Observations and modelling of the solar wind composition variations

Alexis P. Rouillard, Nicolas Poirier, Paul Lomazzi, Simon Thomas, Victor Réville, Bahaeddine Gannouni, Simon Thomas, Jean-Baptiste Dakeyo, Pierre-Louis Belly, Michael Lavarra, Naïs Fargette, Léa Griton, Philippe Louarn, Benoit Lavraud, Vincent Génot

IRAP, Université Toulouse III - Paul Sabatier, CNRS, CNES, Toulouse, France, *Email: alexis.rouillard@irap.omp.eu

The origins and release mechanisms of stellar winds are long-lasting open challenges in astrophysics. Stellar winds play a fundamental role in the long-term evolution of stars and the habitability of their orbiting planets. In the solar case, the wind is observed in at least two states, fast and slow winds, that differ in their bulk properties and composition, pointing to different coronal origins. A theoretical explanation for the slow wind must explain both its variable bulk properties and its peculiar composition. This includes the measured high charge states of minor ions, the abundance variation of Helium during the solar cycle and the high abundance of elements with low first ionisation potential (so called FIP effect) reaching four times the photospheric abundance. SLOW SOURCE is a comprehensive research project that exploits the revolutionary data taken by Parker Solar Probe and Solar Orbiter as well as completely novel models of the solar atmosphere to determine the origin of the slow wind. We are developing new plasma transport models coupling major and all known important minor constituents along realistic coronal magnetic field lines. Combined with data from space and ground-based observatories, these new multi-species, multi-temperature 3-dimensional modelling of coronal plasma provide ways to infer the properties of stellar winds and tools to study the fundamental transport and heating processes of stellar plasmas.

I. Observations of solar wind composition (Charge state and FIP effect)

Varying source temperature: The charge state of solar wind heavy ions such as O or C is set in the collisional part of the solar corona and is strongly dependent on the local electron temperature, **it therefore provides important information on the temperature at the source region of the solar wind**. Figure 1 shows the inverse relation between charge state and the solar wind speed indicating greater heating at the source region of the slow wind. We observe significant variability in charge state values for a narrow range of wind speeds and over short time intervals.

=> What drives these highly variable heating conditions?

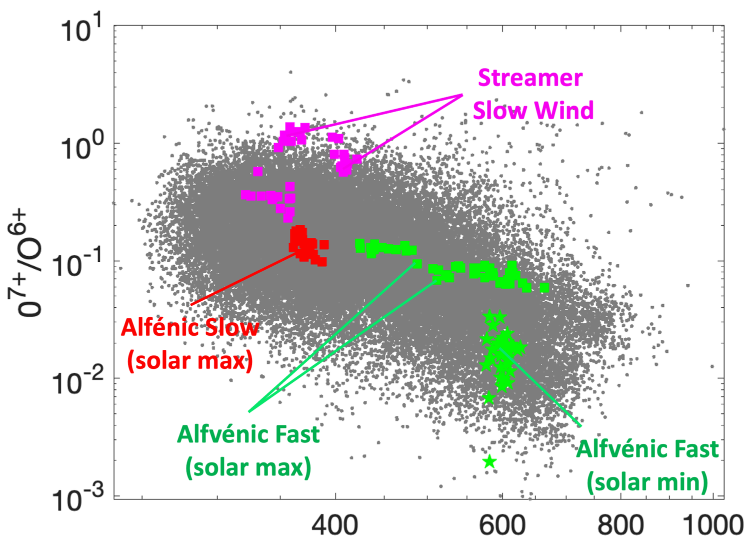

Figure 1: Ionic charge state of Oxygen measured by the Advanced Composition Explorer (ACE) versus the measured solar wind bulk velocity (V, km/s). In color: solar wind intervals of Aflvénic slow and fast solar winds and of the weakly Alfvénic slow wind from the streamer belt (Rouillard et al. 2024).

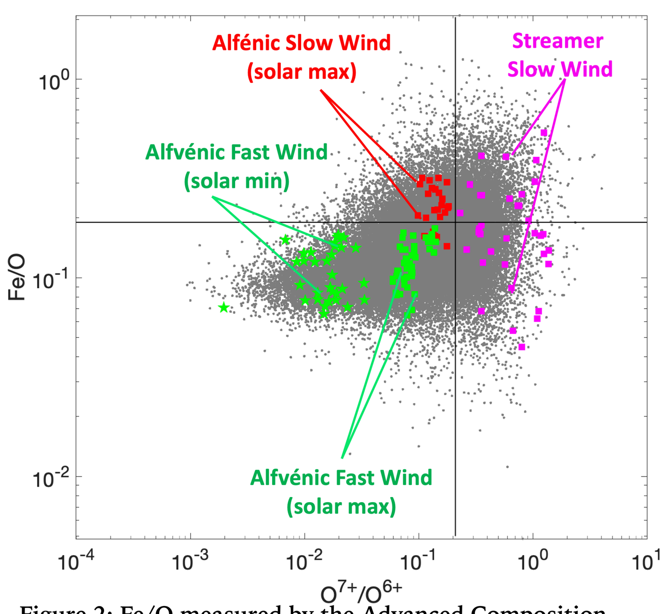

Figure 2: Fe/O measured by the Advanced Composition Explorer (ACE) versus the measured Oxygen charge-state ratio. In color: solar wind intervals of Aflvénic slow and fast solar winds and of the weakly Alfvénic slow streamer belt winds (Rouillard et al. 2024).

Varying composition: The mechanisms that regulate the abundance of heavy ions in the solar wind are highly debated. Figure 2 illustrates the well-known property that the slow wind can transport higher ratios of Fe/O than the fast solar wind.

While the fast (red squares) and slow solar wind (green squares) can have similar coronal source temperatures when they have similar levels of Alfvénicity (Figure 1), their compositions measured by Fe/O are very different suggesting different chromospheric conditions at their sources.

=> What physical mechanisms control solar wind composition (wave-particle interactions or diffusion processes) ?

II. Can we observe the dynamic mechanisms at the Sun that may control the compositional variations ?

Solar Orbiter and Parker Solar Probe have revealed a highly dynamic solar wind near the Sun consisting of bursts of velocity jets and magnetic field reversals (Figure 5).

In a recent study (Hou et al. 2024) we have exploited the IRAP magnetic connectivity tool to infer the source region of these jets and have analyzed images of the Solar Dynamics Observatory (SDO) to study the possible relation between bursts of micro-solar eruptions (Figure 6) and velocity spikes measured in situ (Figure 5).

We have a remarkable correspondence in the periodicity of surface bright points observed remotely and and velocity jets measured in situ (Figure 7).

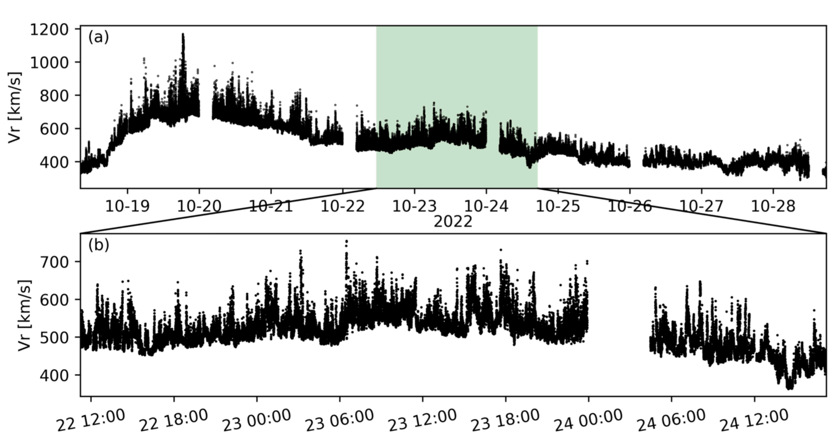

Figure 5: (a) Solar wind radial speed measured by SolO PAS. The green shade region represents a zoom in and has the same time range with panel (b). (b) Zoom in of green shade region.

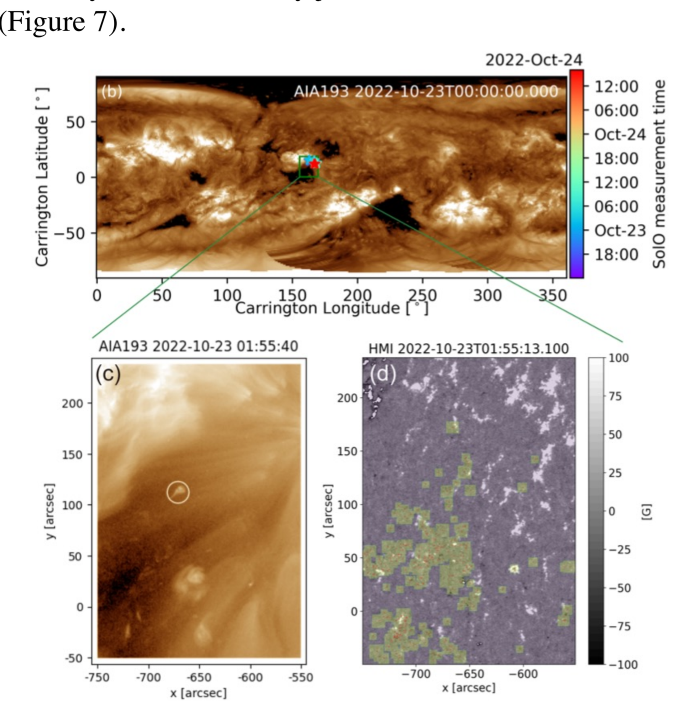

Figure 6: EUV observations taken by the Solar Dynamics Observatory of coronal bright points as

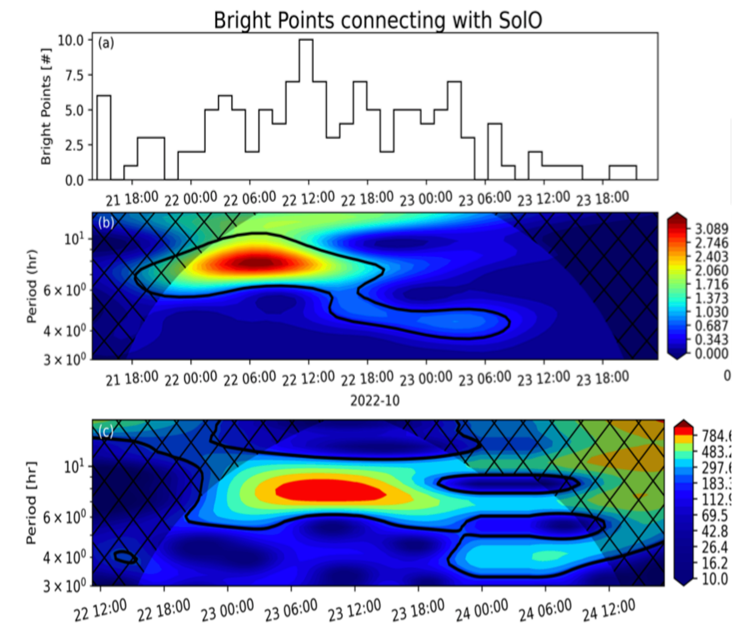

Figure 7: Top panel: number of bright points connected magnetically to Solar Orbiter. Middle panel: wavelet periodogram of bright points counts. Bottom panel: wavelet periodogram of velocity spikes measured in situ (Hou et al. 2024).

III. 2.5-D & 3-D Modelling of Coronal Dynamics

The composition of the solar wind is highly variable suggesting some significant time variability at its source region. Bursts of energy release during these transient phenomena could lead to temperature variations and changes in composition. We have studied the different mechanisms that could potentially explain this variability using full MHD simulations. The 2.5-D MHD model was developed with the PLUTO code by Réville et al. (2020).

We have used the model to study the variability of the slow solar wind coming from streamers and the associated formation of plasmoids and magnetic flux ropes as loop stretch and reconnect near the tip of streamers (see example Figure 3). This process releases plasma that was initially trapped on magnetic loops under streamer cusps through the formation and release of flux ropes. These dynamic processes could explain the high variability of charge states and ionic composition observed in Figure 1 and 2.

To study the variability of electron temperatures at the source of the fast solar wind (Figure 1) and the origin of jets (/switchbacks) we have also carried out some 2.5 MHD simulations of loop emergence inside coronal holes (Figure 4). The simulations of polar plumes reveal the presence of velocity spikes in response to sequences of magnetic reconnection events through the tearing mode instability.

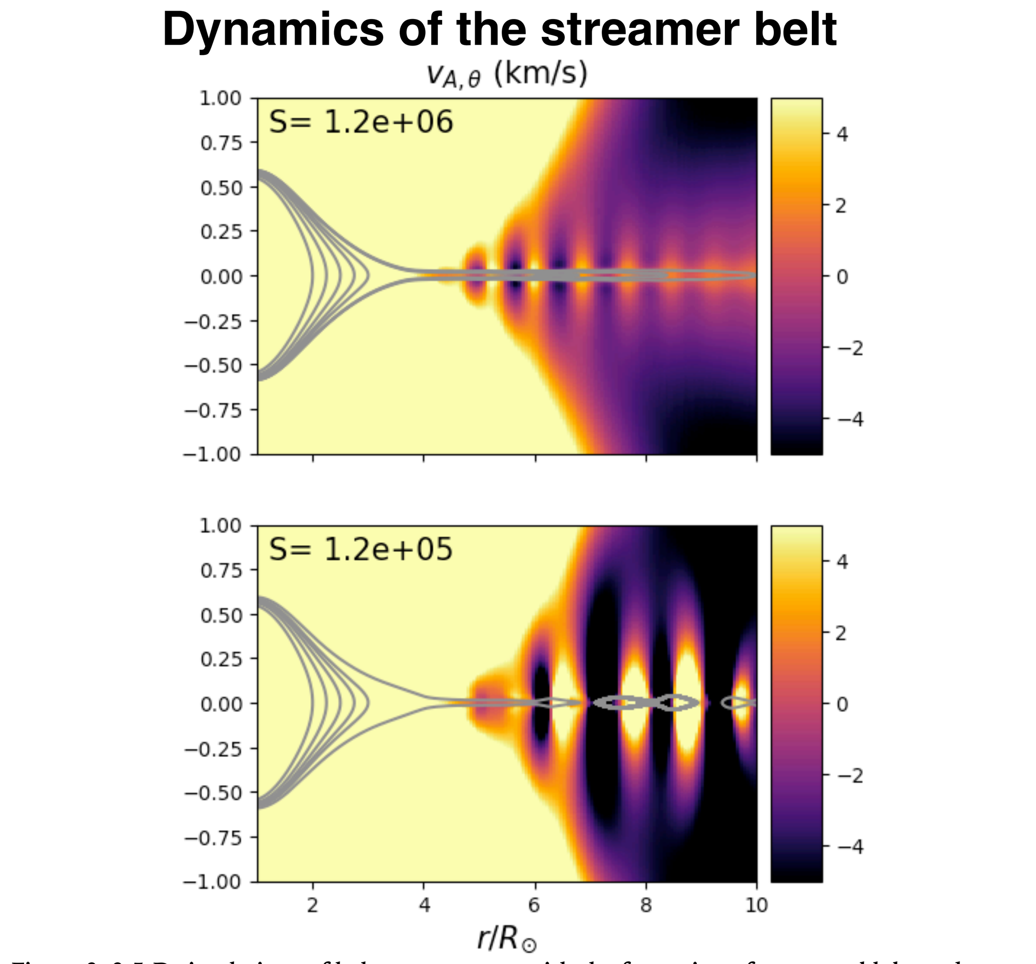

Figure 3: 2.5-D simulations of helmet streamers with the formation of streamer blobs and periodic density structures. The figure displays the onset of the tearing instability (at the end of the linear phase), for S ~10^5 and S~10^5. The tearing mode is easily seen in the transverse component of the magnetic field to the HCS (or here the transverse Alfvén speed v_A,theta). Its wavelength is, as expected, a decreasing function of S (Réville et al. 2021).

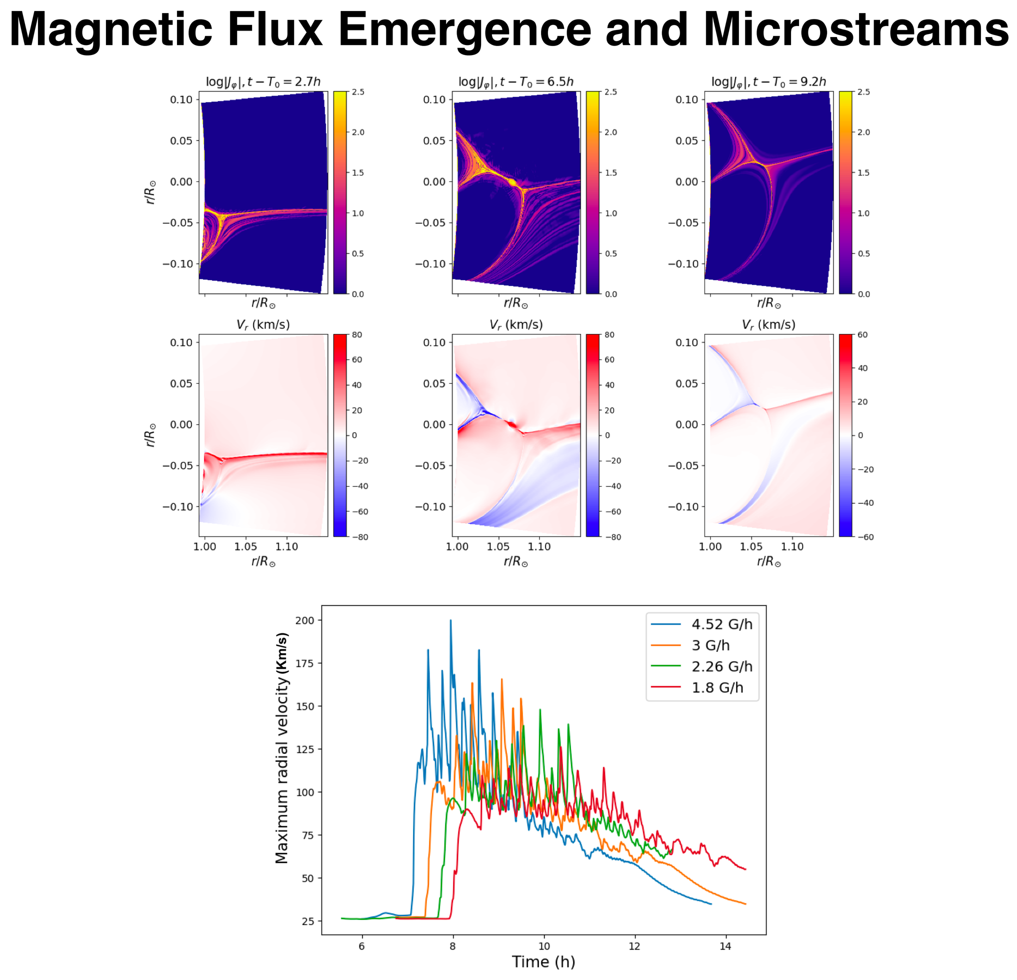

Figure 4 (top) Current sheet evolution during the emergence of magnetic dipole in an otherwise open magnetic field. Logarithm of out-of-plane current (upper row) and radial velocity (lower row) at three time snapshots. (Bottom) the simulated micro stream structure (Gannouni et al. 2024).

IV. Multi-species Modeling of the Solar Wind

To study the transport of heavy ions in the solar atmosphere we developed a new multi-species model, the IRAP Solar Atmospheric Model (ISAM). It is a16-moment kinetic-fluid model that solves for the transport equations (continuity, momentum, energy and heat flux equations explicitly). It derives from the IPIM ionospheric model (Marchaudon and Belly 2016) and the adaptation to the solar corona was achieved during the on-going ERC Slow Source project (Michael Lavarra thesis, 2022, Nicolas Poirier thesis, 2022). See presentations by Paul Lomazzi and posters by Nicolas Poirier and Simon Thomas.

In Figure 8 we show a first application of the model to simulate the fast and slow solar winds and compare to both spectroscopic observations and in situ measurements. For the heating we assume a phenomenological heating characterised by an energy flux and a heating scale height. In this poster we present run results for fast wind. The heating scale height is set sufficiently large to heat the solar wind beyond the sonic point such that the energy deposited is less prone to be lost through downward heat conduction/ radiative cooling but instead accelerate the wind. Heating high also reduces the pressure of the transition region and lowers the mass flux.

We have started exploiting ISAM with fully coupled He, He+, He2+ and heavy ions to study composition variations in the different solar winds.

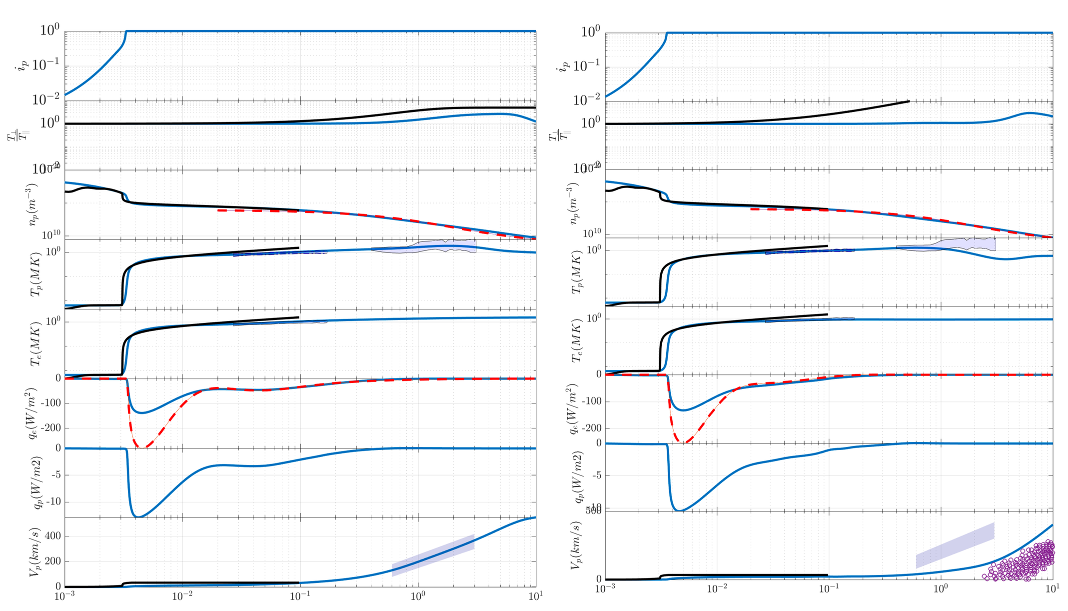

Figure 8: Solar wind parameters from Fast (left) and slow (right) wind simulation. ISAM Density, temperature and velocity profiles (blue line) are compared chromospheric models (Black lines).

Key Results So Far!

- Providing a first explanation to the formation of streamer blobs and quasi-periodic structures in the solar wind as the result of tearing-mode instability developing near the tip of helmet streamers.
- Providing the first link between the occurrence of switchbacks and micro streams with bursts of coronal brightpoints
- Providing an explanation to the varying charge state of heavy ions in the fast and different types of slow solar winds
- Providing self-consistent situations of the the regulation of heavy ion abundances along coronal loops (comparing wave-particle interactions and diffusion processes)
- Proving some first self-consistent simulation of He and heavy ion abundance variations from chromosphere to solar wind.