which allows to decrease the period of the further orbits to about 55 months. Optionally again the attitude control during the near-Sun orbital phase could be provided by radiation pressure, which greatly save electrical power consumption. Table 1 summarizes the necessary mass resources demanded to the spacecraft platform.

III.2 Instrumentation

The payload of the RAMSES probe comprises both in situ experiments allowing for the determination of the parameters of the near-Sun plasma and remote sensing instruments. In situ instruments comprises two sets, respectively devoted to the study of waves (magnetic and electric field) and of particles distribution (distribution function at lower energies up to 10 keV, and energy distribution at higher energies up to 10 MeV) in different energy range. In order to save weight and power consumption, they are very simple, miniaturized.

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FIGURE 2 : Schematics of the RAMSES Probe

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>kg</th>
<th>Comments</th>
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</thead>
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<tr>
<td>Instruments</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Ergols for control</td>
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<td>[\Delta v = 50 \text{ m/s}]</td>
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<td>Attitude control</td>
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<td>Communications</td>
<td>10</td>
<td>5Gbits : 1.5 kg</td>
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<td>Power</td>
<td>30</td>
<td>Pannel : 2x1.35 m²</td>
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<td>shield : 8 kg</td>
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<td>Total 2</td>
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Table 1 : Mass resources demanded by the RAMSES mission
instruments whose performances (geometry factors, sensibility...) are optimized to the expected overall characteristics of the near-Sun plasmas. Table 2 very briefly summarizes their principal objectives and performances:

**IN SITU MEASUREMENTS**

**WAVES**
*Magnetic-field, Alfvén waves up to frec, density fluctuations and plasma waves, thermal noise spectrometry*

- 2 3D-Magnetometers at low frequency (0-4kHz)
- 2 1D-Magnetometers at high frequency (0.01-10 Mhz)
- Direct measurement of currents : Ragotisky’s loop (5-8000Hz)
- Electric field (5 Hz-10 MHz)

**PARTICLES**
*Acceleration & heating processes (electrons and ions)*

- Low energies : electrostatic optics, TOF (1eV-10 keV, \( \Delta \theta = 5^\circ, H, He^+, O \))
- High energies : charge deposit in Si-junctions (50 keV-10 MeV)

Table 2 : Main characteristics of the in situ instruments studied for the payload of the RAMSES probe

The remote sensing instrumentation of the RAMSES payload is thought to be complementary to in situ measurements. They also are relatively simple instruments, that nevertheless will offer a high resolution imagery of both the solar disk (IDSE in EUV) and the inhomogeneity of the surrounding coronal medium (IVCS in white light), due to the very small distances between the observation point and the observed targets near perihelion. Table 3 summarizes their expected performances. Finally Table 4, below, indicates the mass and average power consumption of these instruments as well as the allocation of memory that is needed for their working:

**REMOTE SENSING INSTRUMENTS**

**IVCS : white light polari-imagery**
*tomography of the encountered density structures & plasma filamentation of the corona with rejection of the dust corona (polarimetry)*

- measure of Thomson emissivity ( \( + \int n_e \, ds \) )
- aperture : 3.5 cm, FOV : \([3']^2\)
- resolution : 12 Arcsec
- wave length : 0.65 ± 0.2\( \mu m \), acquisition time : 1s each 10 s

**IDSE : EUV imagery of the solar disk**
*Superfine structures & energy exchanges at chromospheric level*

- resonance line of i) HeII at 304 Å, ii) H at 1216 Å
- aperture : 3 cm, FOV : \([0.6']^2\)
- resolution : 2 Arcsec + 20 km at 3Rs
Table 3: Main characteristics of the remote sensing instruments studied for the payload of the RAMSES probe

<table>
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<th>Instruments</th>
<th>kg</th>
<th>W</th>
<th>Gbits</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVCS</td>
<td>2.2</td>
<td>3.5</td>
<td>2.4</td>
</tr>
<tr>
<td>IDSE</td>
<td>2.3</td>
<td>4.5</td>
<td>0.8</td>
</tr>
<tr>
<td>WAVES</td>
<td>3.1</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PARTICLES</td>
<td>4.3</td>
<td>7.0</td>
<td>0.8</td>
</tr>
<tr>
<td>DPU &amp; CONV.</td>
<td>1.4</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Harness</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub Total</td>
<td>14.5</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Margins</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>25</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4: Mass and power resources foreseen for the RAMSES payload

III.3 Thermal shielding

The conception and design of the thermal shield that will be used to protect the payload and the spacecraft system are obviously essential. Also, near the perihelion, the environment of the probe will be perturbed by the "secondary atmosphere" emanating from the thermal shield. It is thus important to characterize the nature and composition of the ejected materials in order to determine whether they will disturb the performed measurements or not. For these purposes, a test facility (MEDIASE, for Moyen d'Essai et de Diagnostique pour les Ambiances Solaires Extremes) has been designed and instrumented to be used at the 1000 kW solar furnace installed at Odeillo, France. MEDIASE allows:

- to heat samples of candidates materials for the thermal shield (currently C-C matrix composites) up to 2500 K, under high vacuum
- to expose them to intense radiation fluxes (including EUV) and energetic ions
- to characterize their physicochemical and thermomechanical behavior and the thermo-radiative properties of the materials
- to characterize qualitatively and quantitatively the close environment of the samples under such conditions and more particularly, the ejected materials and their ionized components. MEDIASE is now equipped with a two-color optical-fiber pyrometer, that aims at determining the precise temperature of the sample, various radiometers and spectroradiometer for total or directional determination of the spectral emissivity and reflectivity, a quartz microbalance for measuring mass losses and ablation kinetics, and a mass spectrometer for the determination of the ejected neutral and ionized species. Figure 3 schematizes the overall design of the MEDIASE chamber

![MEDIASE Diagram](image.png)

FIGURE 3: Schematics of the MEDIASE chamber [1: hemispherical entrance window, 2: shield and sample support, 3: sample, 4: optical fiber probe, 5: goniometer, 6: quartz microbalance, 7: measurement window, 8: bichromatic pyrometer or pyro-reflectometer, 9: radiometer or spectro-radiometer, 10: mass spectrometer, 11, 12: EUV and ions sources]
IV. CONCLUSIONS

The understanding of the physical processes by which the Sun and other stars interact with the surrounding interstellar medium is an interesting and unresolved problem. Recent missions tailored to studying the heating of the corona and the solar wind, outside the ecliptic plane, have given evidence for two types of winds: a fast wind over coronal holes and a slow wind, over some fraction of the low latitude regions. The flow velocities, temperatures and densities measured in the two regimes are very different, which suggests that there are (at least) two different acceleration processes.

So far the acceleration process(es) of the solar wind has been studied either via in-situ measurements carried out at large distance from the acceleration region, or via remote imagers with a moderate spatial and/or temporal resolution. While important and necessary these approaches involve inherent limitations. As presented in the present paper, the acceleration of the wind is strongly related to, or rather controlled by small scale processes involving high frequency waves, disruption of thin current sheets, and transverse filamentation of the plasma. In order to be able to study these small scale processes a new approach is needed.

As described here, it involves a combination of in-situ measurements and high spatial and temporal resolution imaging of the corona and of the chromospheric network around the magnetic footprint of the probe. In situ measurements are necessary to understand the complex interplay between waves and particles, for instance « High Frequency » ion cyclotron waves have been invoqued to heat ions. These HF waves cannot escape from the corona and can only be observed there. More generally, the signature of acceleration processes in the electron and/or ion distributions can be used to identify the relevant acceleration process, only if measurements are made close enough from the acceleration site. In order to assess the role played by thin current sheet disruptions, in situ measurements are needed to estimate critical parameters (kinetic/magnetic pressure...), as well as white light imaging to replace the local density measurements in their context; the spatial resolution for in situ measurements and for the coronal imager should be of the order of 100 km; which seems to be achievable. The other key issue is to relate the heterogeneities of the medium with the fine structure of the chromosphere; this will be done by combining an EUV imager of the chromosphere (20km spatial resolution) with measurements made in the corona by the white light imager and the in-situ instruments.

When the Solar Corona Probe (SCP) was submitted to ESA for M3, a number of questions were asked by the survey committees. In the present document we have described the answers which have been given to these questions. In particular (i) there is no more a need for an RTG, (ii) multiple passes are possible, thanks to retractable solar panels, (iii) the thermal shield design has been simplified, and (iv) thermal tests lead to the conclusion that the carbon outgassing is less than expected. The RAMSES proposal gives more details about the results which are summarized here.

Then the « green dream » of the H-2000 programme can now become a reality, and we hope that actions will soon be taken to avoid European scientists and ESA from being absent of this challenging and highly scientifically valuable venture. Given the high scientific interest on both sides of the Atlantic, and the matching between the current schedules at NASA (launch of the probe in 2006/2007), and the expected date for F3, around 2007, the solar probe is a good candidate for a joint mission, involving ESA and NASA.

REFERENCES

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