Solar Wind Kinetic Physics
High Time Resolution Solar Wind Measurements from the DSCOVR Mission

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The 1 AU, near-Earth solar wind has been observed by a number of NASA and international spacecraft over the past decades. However, particle instrumentation technology limitations did not allow the direct observation of the varying properties of the thermal solar wind particles in the kinetic regime, which requires measurements with better than 1 Hz cadence. Observations at this kinetic scale are essential to understand how the solar wind is continuously heated as it propagates away from the Sun, how small scale magnetic reconnection operates in the 1 AU solar wind, and how interplanetary shocks can accelerate particles to high energies. The DSCOVR mission, to be refurbished at NOAA expense and launched by the USAF, gives a unique opportunity to NASA to obtain unprecedented time resolution solar wind measurements for a minimal cost. The DSCOVR spacecraft is already built (see Figure 1) and requires only an 18 month refurbishment to be ready for an operational space weather and scientific research mission.

1. SCIENCE OBJECTIVES

The classical theory of the solar wind predicts an expansion of a hot corona reaching high asymptotic speeds with no further heating deposition [*Parker*, 1963]. On the other hand, we have known for some time (e.g., *Parker* [1964a,b]) that some form of heating, starting somewhere near the base of the corona and extending into interplanetary space, is required to generate the high asymptotic wind speeds characteristic of the fast wind. Furthermore, in-situ satellite measurements of the electron and ion temperature profiles from 0.3 AU to 1 AU fall-off more slowly with radial distance than those theoretically predicted by thermodynamics (see *Cranmer et al.* [2009] for a summary of Helios and Ulysses observations illustrating this effect), suggesting some form of local heating. This non-adiabatic heating is likely to be an extension of the non-adiabatic coronal heating that is a necessary ingredient of the acceleration of the fast solar wind [*Parker*, 1964a,b]. Thus the solar wind plasma is far from local thermodynamic equilibrium and electron and ion velocity distributions deviate significantly from local Maxwellians wherever they have been observed (e.g., see the review by *Marsch* [2006]), Thus, properly computing the solar wind temperature from the base of the corona through the solar wind acceleration region will require understanding an assortment of plasma kinetic processes which contribute to the generation and regulation of these non-thermal plasma populations.

Figure 1. The DSCOVR spacecraft in a Goddard SFC clean room.

How do turbulent fluctuations at the Larmor radii or inertial length scales heat the particle velocity distributions?

There is broad consensus that magnetohydrodynamic (MHD) turbulence plays an important role to the local heating of the solar wind (e.g., *Vasquez et al.* [2007], *Cranmer et al.* [2009]). The basic physical picture is that large scale “energy containing” eddies (e.g., posited that the differential motions of adjacent streams are unstable to the generation of large scale Alfvén waves as suggested by *Coleman* [1968]) recursively cascade to smaller scales until reaching a dissipation scale which is determined by wave-particle resonances [*Howes et al.*, 2008a, b; *Schekochihin et al*., 2009]. While much progress has been made in understanding the physics of the cascade in the inertial range (below the driving scale and above the dissipation scale), a clear picture of the dissipation process has not yet emerged. In particular, we do not understand exactly how the energy in the small scale fluctuating fields and flows is converted into internal energy. To answer this question we need to measure the density, temperature and anisotropy of both ions and electrons at cadences faster than 1 s to be able to estimate these fluctuations on length-scales of the order of the Larmor radii and on the inertial scales for both ions and electrons. These measurements have not been made in the long history of near-Earth solar wind research.

What physical processes and conditions control the dissipation-scale spectral break of the interplanetary magnetic field?

The spectrum of magnetic field fluctuations in the solar wind is approximately a power law spectrum from 10^{-4} Hz to 10^{-1} Hz with a typical power-law exponent near 5/3. This inertial range spectrum is followed by a spectral break, a steepening of the spectral slope that typically occurs around 1 Hz in the spacecraft frame at 1 AU. The spectral break is believed to be caused by the onset of collisionless damping at kinetic scales which converts turbulent energy into particle thermal energy (*Leamon et al*., 1998a,b, 1999a,b, 2000). The length scales that mark the transition from large MHD scales to small kinetic scales are the thermal ion cyclotron radius and the ion inertial length. If the fluctuations are primarily composed of Alfven waves propagating parallel to the mean magnetic field B_0, then strong ion cyclotron damping of the left-hand polarized mode occurs when their wavelengths become of the order of the ion-inertial length and this condition will determine the location of the spectral break. On the other hand, if the fluctuations are composed primarily of quasi-perpendicular propagating waves, then there is a transition from the Alfven wave to the kinetic Alfven wave (KAW) when their wavelengths become of the order of the ion-gyroradii and this is the wave number where collisionless (i.e., Landau) damping starts to become significant and the spectral break occurs. Closely related to these mechanisms are the kinetic processes and plasma instabilities that regulate particle distribution functions in the solar wind, many of which remain controversial (*Hellinger et al*., 2006; *Bale et al*., 2009). To address this question we need, besides the density, temperature and anisotropy of the solar wind ions and electrons at these temporal scales, a determination of the wave vector propagation relative to the local magnetic field. To provide closure, the bulk velocity measurements have to have enough temporal resolution to allow for Doppler shifting (if necessary) the observed frequencies into the rest frame of the plasma, measurements that have not been made to date.

How does the electron halo and *strahl* form?

Electrons have been usually considered less important than the ions for the dynamics of the solar wind, because of their small mass and occasional lower thermal energy density. However, electrons are essential to ensure quasi-neutrality, and are the main contributors to the ambipolar electric field via the thermal pressure gradient. They can carry energy in the form of heat-flux driven by the skewed thermal bulk and/or a suprathermal tail of the velocity distribution function. These electron properties are determined mainly by the large-scale interplanetary magnetic field and the self-generated electrostatic potential, by Coulomb collisions in the thermal energy range of ~ 10 eV, and by various other kind of wave-particle interactions. The solar wind electrons are also subsonic, i.e., their solar wind mean speed is considerably lower than their mean thermal speed. Their velocity distribution function, as illustrated in Figure 2, typically include a cold quasi-isotropic Maxwellian core, a hot halo with a power-law like distribution (usually well-modeled by a Tsallis-Lorentzian κ-like distribution function) that sometimes could be anisotropic, and a distinct field-aligned beam called the *strahl*, which carries most of the electron heat flux.

The classical Spitzer-Härm heat law states that the electron heat flux flows down the local temperature gradient. If this is valid at the base of the corona, then some mechanism must be depositing heat into the corona to maintain the local maximum. However, the ratio of the mean free path to the temperature gradient scale at the coronal base is such that non-local transport effects can render the Spitzer-Härm perturbation theory invalid. *Dorelli and Scudder* [2003] have demonstrated (by numerically solving the Fokker-Planck equation) the surprising result that significant non-thermal electron distributions can be maintained at the base of the corona in the presence of Coulomb collisions, in some cases allowing heat to flow *up* the local temperature gradient.

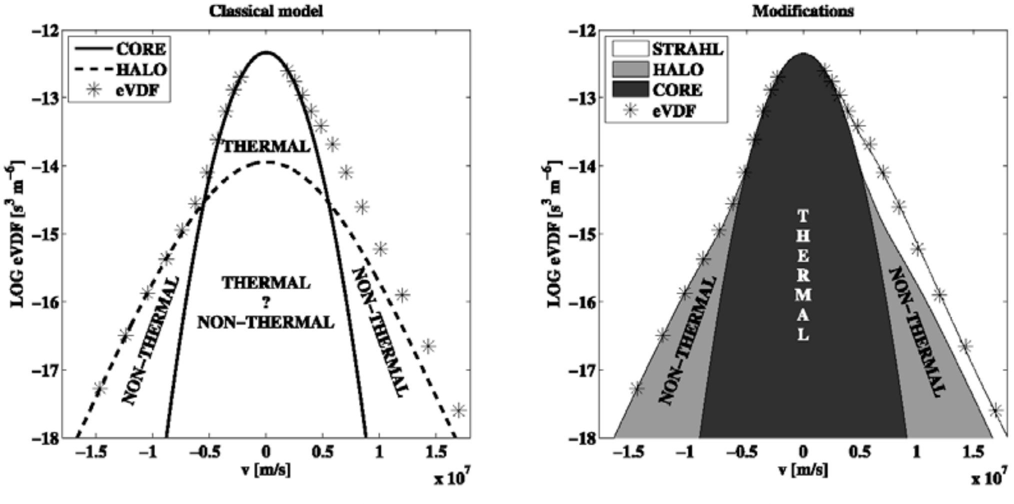

Figure 2. Components of the electron velocity distribution function.

Several processes begin to contribute to the solar wind thermal conductivity as particles move out from the coronal base into interplanetary space along a magnetic flux tube. If the solar wind were completely collisionless, electrons at the coronal base with enough energy to traverse the polarization potential barrier (required to maintain zero radial current density) would be focused into a very narrow beam aligned along the magnetic field. This would form the *strahl* component that indeed has routinely been observed in the fast solar wind from 0.3-1 AU (e.g., *Schwenn and*

Marsch [1991]). But the observed *strahl* component is typically broader than that predicted by magnetic moment conservation alone. In particular, we do not understand exactly how does the *strahl* broaden and how is it regulated. Observations suggest that the formation of the solar wind halo electrons is the result of the scattering of the *strahl* (*Maksimovic et al*. [2005]; *Stverak et. al*., 2009). The premise is founded on observations that connect the decrease in the *strahl* density with radial distance from the Sun with a corresponding increase in the density of the halo. Whether this is due to a long term steady scattering of the *strahl* or occurs in multiple short bursts is not known, nor has there yet been a scattering mechanism identified. To identify this mechanism, sufficiently fast cadence (~ 1 Hz at 1 AU) full electron distribution function measurements in the 1 AU solar wind are necessary.

Another effect that shapes the electron heat flux is the polarization electric field, which acts to decelerate electrons (producing a population of trapped electrons with zero bulk velocity in the Sun's rest frame) and accelerate protons (e.g., *Jockers* [1970], *Lemaire and Scherer* [1972], *Maksimovic* [1997]). In the context of the steady state Vlasov equation, the polarization electric field is the mechanism by which the solar wind protons are accelerated to supersonic speeds. A major difficulty with such collisionless models, however, is that they do not properly take into account the effects of microturbulence driven by the large (unobserved) anisotropies and velocity space discontinuities which tend to occur in steady state Vlasov solutions. And indeed, this electron deceleration process might be closely related to the problem of the broad "strahl" component, also requiring unprecedented ~1 Hz full electron distribution function measurements in the 1 AU solar wind.

Are there small, bursty magnetic reconnection events in the 1 AU solar wind?

Very narrow regions in the interplanetary medium where magnetic field strength abruptly decreases to nearly zero, have been observed for a long time [e.g., *Burlaga and Ness*, 1968; *Burlaga*, 1968], and have been termed magnetic holes by *Turner et al*. [1977]. Two major classes of these magnetic holes have been distinguished: "D-sheets" associated with field rotations [*Burlaga and Ness*, 1968] and "linear' magnetic holes [*Turner et al*., 1977; *Fitzenreiter and Burlaga*, 1978] which show no field rotations. D-sheets are of particularly great interest since they might be the interplanetary signatures of small, bursty reconnection events. Linear magnetic holes on the other hand are believed to be pressure-balanced structures. However, to date, no sufficiently high time resolution solar wind plasma data is available to study these structures. Magnetic holes near Earth, which are not infrequent with a rate of about 1.5/day, move past a spacecraft in the time range of 2 to 130 seconds, the median time being 50 seconds. Thus plasma measurements with a cadence of at least 1 second is required, in conjunction with similarly fast magnetic field observations, to provide the first detailed observations of the internal structure of magnetic holes that would lead to a greater understanding of the magnetic reconnection mechanism.

What is the internal kinetic structure of interplanetary shocks?

While interplanetary shocks have been studies for a very long time, and even the internal structure of MHD shocks is comparatively well understood primarily due to Earth bow shock observations, very little is known about the structural variations due to the various MHD shock types. The nearly stationary Earth's bow shock provides an excellent opportunity to study of fast reverse strong MHD shocks. However, the much richer variety of interplanetary shocks are much harder to study due to their great speed with respect to, and hence short time of passing, a spacecraft. High time resolution (< 1 second) plasma and magnetic field observations are required to open a window into the internal structures of weak and even slow interplanetary shocks hopefully leading to a better understanding of their formation, dissipation and their acceleration of energetic particles.

2. THE DSCOVR SPACE SCIENCE INSTRUMENTATION

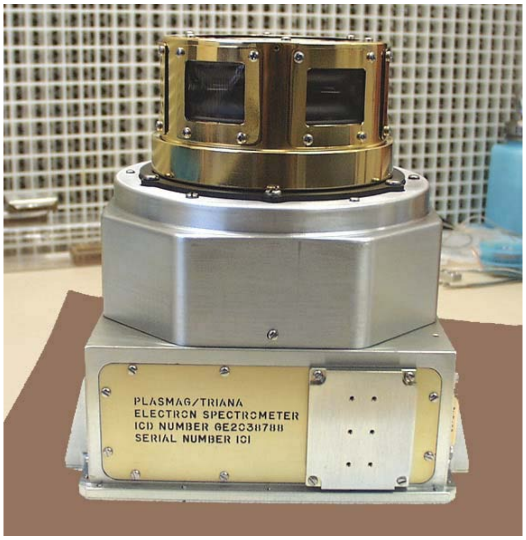

Figure 3. The DSCOVR electron tophat electrostatic analyzer.

The science questions outlined above have it in common that they all require high time resolution (< 1 second) 1 AU solar wind ion moment, full electron distribution and vector magnetic field measurements. The Deep Space Climate Observatory (DSCOVR), formerly known as Triana, spacecraft has a space science instrument package, called PlasMag, that meets these measurement requirements. The PlasMag suite consists of three parts: 1) a Faraday cup to measure the reduced distribution function of the ion component of the solar wind with an unprecedented time resolution of 90 milliseconds, 2) a “tophat” electrostatic analyzer to measure the nearly full 3D electron velocity distribution function in every 800 milliseconds, and 3) a flux-gate magnetometer to make a vector measurement in 30 milliseconds.

The Faraday Cup is particularly suited for precise solar wind measurements on a three-axis stabilized spacecraft because of its large field of view (± 30°). The use of three separate collectors allows the full range of the solar wind deflections (~ ± 15° in all directions) to be accommodated, while still allowing a reduced 3D velocity distribution function to be collected. Thus whole distribution function remains in the field of view at all times so that accurate and high time resolution solar wind moments (density, velocity and temperature) can be computed.

The tophat electrostatic analyzer (Figure 3) will make measurements of the electron distribution function between 5 eV and 2 keV in a time as short as 800 milliseconds. The instrument has a set of six anodes distributed uniformly in azimuth, each with a field of view of 50° x 7° in azimuth and elevation. The coverage in elevation is accomplished by varying the potential of external deflection plates resulting in 15 different elevation angles between +60° and -60° above and below the plane of the anodes. Thus the instrument, sitting at the tip of a 7 m boom, has almost complete 4π sr field of view. This allows the rapid determination of electron temperature anisotropies and any variation in the electron *strahl* component.

Completing the PlasMag instrument package is a standard flux-gate vector magnetometer also sitting on the spacecraft instrument boom. The magnetometer has a sensitivity level of better than 0.1 nT and a native data collection rate of 100 vectors per second, though only every fourth vector is going to be telemetered to Earth.

The combined PlasMag instrument suite will provide all the required measurements identified to accomplish the science objectives outlined at the beginning of this paper.

3. MISSION HISTORY AND ASSOCIATED NASA COST ESTIMATE

In 1998, then Vice-President Al Gore proposed a mission to the earth-sun first Lagrange point (L1) to observe Earth as a planet. This mission was named Triana after the lookout on Christopher Columbus's fleet who was reported to be the first person to see the new world. The mission development proceeded for 21 months and spent an estimated $249M (in FY07$) before being de-manifested from the Space Shuttle. Then the spacecraft was placed in a state of "Stable Suspension" starting in November of 2001 and it was renamed the Deep Space Climate Observatory. (DSCOVR). In 2008, NASA was requested by the United States Air Force (USAF) and the National Oceanic and Atmospheric Administration (NOAA) to complete a study of refurbishing DSCOVR for a launch in 2012. While there had been several previous studies quite similar in nature, this study was unique in that it included funding to remove DSCOVR from storage and perform a power-on test to assess the current status of the observatory. These tests were completed by May 2009 and a refurbishing cost estimate was provided to NOAA. Currently, Congressional NOAA funding is pending to pay for the refurbishing of DSCOVR and a tentative USAF launch vehicle is provided for a December, 2012 launch date.

The NOAA paid for DSCOVR mission is an exclusively real-time space weather monitoring undertaking and, therefore, the NOAA budget includes only elements that are necessary to produce the low cadence space weather measurements. While the DSCOVR spacecraft space science instruments have only a single mode of operation, and therefore, the complete high time resolution data telemetry has to be transmitted to Earth, the NOAA DSCOVR science center is planning to produce only ~ 1 minute cadence solar wind data products. It would fall to NASA to provide the necessary funding to produce the unique, high time resolution data products. Based on the current, highly optimized Wind spacecraft instrument data production experience, the high cadence data products from the three DSCOVR PlasMag instruments would require a yearly NASA funding level of ~ $1M.

4. EVALUATION CRITERIA

Identification as a high priority or requirement in previous studies or roadmaps. An L1 solar wind monitoring mission is explicitly identified by the 2003 Decadal Survey (*The Sun to Earth – and Beyond: A Decadal Research Strategy in Solar and Space Physics*") as a small mission. The Survey moreover discusses the importance of continued L1 space weather predictions also echoed by the 2009 NASA Heliophysics Roadmap. This later document calls for a multi-agency effort to accomplish this goal. The DSCOVR mission, supported by NASA, NOAA and the USAF would fit this objective well.

Makes a significant contribution to more than one of the panel themes. The DSCOVR high time resolution solar wind measurements will address both solar/heliospheric (solar wind acceleration, IP shock structure) and solar wind/magnetosphere interactions science objectives. Also, since DSCOVR is designed to be a real time space weather monitor, it directly contributes to the research to operations theme.

Contributes to important scientific questions facing solar and space physics today. The DSCOVR high time resolution solar wind measurements will directly allow the investigation of solar wind heating, evolution and transient structures.

Contributes to applications and/or policy making. The DSCOVR solar wind proton and magnetic field measurements would be immediately used by NOAA operational space weather forecasting. The operational value of high cadence measurements and electron distribution functions are still a matter of scientific research. But DSCOVR will provide the ideal test case for the transition of these new measurements into operational space weather forecasting.

Complements other observational systems or programs available. A 20131 launch of DSCOVR would provide an ideal overlap with the current ACE and Wind missions. This would not only allow intercalibration of similar instruments, but facilitate multi-point studies.

Is affordable. The cost of obtaining high time resolution solar wind measurements from DSCOVR is eminently cost effective as the brunt of the mission cost is on NOAA and the USAF. For a nominal investment, NASA would obtain a scientifically valuable data set that normally would require the investment of a complete mission. This is a unique opportunity.

Technical readiness. The DSCOVR spacecraft is already completely built, and once the NOAA appropriation is approved, it will take only 18 months to refurbish the spacecraft and its instruments for a USAF launch.

Fits with other national and international plans and activities. The DSCOVR mission fits readily into the US National Space Weather Program.

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