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In Situ Measurement Requirements for a Solar Probe

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Abstract. We present the rationale and *in situ* measurement requirements for a near-Sun mission intended to answer the central questions of the heating of the corona and the acceleration of the solar wind. These conclusions are based on panel discussions and presentations at the Marlboro workshop. We have in mind not a “minimum” mission [1], but rather one that is constrained but feasible within the current mass and telemetry rate restrictions. To distinguish between thermal, wave-driven, and microflare-driven models, the measurements must determine wave levels in a broad range of frequencies, resolve fine-scale structures, find the energetic particle content and its variations, and determine the bulk properties of a few species with detailed distributions for at least electrons and protons. We find that the *in situ* measurements needed to answer the main questions are similar to those proposed previously [4] (magnetic field, plasma, high-energy particles, and plasma wave instruments) but without neutron and dust experiments. Telemetry and mass constraints will be significant but should not be prohibitive.

INTRODUCTION

The primary purpose of a spacecraft encounter with the Sun is to determine the source properties and dynamics of regions responsible for the heating the corona and accelerating the solar wind. As discussed more extensively elsewhere in these proceedings, there are three main candidates for the heating and acceleration mechanisms [9,10]: (1) One possibility is that waves (perhaps turbulent ones) are responsible for both phenomena (*e.g.*, [6]). (2) Another alternative is that the wind is heated and accelerated by “microflares” resulting from a wide spectrum of reconnection events that lead to jets, shock and other heating, field deformation, and particle acceleration (see [3]). (3) Finally, nonMaxwellian particle distributions in the solar atmosphere may lead to an apparent heating through “filtration” of the distribution functions in gravitational and electric fields [13] and a wind acceleration by a nonlocal

heat flux [11]. Other mechanisms, such as diamagnetic ejection of plasmoids, may be seen as possible subsets of these alternatives (see [8]). These views are not necessarily mutually exclusive. For example, the older view that waves were generated in the photosphere and damped when they became large compared to the background field has now been largely ruled out by Ulysses measurements and MHD simulations (see [12]); Ulysses measurements also rule out standard thermal models [2]. In light of this, the wave viewpoint has changed to one in which jets and field kinks associated with microflares lead to high frequency waves that are then damped, producing heating. Moreover, the modified-electron-physics view may require a source such as microflares for the production of nonMaxwellian distributions, and thus these viewpoints may be fundamentally linked. *In situ* (as well as spacecraft-based remote sensing) measurements must distinguish between these interrelated alternatives to advance our knowledge of coronal heating and acceleration.

There are two fundamentally different solar wind states, namely, fast, hot, rarefied flows that arise from coronal holes (*e.g.*, [7]) and streamer-belt related slow, dense, cool flows that arise in or near the streamer belt (*e.g.*, [5]). The latter are usually taken to be better understood, in that traditional thermal models with standard heat flux can reproduce their properties fairly well, but the uncertainty about the exact region of origin of these flows as well as their highly striated structure makes this less clear. Moreover, at times slow flow looks in many respects like fast wind, with anisotropic temperature, differential streaming of protons and α 's, and high Alfvén wave flux, and thus comparisons between fast and slow flows are important in determining the dynamics of both of them. There are also transient events in the solar wind, most notably coronal mass ejections, and while understanding these is probably very useful in understanding the wind acceleration in general, the mission design criteria should not be dependent on seeing an event that occurs relatively infrequently near solar activity minimum.

SPECIFIC ISSUES

Any Solar Probe mission should be able to distinguish and test the above alternative heating and acceleration mechanisms. To do this, we need to be able to make detailed predictions and comparisons. This requires that, first, we understand the morphology of the heating and acceleration region. How filamentary is it? How is the filamentation near the Sun different in slow and fast flows? How does the expansion of what ultimately becomes solar wind plasma vary with distance from the Sun? Answers to these questions, combined with density information, will allow us to determine the velocity of the wind as a function of distance, thereby finally answering the question of whether or not the wind becomes very fast close to the Sun. Correlations of the morphology with detailed structure determinations will allow us to determine

the type of flux tubes (e.g., above a plume or interplume; in the streamer belt or at its edges) that give rise to fast and slow wind respectively.

The central question for any of the models is, "What is the energy source for the heating and acceleration of the wind?" Is there an extended plasma turbulence envelope, and if so does it consist of waves or field aligned-structures, and what is its source? Are microflares sufficiently common and energetic to power the corona and wind? If electron heat flux is energetically important, how does it arise? A related question is, "Is the wind acceleration and heating impulsive or continuous?" By the time spacecraft at 0.3 AU and beyond measure the wind, much has been smoothed out, but greater filamentation occurs the closer to the Sun we look. On a single field line the acceleration may be impulsive, leading to very different near-Sun states than envisaged in steady state models.

Finally, we need to understand the basic momentum and energy transport and dissipation mechanisms in the corona and below. Are waves needed to connect regions of energy generation to regions of energy release? Are they damped effectively enough for this to occur? Is Helium an important ingredient in the energy budget, or is it just heavy hydrogen for most purposes? Is filamentation a basic ingredient of the coronal dynamics, leading, for example, to dissipation in resonant layers? Can localized sources yield a relatively smooth wind farther out? Are shocks the most important source of dissipation, or do other things, such as turbulent cascades or direct particle acceleration due to reconnection, contribute significantly? Are energetic particles merely tracers, or do they influence the dynamics? How do electron distribution functions evolve with distance, and is the heat flux associated with them generated before or after the main acceleration? Can electron heat flux survive the instabilities it might create in the inner coronal region?

MEASUREMENT REQUIREMENTS

The above questions dictate the required *in situ* measurements. In what follows, we assume that there will be 10 kbits/s or more available to *in situ* measurements except for a few hours near closest approach, and that about 2 Gbits of memory could be used to store data to be sent back after perihelion passage. This assumes adequate battery lifetime, or better yet an RTG, although the latter does not seem feasible in the current political climate. The mission could still accomplish major objectives if the high-resolution perihelion data were not available via playback, but it would entail a significant science loss. At all times, compressing the data for transmission will be essential to obtaining the maximum scientific return.

The wind flow speed, density, and temperature are the main things we want to explain, and thus a plasma instrument must yield these parameters. Protons are generally the dominant species, but Helium is likely to be energetically

significant, and thus both of these must be measured and distinguished. Other ions serve as tracers for connections to the solar surface, and thus two of these should be measured, although their charge states are not essential since this makes the measurements difficult and the information may not be that different from that gained farther out in interplanetary space. Electron distributions are also essential in that the electron heat flux may play a significant role in accelerating the wind. To save on telemetry, moments of the particle distributions calculated onboard the spacecraft will be sufficient for higher resolution (1 s may be possible), but distribution functions should be sent as often as possible (perhaps once per minute) both for "ground truth" and because these are needed to understand possible plasma instabilities and wave generation. High resolution moments are needed to distinguish the small scale structures that may be expected associated with localized sources of down to granule size. Nadir viewing would very likely be needed for continuous coverage of the ions, but if this is not feasible there should still be sufficient information available to accomplish the mission goals. Without nadir viewing, it becomes even more essential to have distribution functions to know when to trust the moments. Three-dimensional measurements are also very important for definitive measurements of the plasma parameters in the presence of possible large wave fields. Testing for the presence of specific MHD wave modes requires an angular resolution sufficient to determine the components of the velocity to within 10 km/s. The above requirements could be met with energy ranges of 50 eV to 20 keV for ions and 10 eV to 10 keV for electrons.

Since the mean magnetic field will be strong, magnetic measurements will serve to define the morphology of the flux tubes in addition to determining the fluctuations. Vector measurements will be essential for this, and the relatively small amount of information needed per point would allow 20 vectors/s except near closest approach. This time resolution will overlap with the plasma wave detector (see below) and allow the resolution of very fine scale structures. Measurements from 10 nT to perhaps 0.5 G would be needed due to the strong radial variation of the field and the possibility of highly striated structures near the Sun.

Some of the more recent theories maintain that it is the flux of waves above 1 Hz that is significant for heating and acceleration, and thus detectors must be available to measure these. A search coil that measure the three-dimensional magnetic field up to 10 kHz would overlap nicely with the DC magnetometer, and would measure MHD and somewhat smaller scale waves. Wave amplitudes may be as large as 0.1 G and could produce velocities as high as 70 km/s. Both to determine the mode of these waves and to look for higher frequency phenomena, an electric field instrument covering up to 10 MHz would be needed. The very high frequency waves will not in themselves be energetically significant, but their presence and nature is diagnostic of other processes, and in particular of dissipation mechanisms. Phase information would be needed for correlation with the search coil, although onboard correlations could decrease

telemetry requirements. Four logarithmically spaced frequency channels per decade would be sufficient and might be well accommodated if, for example, low intensity channels are suppressed in the data stream.

Energetic particles provide a significant energy release channel and an important diagnostic of the underlying processes. Since they travel rapidly and are tied to field lines, they give us insights into the source regions and the degree of impulsiveness of energy releases. Electrons from 10 keV to 3 MeV, protons from 10 KeV to 10 MeV, and comparable energies of α 's and one heavier ion would be needed. At least rough pitch angle distributions, from multiple small detectors, would help us understand the field-line topology and the particle scattering mechanisms. The time resolution for these particle measurements should be tied to that for the lower energy 3-D plasma analyzers, with measurements at least as frequent as the transmission cadence of the plasma distribution functions.

Neutron monitors and dust detectors would be of considerable scientific interest, but they do not have a strong direct bearing on the central issues raised above, and thus would not be included.

CONCLUSIONS

Solar Probe *in situ* measurements, coordinated with spacecraft remote sensing observations that reveal global coronal morphology and detailed surface structure and events, should be able at last to unravel the origin of the hot corona and low- and high-speed solar wind streams. An ambitious set of low-mass instruments will be needed, along with carefully designed compression and other onboard processing algorithms. For maximum scientific return, the instruments need to be coordinated in their design such that correlations between the various measurements is straightforward and clearly significant. This is especially true for the coordination of remote sensing and *in situ* measurements; it will be very difficult to make one-to-one correspondences in this case, but both sets of measurements need to lead to expectations for the other. This requires sufficiently high time resolution in the *in situ* case to resolve the fine scales implicit in images, and at least one set of images of sufficient time resolution to begin to separate temporal from spatial dependence in the *in situ* time series. Such a coordinated approach would yield not only much deeper insights into fundamental problems of coronal and solar wind physics, but also a clear view of the many surprises we will find on an exploratory mission to the extreme environment near the Sun.

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