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(Research Article)

Investigation of Solar Events Propagation in the Interplanetary Space

Sabri, S.[1] ✉ | Poedts, S.[2,3]

1. Department of Space Physics, Institute of Geophysics, University of Tehran, Tehran, Iran.
2. Department of Mathematics, Center for mathematical Plasma Astrophysics, Leuven, Belgium.
3. Institute of Physics, University of Maria Curie-Skłodowska, Lublin, Poland.

Corresponding Author E-mail: s.sabri@ut.ac.ir

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Abstract

Coronal Mass Ejections (CMEs), large-scale eruptions of plasma and magnetic field from the solar corona, have been detected as for a cause of significant space weather effects. Fundamental research on solar events complexity variations from the solar corona to 1 AU and beyond is critical to our physical understanding of the evolution and interactions of transients in the inner heliosphere. In the nonhomogeneous background solar wind flow, a three-dimensional, time-dependent numerical magnetohydrodynamic (MHD) model is considered to study the propagation of CMEs and their interaction with the background solar wind structures. A comprehensive analysis of the period from 2 to 8 June 2023, considering the complex structure, is investigated. This study addresses the need to explore the interplanetary evolution of CMEs and especially their complexity in the inner heliosphere. To analyze the accurate impact of the solar event on Earth, the Disturbance Storm Index (Dst) calculated by the numerical EUHFORIA code, is shown and verifies a calm phase followed by a mild disturbance from 2 to 8 June 2023. In summary, it is found that CMEs that occurred between 2 and 8 of June 2023, which were not significant and lacked considerable height time development, did not experience any increase during the propagation in the interplanetary space. Overall, it is found that EUHFORIA demonstrates the potential to investigate and even predict geomagnetic storms. This enables us to protect our technologies from the enormous financial damage of solar storms.

Keywords: Space-weather, EUHFORIA, Magnetohydrodynamic, CME, Solar wind, Interplanetary space, Dst, Geomagnetic storms.

1. Introduction

Different factors define space weather, such as eruptions at the Sun and their propagation from the solar corona to the planets and satellites in the inner heliosphere (Riley & Ben-Nun, 2021; Kay et al., 2020). Magnetohydrodynamic (MHD) modelling is useful for studying the propagation of CMEs and their interactions with solar wind structures and other CMEs, as well as for predicting their geoeffectiveness. Coronal Mass Ejections (CMEs) occur when a significant amount of plasma is discharged from the Sun's corona and released into outer space. CMEs are powerful solar events that involve the forceful expulsion of plasma and magnetic fields, resulting in the creation of notable structures. The sudden transformation of magnetic structures, known as magnetic reconnection, can release substantial amounts of magnetic energy. This release of energy occurs when there are rapid changes in the magnetic structures through a process called magnetic reconnection (Sabri, 2018, 2019, 2020a, 2020b, 2021a, 2021b, 2022, 2023; Kumar, 2024). The interactions between interplanetary CMEs can substantially change their geo-effectiveness; in other words, these interactions can result in notable impacts on the Earth's magnetosphere and ionosphere (Sabri, 2024a, 2024b).

The Dst index is a value that quantifies the severity of geomagnetic storms, and the more negative the Dst, the more intense the geomagnetic storms are (Siscoe et al., 2006). The most severe geomagnetic storm on March 13, 1989 had a minimum Dst of -548 nT. It led to the collapse of Canada’s Hydro-Quebec power grid, resulting in the loss of electricity to six million people for up to nine hours. Therefore, recognizing extreme space weather has become vital to modern society and its technological infrastructures (Cliver and

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E-mail: (2,3) stefaan.poedts@kuleuven.be

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Svalgaard, 2004).

The solar wind is a continuous flow of charged particles from the solar corona moving outward from the hot corona into interplanetary space. Solar wind exists in two different types, namely, fast and slow solar wind, with different densities and chemical compositions. Their speed, measured at 1 AU heliocentric distance, is typically 300 km/s for the slow wind and 800 km/s for the fast wind (Schwenn, 2006). The slow solar wind's sources are located in the equatorial belt with closed magnetic fields in coronal loops and active regions (Cranmer et al., 2017). On the other hand, the fast solar wind originates from the 'open' magnetic fields of the solar coronal holes (CHs). CHs are localized areas with low density and temperatures that are slowly evolving and may persist for several solar rotations (Schwenn, 2006). At all phases of the solar cycle, high-speed solar wind streams have a dominant effect, resulting in enhancements of the Van Allen belt electron fluxes to relativistic electrons (Paulikas & Blake, 1979; Jaynes et al., 2015; Kilpua et al., 2015). Therefore, considering the background solar winds is an essential factor in studying the propagation of CMEs.

Different Space Weather-oriented methods have been developed to predict the magnetic structure of CMEs. However, a significant hurdle for such empirical-based methods is accounting for the dynamics of CME propagation, especially for complex cases that include interacting solar wind structures. To address the growing need for more accurate space weather predictions, a new model named EUHFORIA (EUropean Heliospheric FORcasting Information Asset) was developed. EUHFORIA's approach is to employ physics-based modeling, such as magnetohydrodynamic simulations, that self-consistently capture the complex dynamics. Besides, a major complication is that not all CMEs are equally geoeffective, and thus, it is important to improve our ability to predict their geo-effectiveness. Therefore, the main aim of this study was to investigate how moderate CMEs (with moderate initial velocity) evolve in interplanetary space.

In recent decades, numerous solar wind models have been developed using different approaches. Some models include physics-based algorithms or MHD, such as ENLIL (Odstrcil & Pizzo, 1999), which use synoptic photospheric magnetic field maps as input (Linker et al., 1999). Due to the growing demand for more accurate space weather forecasting, EUHFORIA was developed (Pomoell & Poedts, 2018). In this study, we used EUHFORIA to investigate how CMEs propagate in interplanetary space while considering the solar winds and their interactions with the evolving CMEs.

2. Observations

In this section, we describe the observational properties of the CMEs that occurred between 2 and 8 June 2023. Figure 1 illustrates the CME height-time curves, and it is evident that there were no very significant CMEs between 2 and 8 June 2023. Indeed, all CMEs are moderate CMEs without any considerable velocity, meaning that the derivatives of the height-time curves are modest. Hence, it was expected that these events would not have any significant geoeffective impacts. Observations and continuous monitoring are important, but observations are sometimes limited or difficult to interpret due to projection effects. Besides, some important parameters such as the internal magnetic field of the CMEs or their density and temperature, cannot be detected directly. In these cases, we have to rely on mathematical modelling. Therefore, in the following part, the propagation of the CMEs and their interactions with the background solar wind will be discussed using the numerical MHD model.

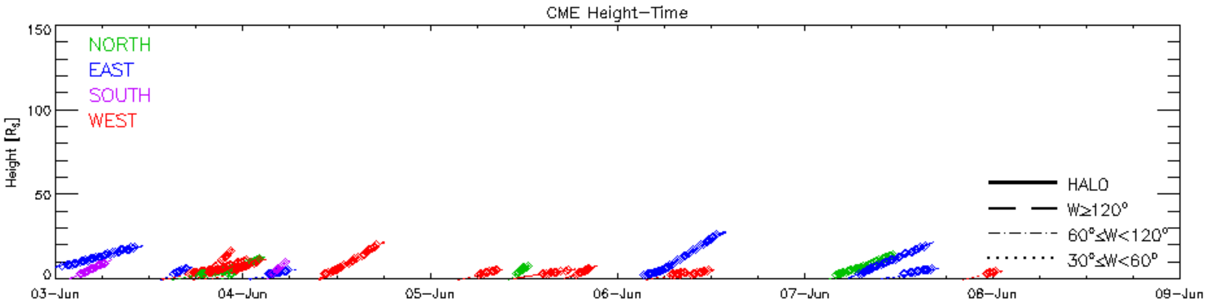

Figure 1. Overview of the CMEs eruptions 3-8 June 2023.

3. Solar wind modelling with EUHFORIA

Observational and modelling investigations have shown that CMEs undergo several variations during propagation, especially due to their interaction with high-speed streams, corotating interaction regions, the heliospheric current plasma sheet, the background solar winds, and other CMEs. Therefore, the evolution of CMEs is still open for discussion.

4. MHD Model

After many years of study, the precision of long-term space weather predictions remains only moderately reliable. The community has placed considerable emphasis on forecasting the arrival time of CMEs. Zhao and Dryer (2014) examined various methods, including both empirical and physics-based approaches, and discovered that the root-mean-square error for predicting arrival times is typically 12 hours, while the mean absolute error is around 10 hours.

While predicting the time of arrival is certainly crucial, a major complication is that not all CMEs are equally geoeffective, and thus, it is important to improve our ability to predict their geo-effectiveness (see e.g. Siscoe, 2007; Zheng, 2013; Lavraud & Rouillard, 2013).

Only recently the space weather-oriented methods that aim to predict the magnetic structure of CMEs have been constructed (e.g., Savani et al., 2015; Isavnin, 2016; Kay et al., 2017). A significant hurdle for such empirical-based methods is accounting for the dynamics of CME propagation, especially for complex cases that include interacting solar wind structures. EUHFORIA’s approach is to employ physics-based modeling, such as magnetohydrodynamic simulations, that self-consistently capture the complex dynamics.

EUHFORIA is a 3D physics-based MHD model to track the CMEs from the Sun to the Earth. It includes two different parts: first, the corona is modeled using the semi-empirical Wang-Sheeley-Arge (WSA) model, driven by the synoptic magnetogram maps. The output of the coronal model is provided as a boundary condition to the 3D time-dependent MHD model of the heliosphere.

EUHFORIA is a physics-based simulation model with three essential parts: a coronal model, a heliospheric model, and a CME evolution model. The simple, semi-empirical coronal model aims to determine realistic plasma properties of the solar wind at r = 0.1 AU, between the coronal and heliospheric models. The heliospheric model calculates the time-dependent variation of the plasma from r = 0.1 AU by numerically solving the MHD equations with the boundary conditions defined by the coronal model. EUHFORIA uses standard synoptic Global Oscillation Network Group (GONG) magnetograms or GONG Adpat maps as input for the coronal part to simulate the coronal potential magnetic field structures. An empirical Wang-Sheeley-Arge-like model (Arge et al., 2003) is used to determine the solar wind plasma properties at the inner boundary of the heliospheric model.

5. Results and Discussions

This section presents the results of the EUHFORIA simulation for the evolution of the solar wind and CMEs in the inner heliosphere during 2 - 8 June 2023. The background solar wind and the CMEs during that period were simulated.

Based on recent studies, the complexity of CMEs increases during their evolution in the inner heliosphere, mainly due to the interaction with large-scale solar wind structures (Winslow et al., 2021a; Scolini et al., 2022b). The initial background solar wind properties, defined by the empirical Wang-Sheeley-Arge-like model, are shown in Figure 2. The plasma radial velocity, density, temperature, and magnetic field at 0.1 AU are depicted in this figure. It must be noted that these solar wind characteristics are applied as inner boundary conditions for the heliospheric model.

The evolution of CMEs due to interactions with each other and the background solar wind is as important as the initial characteristics of the CMEs. According to Figure 1, there are no significant CMEs in the considered time window. This means that all of the CMEs that occurred in that window are moderate CMEs, and it was expected that they would not result in any severe geomagnetic storms. Since the interactions of the CMEs with each other and with the also magnetized background solar wind structures are essential and play a major role in determining the CMEs' ability to cause geomagnetic effects, the propagation of the CMEs is simulated, and snapshots of this simulation are illustrated in Figure 3. However, it is not certain that the CMEs' magnetic complexity increases with increasing distance, as this is not always the case (Janvier et al., 2019). Therefore, this study could shed light on the behavior of the CMEs in interplanetary space and their interactions with the background solar wind structures.

In each of the six panels of Figure 3, the left image shows the plasma density contours in the heliographic equatorial plane, while the right image displays the density contours in the meridional plane that contains the Earth. In addition, circles are shown with heliocentric radii set at values of 0.5, 1, 1.5, and 2 AU. It is important to mention that the positions of the inner planets and the locations of the STEREO spacecraft are denoted using markers.

In the first row of Figure 3, there are no CMEs, only the solar winds' interactions with Earth. The first panel of the second row of Figure 3 depicts a later snapshot in which one CME, which is not Earth-directed, occurs. Yet, its propagation and interactions with the solar wind lead to perturbations around Earth. Finally, in the snapshots shown in the third row of Figure 3, an Earth-directed CME is visible and propagates toward Earth, resulting in some disturbances around it.

Overall, Figure 3 indicates that the near-Earth environment does not experience any significant variations. In other words, there are no significant increases in the plasma density in interaction with Earth, the location of which is shown by the blue circle. Therefore, it is found that these events did not lead to any significant geoeffective impacts, as was observationally predicted.

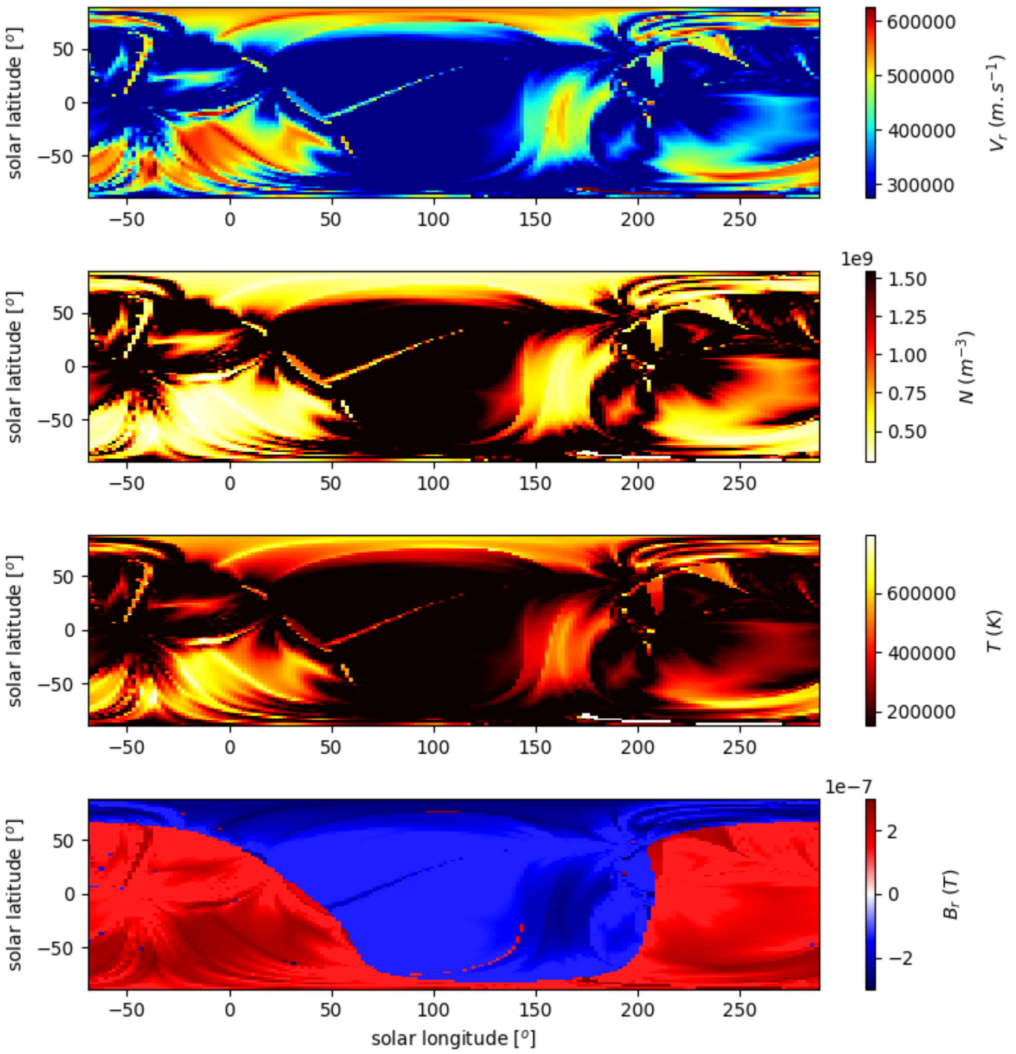

Figure 2. Solar wind plasma properties an inner boundary of the heliospheric model.

Different geoeffective indices, such as Kp and Dst, are used to define the strength of geomagnetic storms to quantify the impact of the solar events on Earth. The Dst index quantifies the reduction of the horizontal magnetic field on the ground due to the enhancement of the magnetospheric ring current. It is computed every hour from a network of mid-latitude ground observations. It is defined that the strength of geomagnetic storms, with minimum Dst values of less than -50, -100, -200, and -250 nT, corresponds to moderate, severe, intense, and superstorms, respectively. Geomagnetic superstorms can damage satellites, power grids, and disrupt communications, making the development of appropriate prediction and mitigation strategies important for our technology-dependent society.

Burton et al. (1975) were the first to calculate an empirical value to predict the ground-based Dst index and, thus, the strength of the geomagnetic storms. Since then, many others have tried to develop solar wind-to-Dst index models, including empirical and semi-empirical approaches (e.g., O’Brien & McPherron, 2000).

The disturbance storm index, calculated with the empirical model of O Brien and McPherron (2000) using synthetic input from the numerical EUHFORIA code, is shown in Figure 4. The Dst value does not drop below -50. Therefore, the measure of geomagnetic activity at Earth confirms a calm phase followed by a mild disturbance from 2 to 8 June 2023.

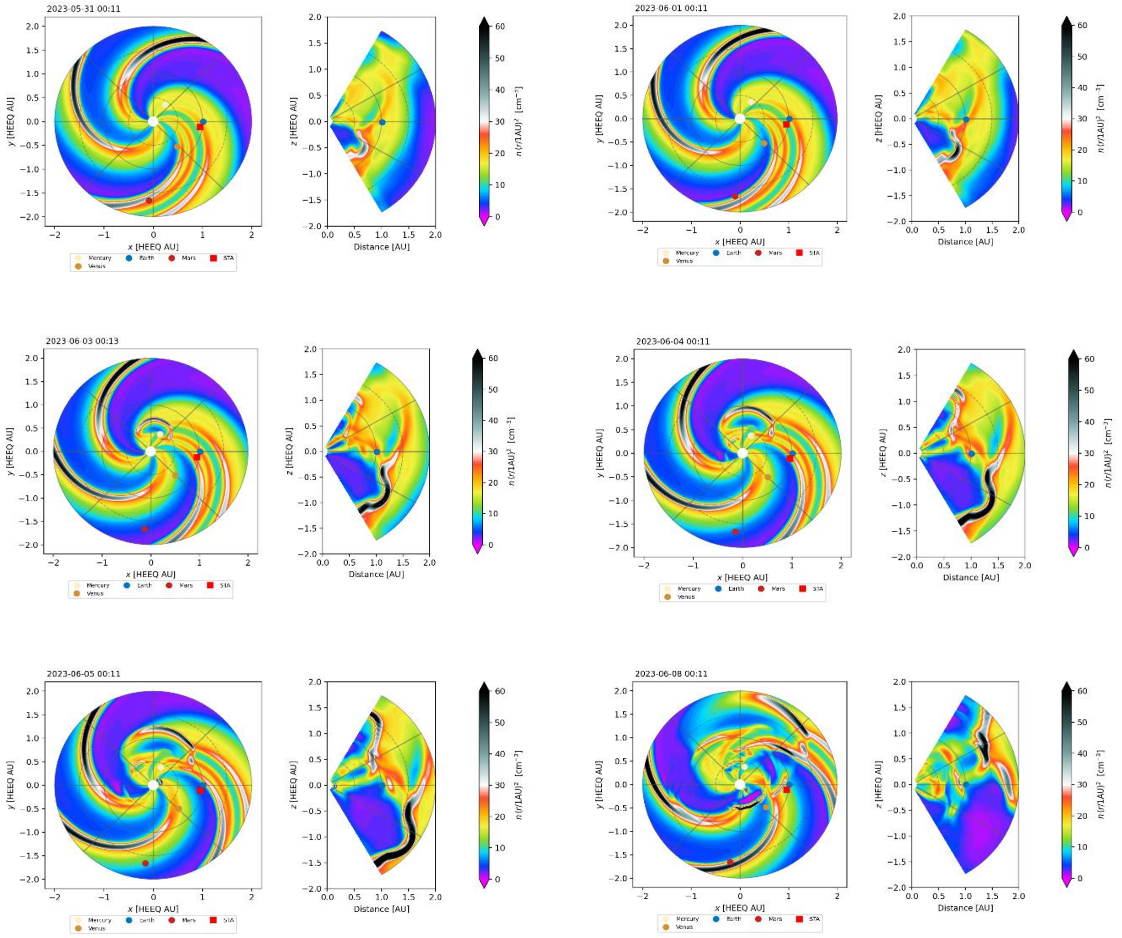

Figure 3. Snapshot of solar wind particle density from the MHD simulation with EUHFORIA. In each row, the left images depict the solution in the heliographic equatorial plane, and the right panels demonstrate the meridional plane that includes the Earth (blue circle). The two panels in the first row illustrate the background solar wind propagation in interplanetary space without any CMEs. The two panels in the second row show a non-Earth-directed CME, its propagation in interplanetary space, and its interaction with the background solar wind. The two panels in the last row depict an Earth-directed CME; the left panel shows the initial time when CME occurred, and the right panel illustrates its evolution in space.

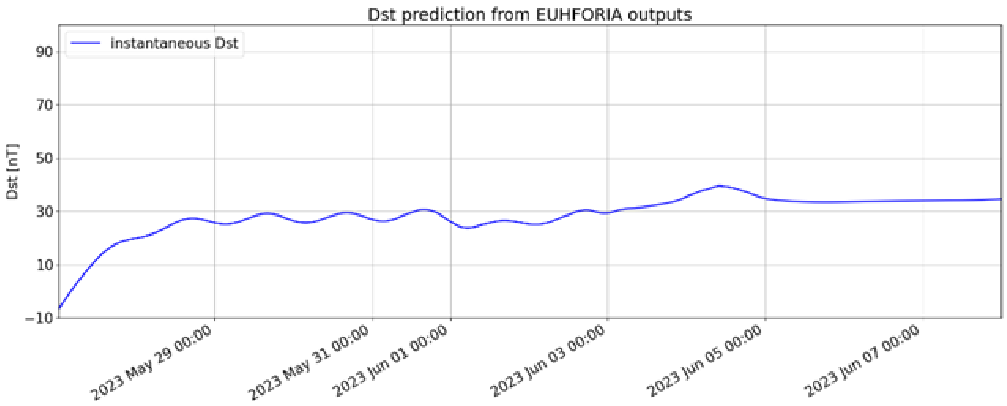

Figure 4. Dst index calculated by EUHFORIA.

6. Conclusion

CMEs are large-scale eruptions of plasma and magnetic fields launched from the Sun into the solar wind. They are considered the main drivers of geomagnetic effects on Earth. Despite unresolved science questions regarding these enigmatic events, studies have gradually advanced in recent years, shifting from fundamental CME research toward understanding and forecasting their impact on space weather. Recent advances in computational capabilities, high-resolution observations, and the ability to model interactions of CMEs with each other and with the background solar wind as they propagate between the Sun and Earth have increased interest in space weather research and prediction. Computational developments have resulted in semi-realistic MHD numerical simulations of CMEs that reproduce many characteristics of observed events from the low solar corona to Earth with significant accuracy (Toth et al. 2007; Manchester and Van der Holst, 2014; Jin et al., 2022).

We know that not all CMEs are geoeffective, and thus, it is important to improve our ability to predict their propagation. While significant CMEs are easier to track in interplanetary space when considering the background solar wind, tracking non-significant CMEs poses a challenge and requires greater accuracy. This study demonstrates the behavior of non-significant CMEs as they propagate in interplanetary space.

We have used a three-dimensional, time-dependent numerical MHD model to study large-scale background solar wind structures and investigate the propagation of specific CMEs in interplanetary space while considering the background solar wind structures.

It is illustrated that CMEs occurred between 2 and 8 June 2023, which are not significant and lacked considerable height-time development, did not experience any increase due to interactions with the background solar wind and other nearby CMEs. **To assess the impact of the solar events on Earth,** Dst, calculated using the O'Brien and McPherron (2000) model with synthetic input from the EUHFORIA code, indicates a calm phase followed by a mild disturbance during this period. Overall, the study found that the CMEs during this period did not show significant changes in their propagation characteristics. Besides, we know that sometimes interactions between CMEs and the background solar wind lead to corotating interaction regions (CIRs), which can intensify the CMEs properties. In this study, it was found that the propagation of these non-significant CMEs did not result in any significant CIRs. Thus, EUHFORIA shows promise for investigating and predicting geomagnetic storms, which is crucial for protecting our technologies from the substantial financial impacts of solar storms.

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