1. Background and Motivation

The ultimate goal of the proposed, future, multi-point, cross-scale measurements at the orbits and Lagrange 1, 3, 4, and 5 points of Mercury, Venus and Earth is 1) to improve of our understanding of the basic plasma physics in the solar wind, 2) to reveal the evolution of the solar wind in the interplanetary region, and 3) to monitor the upstream solar wind conditions for downstream space missions.

Over half a century of solar wind observations have established a picture of a highly-structured (Borovsky 2008), multi-scale, collisionless plasma (Marsch and Goldstein 1983), with mostly supersonic, non-thermal-equilibrium, and turbulent nature. This motivates us to expand on this knowledge, which includes but is not limited to basic plasma physics, turbulent and complex system theory, as well as challenging our solar wind modeling capability. There are still many critical, open questions in solar wind physics that have not been well understood from the magnetospheric scale to the kinetic scales due to the lack of multi-point, high-resolution, in-situ observations.

Coronal mass ejections (CMEs), co-rotating interaction regions (CIRs), and interplanetary (IP) shocks are mostly observed at the orbit of Earth-Sun Lagrange 1 (L1) point with a single spacecraft. Their detailed evolution in the inner heliosphere region and properties of their sub-structure have not been fully investigated yet, due to the lack of multi-scale, in-situ observations. Furthermore, the large-scale structure and properties of the solar wind have crucial impact on the magnetospheric processes. The single spacecraft measurements at the Earth-Sun L1 point neither provide sufficient warning time for space weather operations, nor can provide accurate characteristics of the solar wind structure on magnetospheric scale (Burkholder et al. 2020), which can lead to inaccuracies when forecasting or developing various space weather warnings, e.g., for radiation belt electron flux enhancements etc. This can can also lead to wrong conclusions when interpreting the onset conditions of the physical processes at the magnetopause, and in statistical magnetospheric studies that use lagged observations from a single solar wind monitor at L1 for characterizing solar wind properties and IMF orientation at the bow-shock nose.

Much research has been devoted understanding the origin of the fast and slow solar wind (Sheeley et al. 1976; Abbo et al. 2016) as well as the nature of turbulence in the solar wind, both in the inertial and dissipation range (see e.g., (Belcher and Davis Jr. 1971; Goldstein et al. 1994; Leamon et al. 1998; Bale et al. 2005)). Unlike regular fluids, space plasmas involve different scales (fluid, ion and electron scales) which makes understanding of the physical mechanisms responsible for energy and plasma transport between these scales a challenge (Nykyri et al. 2020). Due to the supersonic and super-Alfvénic nature ($V_{sw} \gg V_{in}$) of the solar wind, the Taylor hypothesis is typically used to derive wavenumber spectra along the plasma flow direction from the frequency-space observation in the spacecraft frame. This hypothesis is valid when the solar wind speed, $V_{sw}$, is higher than the phase speed, $V_{in}$, of the waves/fluctuations and is typically satisfied for MHD scales but can fail at the electron scales (Huang and Sahraoui 2019), indicating that single spacecraft measurements cannot well resolve the energy dissipation processes at the electron scale in the solar wind. The particle acceleration (e.g., Solar Energetic Particles (SEPs)) mechanisms and SEP dynamics in the solar wind are also long-debated topics, solving of which also demands multi-scale, in-situ observational network.

During the last twenty years multi-spacecraft magnetospheric missions, i.e, Cluster1, THEMIS 2 and MMS 3 have revolutionized understanding of the physical processes that enable energy and plasma transport from the solar wind into the Earth’s magnetosphere. The tetrahedron formation of Cluster and MMS have allowed the calculations of the gradients and curls in the plasma and magnetic field (Dunlop et al. 2002; Sundkvist et al. 2003; Shuster et al. 2019), constructing power spectra of the magnetic field fluctuations in the wave-number space (Sahraoui et al. 2006), construction of the experimental dispersion relations of the different plasma wave modes in the plasma frame (Sahraoui et al. 2003; Dimmock et al. 2013; Moore et al. 2016; Nykyri et al. 2020), as well as allowed the evaluations of the terms in the generalized Ohm’s law (André et al. 2004; Torbert et al. 2016; Burkholder et al. 2020), for the first time. However, in the pristine solar wind there have only existed single or dual spacecraft missions between Sun and Earth making it difficult to study and continuously monitor the 3-D structure and multi-scale physics of the solar wind using in-situ measurements.

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1 Introduction The Cluster mission (Escoubet et al. 2001)
2 Time History of Events and Macro-scale Interactions During Substorms (Angelopoulos 2008)
3 Magnetosphere Multi-Scale (Burch et al. 2016)
2. Open Science Questions

In the next 10 to 30 years the small-satellite revolution, durable components and partnerships with academia, industry and government will make it possible to build multi-point, multi-scale spacecraft constellations more cheaply, which is required both for understanding the physics of the supermagnetosonic plasma regime as well as for developing more accurate and advanced space weather warnings for the Earth and for the missions to the Moon, Mars and to the other planets.

<table>
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<tr>
<th>Plasma Parameters</th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
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</thead>
<tbody>
<tr>
<td>Density (cm(^{-3}))</td>
<td>84</td>
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<td>7</td>
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<tr>
<td>Temperature (eV)</td>
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<td>120</td>
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<td>Electron gyrorADIUS transition time (s)</td>
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<td>0.004</td>
<td>0.007</td>
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</table>

Table 1. Typical solar wind properties and scale transition times at the orbits of Mercury (\(r \approx 0.3\) Au), Venus (\(r \approx 0.7\) Au), Earth (\(r \approx 1\) Au).

To address the 3-D structure of the CMEs and instabilities, that can evolve at the sheath-ejecta boundaries (Foullon et al. 2013; Nykyri and Foullon 2013) and which can change the drag forces and thus alter the direction of the CMEs, would require nested constellations from CME-scales (\(r \geq 0.25\) Au) to kinetic scales. The simultaneous, phase synchronized constellations at the orbits of Mercury and Venus would be required to address the large-scale and small-scale structure of the CMEs. Table 1 lists typical plasma properties, length scales and transition times it takes from a structure at given kinetic scale to pass a spacecraft. It is clear, that to resolve the dispersion relations of the electron scale plasma waves and corresponding velocity distribution functions to resolve physical processes responsible for wave generation and damping at the “dissipation range”, will thus require very small spacecraft separations from 100s of meters to few km and very high instrumental sampling rates, in order to measure the phase difference of the waves and Doppler shifts. Furthermore, to increase likelihood that the phase velocities of the waves from MHD to kinetic scales would align at least along two spacecraft requires nested tetrahedron constellations of \(r \geq 12\) spacecraft (at least 4 in each scale). The simultaneous, multipoint and multi-scale observations at the orbits of Mercury, Venus, Earth, and their Lagrange points would allow continuous coverage in the inner heliosphere and allow addressing the following compelling science objectives:

Science Objective 1: Improved understanding of the physics of the magnetized, super-magnetosonic plasma regime at 0.3 Au \(\leq r \leq 1\) Au from the Sun.

A) The process of magnetic reconnection, which converts the magnetic energy to heat and kinetic energy of the plasma, is relatively well understood in the subsonic plasma regime enabled by multi-point magnetospheric missions (Burch et al. 2016). However, understanding both the external conditions leading to thin current sheet formation and the microphysics of magnetic reconnection in the solar wind is lacking. How do these current sheets form and evolve in the inner heliosphere? Which processes lead to de-magnetization and energization of the electrons? What is the structure of thin current sheets in kinetic scales in the solar wind? Is it “electron-only” reconnection or are the ion jets also observed?

B) Currently, the onset of the energy dissipation range and origin of the knee close to the ion-inertial scale in the solar wind magnetic field power spectra is presumed to be due to the damping of the various kinetic plasma wave modes. However, this could potentially also be formed by the reconnection of the thin current sheets in the sub-Alfvénic solar wind structures that would locally satisfy \(V_A > V_{sw}\). The microphysics producing the “knee” in the spectra can only be understood with multi-point measurements at the ion and electron scales.

C) Because solar wind is magnetized fluid, it is surprising that the inertial range spectral index satisfies the hydrodynamic Kolmogorov scaling with a slope of -5/3 (Kolmogoroff 1941). In MHD, oppositely propagating fluctuations can give rise to a turbulent energy cascade due to the non-linear interactions. If a strong magnetic field is applied, the cascade is suppressed in the direction of the magnetic field and one would expect the -3/2 power law (Kraichnan 1965). Multi-scale constellation in the solar wind capturing flux tube boundaries as well as plasma within individual flux tubes is required to test whether the turbulence within the flux tubes is actually satisfying the -3/2 power law.

Science Objective 2: Advanced determination of the solar wind and IMF structure and energetic particle dynamics.

A) Often, the first sign of a CME hitting the Earth environment is the plasma density jump due to the shock wave created by the CME. Coronagraph images are used to estimate the size, speed, direction, and density of a CME, and whether CME might hit the Earth. In order to predict the CME geo-effectiveness the estimates of the magnetic field are crucial. At the present time, magnetic field cannot be directly determined until it is measured by a monitoring satellite when CME passes over it. Multi-spacecraft constellations at the orbits of Mercury and Venus and their respective Lagrange points would provide direct IMF and solar wind plasma measurements to estimate the IMF orientation and plasma properties at Earth with \(\sim 1-2\) day warning, as well as help predict CME severity and dynamics. Because CME angular width typically...
varies from 20-70 degrees, it is possible, using scale-optimized constellations at Venus and Mercury orbits (and their Lagrange points) to capture the same CME both at Mercury and Venus orbits and determine their structure in the inner heliosphere.

B) Understanding the conditions leading to current sheet formation in the solar wind and resulting magnetic reconnection in the solar wind is also important because it can result in the topological changes of the large-scale magnetic field in the solar wind flux tube boundaries affecting propagation of the Solar Energetic Particles (SEPs) through the heliosphere. Future manned missions to the Moon and Mars require better forecasting capabilities of the SEP dynamics in order to limit radiation exposure on astronauts.

References


