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Oral
Forecasting the solar wind is undergoing a paradigm shift driven by the fusion of physical models and machine learning. This presentation introduces a comprehensive framework for next-generation solar wind modeling, targeting two critical bottlenecks: the semi-empirical definition of boundary conditions and the computational cost of global heliospheric simulations.

First, we present WSA+, a neural enhancement to the operational Wang–Sheeley–Arge model. By embedding a differentiable physics-constrained pipeline, WSA+ systematically optimizes empirical parameters using in-situ observations. Utilizing a SWIN-Transformer to map magnetogram features to optimized speed maps, this approach yields a 40% improvement in forecast accuracy over traditional WSA. We further discuss the release of an open-source Python package to facilitate community adoption and reproducibility.

Second, we address the scalability of heliospheric propagation using neural operators to emulate 3D MHD plasma dynamics. Traditional MHD solvers, while accurate, are too computationally expensive for large-scale ensembles. Our approach employs a hybrid training scheme combining supervised learning with physics-informed conservation laws. This surrogate model captures complex structures with high fidelity while generating solutions orders of magnitude faster than conventional codes.

This work highlights the transformative potential of ML-surrogates, demonstrating their capability to ensure both physical consistency and computational efficiency. These advancements are crucial for enabling high-resolution, real-time, and ensemble-based space weather forecasting. Furthermore, the fully differentiable nature of the entire pipeline allows for the application of partial or global constraints on solar wind solutions using solar wind observations. This synergy makes the model particularly valuable when integrated with PUNCH observations.
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