Multi-Point Compositional Measurements of Solar Wind and Transient Phenomena

White paper for the Heliophysics 2050 workshop

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Motivation: Since the start of space exploration in the 1960s, solar probes have measured solar plasma on a multitude of spatial and temporal scales at several locations around our solar system, both remotely and in situ. However, we still lack a fundamental understanding of the transfer of energy between the Sun and the surrounding heliosphere. There are still unanswered questions pertaining to processes are driving the release, heating, and acceleration experienced by the solar wind and transients. For more details on these specific questions, see white paper by *Viall et al.* In this paper, we argue that to effectively address these questions, **it is absolutely critical that we understand the evolution of the plasma between the Sun and the heliosphere**. **However, one of the largest inhibitors to the progress in this area is our inability to definitively connect remote and in situ plasma measurements.**

Background: Many studies have indicated that chemical and ion composition hold important clues to deciphering the energization of the solar wind. This is due to the wealth of information that densities of numerous/multiple ions can provide about the origin and radial evolution of the plasma. For instance, as a consequence of the first ionization potential (FIP) effect, which preferentially enhances low FIP elements in different plasma structures at the Sun above their photospheric abundances, different solar regions have contrasting elemental fractionation patterns. This FIP effect is imprinted on the emanating solar plasma in its chemical composition, **therefore the composition of plasma is a strong indicator to its solar source.** Furthermore, the plasma's ion composition can be examined to indirectly determine the plasma's thermodynamic evolution as it accelerates from the Sun. The ion densities measured by ion mass spectrometers in the heliosphere are a direct product of ionization and recombination processes in the low corona; therefore**, charge state distributions can serve as sensitive diagnostics to temperature, density, and acceleration to quantify the energy deposition during the solar wind's propagation away from the Sun.**

The kinetic properties of heavy ions can also provide a unique window to signatures of the heating and acceleration mechanism(s) in the solar plasma. For instance, velocity distribution functions (VDFs) of ions observed in situ and remotely, through spectral profiles, can provide clues of non-thermal processes, such as wave-particle resonances, that develop during radial evolution that can inform on the governing processes taking place (Cranmer et al 2017 and references therein). For example, ion cyclotron heating is a leading theory aimed at explaining the apparent quasi mass-per-charge dependency observed in the temperature and velocities near the Sun and in the solar wind (Landi and Cranmer ApJ 2009, Berger et al PRL 2011). **However, it remains unclear where, when, and how these properties arise during the radial flow, and if all solar wind types and transients behave in the same manner.**

Current missions are attempting to close this gap, but they lack the spatial and continuous coverage of ion measurements needed to address these open questions. Parker Solar Probe (PSP) is flying through the outer tendrils of the corona to take in situ measurements, however it lacks a plasma composition instrument capable of resolving heavy ions that is vital to understanding solar wind release and energization. Solar Orbiter does carry a composition payload (the Solar Wind Analyser (SWA)), but is limited by its orbit which only reaches 0.28 AU, and by the fact that it provides only single point measurements at these distances. It will not reach the same proximity to the Sun as PSP which leaves a critical gap in our measurement space and understanding. While Solar Orbiter SWA will provide local solar wind properties and Solar Orbiter SPICE will take spectroscopic observations of the Sun, these two instruments will still suffer from the same problems we face in linking remote and in situ observations as they do not observe the same elements and are not in the appropriate configuration to be effectively linked.

Overarching goals for 2050

Continuous 4π coverage of compositional measurements to study plasma between the Sun and heliosphere. For a comprehensive understanding of the solar wind's method of release and its energization, it is critical to make continuous, long-term compositional measurements between the Sun and the interplanetary medium. The Sun operates at a large range of time and spatial scales, from characteristic timescales of wave-particle interaction to the 11 year solar cycle and beyond, all of which are important to build a global picture of the Sun and associated solar processes. However, up to the present, there is only a small window, limited opportunities, and restricted to ecliptic-based measurements (until Solar Orbiter climbs to higher latitudes) in which solar observatories assemble into a configuration where plasma emerging from the limb, in the perspective of one instrument, can be sampled with instruments orbiting the Sun. The infrequent manner in which this configuration occurs inhibits an in-depth temporal analysis of regions on the Sun to examine trends and signatures that develop during the plasma's radial evolution. The lack of such observations has delayed serious progress in understanding how the solar wind emerges from different regions of the Sun, as well as a comprehensive understanding of kinetic processes taking place during its radial expansion.

In addition, coronal mass ejection (CME) studies are even more restricted due to this issue. Given their sudden and unpredictable release and rapid liftoff from the eruption site, they are largely missed by slit spectrometers pointed at the Sun and, if captured at the Sun, are often not in the appropriate configuration for instruments in the heliosphere to sample the ejecta in situ. Furthermore, if measured in the heliosphere, the lack of multi-point measurements inhibits a comprehensive sampling of its 3D structure. This limitation has hindered significant scientific progress in understanding the mechanism responsible for supplying the energy that heats and accelerates the CME plasma, as well as addressing the role of heating and scarcity of spatial sampling in the absence of low ionized filamentary material measured in the heliosphere (Lepri et al ApJ 2010). This limitation can be largely minimized by providing continuous coverage of the solar limb with an accompanied in situ instrument in a quadrature configuration. For instance, observations of the full corona with imagers that can resolve individual spectral lines, similar to future UCoMP (Landi et al JGR Space Physics 2016), can provide measurements that enable sensitive calculations of plasma and compositional properties along with the spatial coverage to capture the plasma evolution beyond the surface. Additionally, in situ instruments can further investigate the ion and chemical composition of plasma to explore processes occurring throughout its propagation from the Sun by connecting these measurements with nonequilibrium ionization modeling (Landi et al ApJ 2012, Rivera et al ApJ 2019a, ApJ 2019b).

Dedicated and complementary remote and in situ measurements that can be meaningfully compared. Measurements of the same element and charge states are required at the Sun and the heliosphere to effectively study and connect solar wind streams to source regions. The manner in which composition is measured at the Sun is through the intensity ratio of a high FIP and a low FIP ion with the same, or similar, formation temperature such that each line is assumed to be formed in the same manner. This poses limitations to the available elements that can be used in this method given that instruments observe a specific waveband which does not always contain emission from the same elements as those observed by compositional instruments in the heliosphere. For instance, Sulfur has been identified as a sensitive diagnostic of fractionation processes occurring at the Sun which can provide a distinctive signature to the magnetic topology and possible release of the emerging plasma (Laming et al ApJ 2019). However, it is difficult to determine the heliospheric densities of Sulfur ions with certainty with current time-of-flight mass spectrometers because the ions have time-of-flight and energies that are close to those of Mg, Si, and Fe, making it difficult to cleanly separate their contributions. However, in remote observations, the S X to Si X high to low FIP ratio is routinely used to determine composition of structures at the Sun. This means that we are unable to meaningfully compare the chemical composition of emerging plasma to its counterpart in the heliosphere. This serious mismatch of available measurements between the remote and in situ communities can lead to significant ambiguities and misinterpretation in scientific results. **Therefore, there is a critical need for complementary measurements between the Sun and heliosphere to properly connect and study these regions.**

By 2050, we need to be able to connect these regions of the Sun effectively, which will include both tracking parcels across all properties better (see white paper by *Mason et al*), but should also include innovative remote and in situ techniques and technologies to enable definitive tracking. This could include new spectroscopic instruments, leveraging machine learning, adopting new Heliophysics mission concepts such as that used by the Cassini-Huygens probe which intentionally maneuvered an end-of-mission dive into Saturn's atmosphere to gather data, as well as technology to that enable continuous 4π coverage of the Sun.

Current State	Needed observations	Desired state 2050
Primarily Sun-earth line remote and in situ instruments that inhibit a meaningful link between emerging plasma and its heliospheric counterpart	Continuous and long-term 4π observations of ion composition. Ability to meaningfully compare remote and in situ measurements of ion and chemical composition to investigate thermodynamic and kinetic properties of solar plasma	Ability to map parcels of solar wind and transients between their release at the Sun and their propagation into the heliosphere and to use measurements of ion and chemical composition to to address long standing questions on the release and energization of solar plasma.