How *Firefly* Would Advance Our Understanding of the Solar Wind

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Synopsis

The proposed *Firefly* mission consists of two spacecraft orbiting the Sun at high heliolatitudes and two spacecraft orbiting close to the ecliptic plane [46]. Each spacecraft will carry telescopes capable of measuring the photospheric magnetic field, as well as instrumentation that will provide in situ measurements of the solar-wind plasma and solar-wind magnetic field. *Firefly*'s 4π-steradian measurements of the photospheric magnetic field will make it possible to reconstruct the global magnetic field within the heliosphere with unprecedented accuracy, including the source regions of the solar wind within the solar atmosphere and corona. *Firefly*'s in situ measurements will provide additional observational constraints for testing and refining this global magnetic-field reconstruction. These new observations will lead to major advances in our ability to understand and model the solar wind.

1 The Current State of High-Heliolatitude Observations

In 1990, ESA and NASA launched *Ulysses*, a spacecraft that revolutionized our understanding of the global structure of the solar wind. Like the proposed *Firefly* mission, *Ulysses* probed the high-latitude solar wind. However, unlike *Firefly*, *Ulysses* was unable to remotely observe the photospheric magnetic field near the Sun's poles, which remains a key hole in our observational picture of the coupled coronal/solar-wind system. Over a series of polar passes around the Sun, *Ulysses* revealed that most of the time the majority of the volume of the heliosphere is filled by solar wind flowing at $700 - 800$ km s^{-1}, speeds that greatly exceed the speeds of $300 - 400$ km s^{-1} that are typically seen near the ecliptic plane. *Ulysses* also provided a detailed description of the bulk properties of the high-latitude solar wind as well as the turbulent magnetic fluctuations that pervade the heliosphere.

2 How *Firefly* Will Advance Observations of the Solar Magnetic Field

Traditionally, observations of the photospheric magnetic field have been limited to the field of view seen from Earth. These observations suffer from two important shortcomings. First, only half of the solar surface can be imaged from Earth at any one time. Yet, to reconstruct the magnetic field within the solar atmosphere and solar wind, one needs to the know the photospheric field over the entire surface of the Sun, and thus the magnetic field on the far side of the Sun has to be guessed (e.g. from previous observations using an assumption that the magnetic field is unchanging in a frame that rotates with the Sun's average angular velocity). Second, the accuracy of these magnetic-field measurements decreases towards the solar limb, and thus there is a large observational uncertainty surrounding the magnetic field near the Sun's poles.

The *Solar Orbiter* spacecraft, launched by ESA and NASA in 2020, will eventually reach an orbit that is inclined by approximately 30° with respect to the ecliptic. *Solar Orbiter*'s Polarimetric and Helioseismic Imager (PHI) will measure the photospheric magnetic field from *Solar Orbiter*'s vantage point and will thus mitigate some of the aforementioned shortcomings. However, even with *Solar Orbiter*, we will still be unable at any given time to measure the magnetic field near both of the Sun's poles.

In contrast, *Firefly*'s four spacecraft will provide near-continuous 4π-steradian observations of the dynamically evolving photospheric magnetic field. These observations will provide the critical inner boundary condition that drives solar-wind models and solar-magnetic-field models. The increased accuracy with which we can determine this inner boundary condition will help solve critical unsolved problems in solar-wind science, as discussed further below.

3 The Current State of Theoretical Modeling of the High-Heliolatitude Fast Solar Wind

Data from *Ulysses* and in-ecliptic missions such as *Helios*, *SOHO*, *Wind*, *ACE*, and *Hinode* have spurred tremendous progress in our understanding of how the Sun launches the solar wind. Remote observations of the solar corona combined with in situ measurements of the solar wind and numerical and theoretical modeling have led to a growing consensus that the fast solar wind emitted by the Sun's polar coronal holes is driven to a large extent by an energy flux of Alfvén waves. This idea was first proposed by Parker in 1965 [43] and subsequently elaborated upon by many authors, including [14, 16, 17, 19, 25, 40, 51, 52, 53, 57, 59]. At present, the leading version of this model proceeds through four stages, which are illustrated in Figure 1.

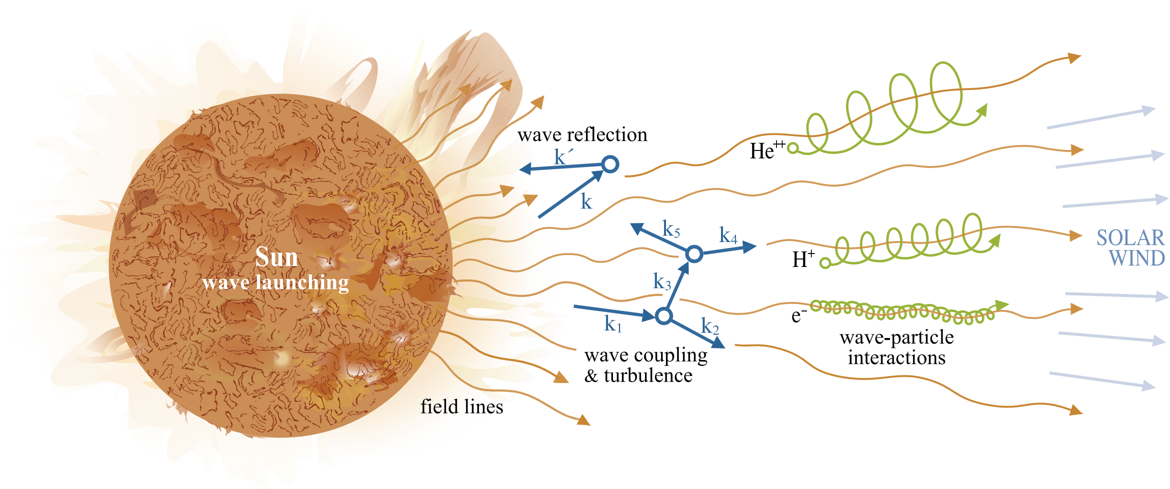

Figure 1: Four stages of fast-solar-wind generation: (1) wave launching and outward energy transport, (2) wave reflection and turbulent energy cascade, (3) dissipation of turbulence, causing coronal heating and solar-wind heating (4) acceleration of the solar wind by thermal pressure and wave pressure.

In the first stage, some process on the Sun, such as photospheric motions or reconnection, launches Alfvén waves that propagate out through the solar atmosphere. These waves carry an outward energy flux that is the dominant element of the energy budget of the fast solar wind [2, 7, 16].

In the second stage, these outward-propagating Alfvén waves partially reflect, producing a mix of counter-propagating Alfvén waves. This partial reflection occurs in part because of the phenomenon of non-WKB reflection, which refers to the reflection process that arises when the radial wave lengths of the Alfvén waves become an appreciable fraction of the radial scale length of the background solar wind [25, 56]. In this limit, the Alfvén speed at one end of a wavelength is appreciably different from the Alfvén speed at the other end, and an Alfvén-wave packet that is initially traveling away from the Sun "excites" Alfvén waves that propagate back toward the Sun [29]. Observations of the motions of magnetic bright points on the solar photosphere [16], spicule motions in the low corona [18], Faraday-rotation fluctuations of linearly polarized radio transmissions from the *Helios* spacecraft [26], and in-situ Alfvén-wave-like motions in the solar wind [5] indicate that much of the power in Alfvén-wave-like fluctuations is at periods of several minutes to hours. Given the large Alfvén speeds in the corona and near-Sun solar wind, these long periods translate into large radial wavelengths, making non-WKB reflection an efficient process [10, 19, 44, 54]. Additional inward-propagating Alfvén waves can be produced by other processes, such as parametric decay [13, 24] and Kelvin-Helmholtz instabilities triggered by velocity shear [48].

In the third stage of solar-wind generation by Alfvén waves, counter-propagating Alfvén waves interact nonlinearly to produce turbulence [32, 36]. This turbulence causes wave energy to cascade from large scales to small scales (i.e., large wavelengths to small wavelengths). Although Alfvén waves at large scales undergo negligible dissipation, the small-scale fluctuations produced by the turbulent cascade dissipate rapidly via a number of different mechanisms, such as stochastic heating [6, 8, 11, 21, 39, 41] cyclotron heating [28, 33, 35, 49], and Landau and transit-time damping [30, 31, 37, 45, 50].

In the final stage of solar-wind generation, the dissipation of turbulence raises the coronal temperature to $\gtrsim 10^6$ K, thereby increasing the density scale height and loading a large amount of plasma into the corona all the way out to the sonic critical point at a heliocentric distance r of several solar radii $R_{\rm s}$. At $r \sim R_{\rm s}$, the Sun's gravity loses its grip on the plasma and is unable to prevent the plasma from expanding rapidly outward into the interplanetary medium, as first described by Parker in his pioneering 1958 paper proposing the existence of the solar wind [42]. The outward force exerted on the plasma by the radial gradients in the plasma pressure and wave pressure further accelerate the outflow, enabling the wind to reach speeds of $700 - 800$ km s^{-1} [17, 58].

This general picture, which is rooted in the early work of Parker [43] and Coleman [14] and which has been refined by many authors, is supported by a large array of observations and modeling results. Remote observations of the corona from the *Hinode* telescope have revealed a pervasive field of Alfvén-wave-like motions in the corona that carry an energy flux sufficient to power the solar wind [18]. The aforementioned measurements of Faraday rotation of linearly polarized radio transmissions from the *Helios* spacecraft demonstrated that the amplitudes of the magnetic-field fluctuations at $r = 2 - 18 R_{\rm s}$ were consistent with the amplitudes required to power the solar wind in Alfvén-wave-driven solar-wind models [27]. Measurements from *Parker Solar Probe* and *Helios* show that the amplitudes of Alfvén-wave-like fluctuations in the solar wind are consistent with the amplitudes that are found in Alfvén-wave driven solar-wind models [12, 16]. Alfvén-wave-driven solar-wind models are also consistent with numerous additional solar-wind observations, including the radial profiles of the plasma density, electron temperature, proton temperature, proton temperature anisotropy, and outflow velocity [7, 17, 59, 51, 55].

4 Critical Unsolved Problems, And How *Firefly* Will Help Solve Them

Although the community has made substantial progress in its understanding of the mechanisms that generate the fast solar wind, a number of important unsolved problems remain. We describe several of these here, and discuss briefly how *Firefly* would help solve these problems.

4.1 To What Extent Does the Wave-Turbulence Model Explain the Slow Solar Wind?

Several studies have conjectured that the wave-turbulence paradigm discussed in Section 3 can explain not only the fast solar wind but the slow solar wind as well [9, 15, 17]. For example, [9, 17] investigated how the asymptotic solar-wind speed U_∞ (i.e., the wind speed far from the Sun) depends upon the the super-radial expansion factor $f_{\rm max}$ of the magnetic field within the coronal source region of a solar-wind stream. The models developed by these authors were reasonably successful at explaining the dependence of U_∞ on $f_{\rm max}$ observed near Earth [60]. This success supports the notion that slow solar wind is produced by an Alfvén-wave energy flux much like the fast solar wind, but on flux tubes that undergo more superradial expansion in the corona.

This notion is also supported to some extent by observations from *Parker Solar Probe* (PSP), which has found that 'Alfvénic slow wind' is common in the near-Sun solar wind close to the ecliptic plane. This type of wind shares many properties with the fast solar wind originating from the Sun's polar coronal holes, such as the dominance of outward-propagating Alfvén waves over inward-propagating Alfvén waves and a comparatively large helium abundance [4, 12, 34]. Mapping of these solar-wind streams back to the Sun shows that they typically originate in small, low-latitude coronal holes [3].

However, other considerations suggest that the slow solar wind cannot, at least in its entirety, be explained via the wave-turbulence paradigm. For example, PSP, *Helios*, and other spacecraft commonly measure non-Alfvénic slow solar-wind streams with properties that are very different from those of fast solar-wind streams. Also, although theoretical models are able, as mentioned above, to explain the dependence of U_∞ on $f_{\rm max}$ observed in the ecliptic, they struggle to explain this dependence while at the same time explaining the dependence of U_∞ on heliolatitude observed by *Ulysses* [17].

In order to clarify which types of solar-wind streams can be explained by the wave-turbulence paradigm, it is essential to reduce the uncertainty surrounding the magnetic field in the solar-wind source region (i.e., within the chromosphere and corona). The magnetic field in these regions has a large effect on the properties of the asymptotic solar wind, but our knowledge of this magnetic field is limited, particularly in the source regions near the Sun's poles that feed the high-heliolatitude fast solar wind. Uncertainties in the solar magnetic field translate into a larger freedom to adjust model parameters to match the observations. By reducing uncertainties in the solar magnetic field, *Firefly* will pin down the parameters in wave-turbulence solar-wind models to a greater degree than has previously been possibly, which will lead to a significant advance in our ability to determine exactly which types of solar wind are driven by an Alfvén-wave energy flux.

4.2 What Other Mechanisms Power the Slow Solar Wind?

An important question related to the preceding subsection concerns the generation mechanism for slow solar-wind streams that are not driven by an Alfvén-wave energy flux. Several generation mechanisms have been proposed, including interchange reconnection near the boundaries of coronal holes [22, 23], and eruption or instability of the tops of closed loops [20, 47], possibly arising at a complex web of locations at the Sun [1]. The solar magnetic field is the critical ingredient in all of these models, and the improved magnetic-field measurements from *Firefly* will lead to major improvements in our ability to test these and other models.

4.3 The Open-Flux Problem

Reconstructions of the heliospheric magnetic field based on observations of the photospheric magnetic field systematically underestimate the strength of the radial magnetic field in the distant solar wind, or, equivalently, the amount of magnetic flux contained within each hemisphere of the heliosphere [38]. This discrepancy could indicate that current observatories significantly underestimate the magnetic field in the Sun's polar regions, which are magnetically connected to bulk of the volume of the heliosphere near solar minimum. Alternatively, it is possible that regions on the Sun that are not currently thought of as solar-wind sources are in fact magnetically connected to the solar wind, thereby enabling such regions to contribute substantial magnetic flux to the heliosphere that is not captured in existing models. *Firefly*'s 4π-steradian imaging of the photospheric magnetic field is precisely what is needed to solve this problem.

4.4 Improving the Fidelity and Predictive Power of Physics-Based Numerical Solar-Wind Models

A major goal of heliospheric physics is to develop first-principles, physics-based numerical models of the global solar wind that are driven by observations of the Sun. Such models are highly desired from the point of view of space-weather prediction, as an accurate global solar-wind solution is needed in order to accurately model the propagation of coronal-mass-ejection shocks and solar energetic particles from the Sun to the Earth. Such models also offer a means for the heliospheric-physics community to make a major contribution to the field of astrophysics. In heliospheric physics, we can use a wealth of in situ and remote observations to test and refine the ways that our global models treat the physical processes (such as turbulence, magnetic reconnection, and wave-particle interactions) that give rise to coronal heating and solar-wind generation. These same physical processes play a role in more distant astrophysical systems, but we lack detailed observations of such systems.

However, if we can learn how to describe these physical processes accurately within the heliosphere, then we can use this knowledge to build better physics-based models of outflows from distant astrophysical objects, such as red-giant stars and black-hole accretion disks. *Firefly*'s observations of the photospheric magnetic field would enable us to drive global solar-wind models with correct time-dependent inner boundary conditions, leading to much more rigorous tests of these models, including their treatments of microphysics, such as turbulence and turbulent heating. These tests would in turn lead to significant improvements in our modeling capabilities.

Summary

Firefly's nearly continuous 4π-steradian measurements of the photospheric magnetic field would have a transformative impact on our understanding of the magnetic field within the solar atmosphere and solar wind. *Firefly*'s observations would enable us for the first time to gain an accurate picture of the different magnetic-field properties that prevail across the full spectrum of solar-wind source regions, including the Sun's polar coronal holes. These observations will help solve several important problems in heliospheric physics and move the community substantially closer to one of its longstanding goals: to develop rigorously tested, first-principles theories and models of the solar wind that can be used to predict space weather as well as understand plasma outflows elsewhere in the universe.

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