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Forecasting space weather drivers and geomagnetic events via physics-based machine learning

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The solar wind, along with solar flares and eruptions, impacts the Earth's magnetosphere, potentially initiating geomagnetic storms that disrupt the near-Earth space environment, with possible severe consequences for human activities and ground- and space-based infrastructures. A branch of solar physics that is gaining increasing attention is Space Weather: it studies how solar-terrestrial interactions affect the geospace environment; specifically, it involves predicting major solar disturbances that can pose significant risks to terrestrial facilities, with potential economic and security implications. Among these, the most energetic and potentially harmful are the Coronal Mass Ejections (CMEs), massive expulsions of magnetized plasma from the solar corona, the outermost layer of the Sun's atmosphere [2]. There is therefore a growing interest in predicting these phenomena well in advance: this talk focuses on forecasting the arrival of CMEs to Earth and the severity of the induced geomagnetic storms. In order to predict the arrival time of CMEs, a physics-driven artificial intelligence (AI) method is proposed, in which physical information is encoded into the neural network training process by including the drag-based model [1,5] in the definition of the loss function [3]. Results from remote and in-situ solar observations have shown that the physics-driven AI approach performs better than a fully data-driven algorithm both in terms of mean absolute error and prediction robustness. To predict the degree of severity of CME-induced geomagnetic storms, i.e., their geoeffectiveness, the problem was instead tackled as a binary classification using recurrent neural networks from time series of solar wind plasma and magnetic field measurements acquired in situ at the L1 Langragian point, 1.5 million km from Earth in the Sunward direction. The inherently unbalanced nature of the classification problem is addressed by using an appropriate loss function that is adapted to automatically optimize a suitable skill score appropriate for evaluating predictions in the case of highly unbalanced datasets [4]. Finally, the importance of the solar wind energy for predictive purposes will be demonstrated in the talk by using a correlation-driven feature selection method to rank the most relevant characteristics involved in the neural network prediction model.

References

1. P. J. Cargill, "On the aerodynamic drag force acting on interplanetary coronal mass ejections", *Solar Physics*, **221**, 135-149, 2004.
2. N. Gopalswamy, "Coronal mass ejections and space weather", In *Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium* (pp. 77-120). Tokyo, Japan: Terrapub, 2009.
3. Guastavino, S., Candiani, V., Bemporad, A., Marchetti, F., Benvenuto, F., Massone, A.M., Mancuso, S., Susino, R., Telloni, D., Fineschi, S., Piana, M., "Physics-driven Machine Learning for the Prediction of Coronal Mass Ejections' Travel Times", *The Astrophysical Journal*, **954**:151 (9pp), 2023.
4. Marchetti, F., Guastavino, S. , Piana, M., Campi, C., "Score-Oriented Loss (SOL) functions", Pattern Recognition, **132**, 108913, 2022.
5. B. Vršnak, T. Žic, T.V. Falkenberg, C. Möstl, S. Vennerstrom, & D. Vrbanec, "The role of aerodynamic drag in propagation of interplanetary coronal mass ejections". *Astronomy & Astrophysics*, **512**, A43, 2010.