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Editorial

Editorial to the Special Issue "Propagation of Coronal Mass Ejections"

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Coronal mass ejections (CMEs) and their associated shocks are one of the main drivers of heliosphere variability, causing both interplanetary and planetary perturbations. Therefore, understanding and predicting their propagation is an extremely important aspect of solar and heliospheric physics and space weather. In recent years, numerous propagation models have been developed by research groups around the world, varying in input, assumptions, and complexity, ranging from simple empirical and analytical models to complex machine-learning and numerical models see reviews by, e.g., [1–4]. By comparison with observations, these models must be evaluated, developed, and even reinvented. On the other hand, understanding and predicting CME propagation also requires reliable observational data. Our current observational capabilities include both remote sensing and in situ measurements at various locations in the heliosphere. Although significant progress has been made in recent years to use these observations for reliable observational input to various propagation models, many challenges remain, e.g., [5]. This Special Issue brings together five original research contributions covering various topics related to CME propagation, including the derivation of relevant and reliable observation-based inputs to CME propagation models and new and advanced modeling efforts.

Riley and Ben-Nun [6] introduced *sunRunner1D*, a new tool for exploring the dynamical evolution of ICME profiles from near the Sun to 5 AU. Although based on a sophisticated astrophysical MHD code (PLUTO), it is a spherically symmetric 1D model launched by a user-friendly Python script. CMEs are modeled with simple pulses, where the model input is the solar wind conditions upstream of the CME (density, temperature, radial velocity, and transverse magnetic field) and the initial CME properties (density, radial velocity, transverse magnetic field, and radial extent, i.e., duration). Riley and Ben-Nun [6] performed four case studies of events representing (a) extreme (Carrington-like) CMEs, (b) overexpanding CMEs, (c) multiple interacting CMEs, and (d) streamer blowout flux rope type CMEs. The simulated profiles generally manage to capture the essential features of ICMEs with significant shock contributions (case studies 1–3), but do not appear to illustrate the dynamics of flux rope-type CME that does not drive the shock, likely related to the nature of CME initiation (using a simple pulse). Nonetheless, sunRunner1D shows its potential for fast and accurate estimates of CME arrival time.

Zhang and Feng [7] developed a new solar wind model by applying a novel third-order numerical method based on a divergence-free finite volume scheme to solve the MHD equations. The model uses a "classical" set of initial and boundary value conditions based on Wilcox Solar Observatory (WSO) synoptic magnetograms and potential field source surface (PFSS) model of the coronal magnetic field with a source surface height of 2.5 R_{SUN}. These are complemented by plasma properties based on the initial density, pressure, and velocity distributions of the Parker solar wind flow. Zhang and Feng [7] tested the model on Carrington rotation 2207 (period from 6 August to 2 September 2018) and obtained stable numerical results that could simulate typical solar wind structures at

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solar minimum. The results were compared visually with LASCO/C2 observations and with in situ measurements back-mapped to 20 R_{SUN} using a ballistic approximation. Good agreement was found between the model and the observations, albeit with some discrepancies. Nevertheless, this study represents a promising first step toward the development of a new 3D MHD heliospheric model.

Belov et al. [8] performed an observational study of the dependence of CME transit speed and transit time on initial CME properties. They analyzed 288 CMEs associated with solar flares from 1995 to 2020 and found that the CME transit speed and transit time depend on the initial CME velocity and on the longitude of the solar source. Based on their results, they propose a simple empirical model that is already in operational use by daily forecasters at the IZMIRAN Space Weather Prediction Center. The model has yet to be extensively tested on a large statistical sample and compared with other forecast models, but its simplicity and computational efficiency make it a promising first-alert space weather tool.

Zhou and Feng [9] used a 3D numerical magnetohydrodynamics (MHD) simulation 3D SIP-CESE, to study the propagation and interaction of three halo CMEs. The CMEs originate from the same active region on 4–5 November 1998, and are later detected in situ at Earth in immediate succession, with the first CME compressed, followed by a complex structure formed by the merger of the second and third CMEs. The CMEs are modeled as simple spherical plasmoids and initiated consecutively in the simulation to better isolate the contribution of individual CMEs to the final simulation results and the effects of CME-CME interactions on the propagation of the isolated CMEs. The results are consistent with observations indicating the merging of the second and third CMEs, changing their morphology, kinematics, and magnetic structures. Moreover, the consecutive inclusion of the CMEs clearly shows the influence of the preconditioning of the interplanetary space on the propagation of the CMEs.

Zhong et al. [10] analyze the locations of source regions and the propagation direction of 71 Earth-impacting CMEs from mid-2008 to the end of 2012. They analyze the CME parameters derived based on the 3D CME reconstruction with the Graduated cylindrical shell (GCS) model. They find that the majority of the Earth-impacting CMEs originate from the [30S,30N] x [40E,40W] region on the solar disc, where the CME half-width includes the central meridian. This results in an empirical rule for determining whether the CME will impact the Earth. In addition, a negative correlation is found between velocity and acceleration, and propagation time is inversely proportional to velocity. This results in an empirical rule for determining when the CME might reach the Earth. Based on the results, an empirical model is constructed and compared with a drag-based model of CME propagation, which provides promising results for future applications.

The studies presented in this Special Issue also highlight some of the problems associated with the propagation of CMEs, such as the need for computationally efficient forecast models [6,8,10], understanding and modeling complex CME-CME interactions [6,9], the importance of stable and reliable heliospheric modeling at quiet times [7], and preconditioning of interplanetary space [9]. These challenges should be addressed in the coming years to better understand and thus predict the propagation of CMEs.

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