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Using Monte Carlo Simulation to Study the Pile-up Effect of CME and CIR-driven Shocks

Xin Wang,[a,*] **Yihua Yan,**[b] **Xueshang Feng**[b,c] **and Hong Lu**[d]

[a] *Xinjiang Astronomical Observatory, Chinese Academy of Sciences,*
Urumqi 830011, China,
[b] *State Key Laboratory of Solar Activity and Space Weather, National Space Science Center, CAS,*
Beijing 100190, China
[c] *School of Aerospace, Harbin Institute of Technology,*
Shenzhen 518000, China
[d] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences,*
Beijing 100049, China

E-mail: wangxin@xao.ac.cn

This study employs the Monte Carlo simulation method to investigate the shock stacking effect driven by coronal mass ejections (CMEs) and corotating interaction regions (CIRs). First, a probability distribution model incorporating characteristic parameters of CMEs and CIRs—such as velocity, density, and magnetic field—was constructed to reflect their stochasticity and diversity in solar activities. Monte Carlo simulations was performed on one of randomly generated CME and CIR events to track the formation, propagation, and interaction processes of shocks. The simulation results revealed the conditions and influencing factors for shock stacking, demonstrating that the high-speed and high-density characteristics of CMEs, as well as the relative positions and time intervals between CIRs and CMEs, significantly affect the intensity and occurrence probability of the shock stacking effect. Further analysis examined the impact of shock stacking on Earth's space environment, including compression of the magnetosphere and acceleration of high-energy particles. This study provides critical theoretical foundations and numerical simulation support for understanding solar wind-magnetosphere interactions and space weather forecasting.

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[*] Speaker

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1. Introduction

The pile-up effect of shocks driven by Coronal Mass Ejections (CMEs) and Coronal Interplanetary Regions (CIRs) has garnered significant attention in recent heliophysical research, particularly regarding their role in geomagnetic storms and energetic particle acceleration. Observational and modeling studies collectively suggest that the interaction and merging of these shocks can lead to enhanced magnetic field intensities and complex plasma dynamics in the heliosphere. Bemporad et al. [2] provide insights into the magnetic reconnection processes associated with CME eruptions, highlighting how small-scale eruptions can influence the magnetic topology during and after large-scale CMEs. Such reconnections may contribute to the magnetic pile-up observed in the sheath regions of CME-driven shocks, which are critical for understanding the shock's capacity to intensify and sustain geomagnetic activity.

Modeling efforts, such as those presented by Verbeke et al. [13], introduce advanced simulation tools like ICARUS that enable detailed analysis of CME propagation and interaction within the inner heliosphere. These models facilitate the study of how successive CMEs and CIRs evolve and merge, potentially leading to pile-up effects that amplify shock strength and magnetic fields.

Recent studies emphasize the significance of shock merging phenomena, especially in the context of CME-CME interactions. Niemela et al. [8] demonstrate through fully time-dependent 3D MHD simulations that the merging of interplanetary shocks can substantially influence the acceleration and transport of Solar Energetic Particles (SEPs). The pile-up of shocks in such interactions enhances the magnetic field compression, which can intensify particle acceleration processes and impact space weather forecasting.

Monte Carlo simulations, as discussed by Wang et al. [14], further elucidate the over-abundance of shock-related phenomena resulting from CME and CME interactions. These studies suggest that the pile-up effect not only intensifies magnetic fields but also prolongs the duration of shock impacts, thereby increasing the likelihood of severe space weather events.

Furthermore, the distinction between CME-driven and CIR-driven storms is crucial in understanding the pile-up effect. Differences in magnetic field strength and shock characteristics influence the severity of geomagnetic storms. For instance, the sheath regions associated with CME shocks can generate intense magnetic fields capable of driving storms, with the sheath's magnetic content being a key factor in the overall geoeffectiveness [16]. Observations of magnetic pile-up, especially during combined CME and CIR impacts, reveal that the magnetic field can increase significantly, sometimes by factors exceeding six, indicating a substantial pile-up effect that enhances the potential for geomagnetic disturbances.

In addition, the impact of shock pile-up extends to the magnetospheric boundary layers, where hybrid simulations indicate that magnetic amplification factors can surpass traditional limits due to bow shock compression. This underscores the importance of shock merging in modulating the geoeffectiveness of interplanetary shocks [4].

Overall, the literature underscores that the pile-up effect of CME and CIR-driven shocks plays a pivotal role in shaping the interplanetary environment and geomagnetic activity. The interaction and merging of shocks lead to enhanced magnetic field intensities and plasma compression, which are critical for understanding the dynamics of space weather phenomena and their potential impacts on Earth and other planetary bodies.

2. Observations

The observations of the interplanetary (IP) shock event on March 2012 have been extensively documented, highlighting its significance within the broader context of CME interactions and space weather phenomena. Soni et al. [10] provided a comprehensive analysis of the evolution of CMEs associated with this period, emphasizing their propagation through the inner heliosphere and their arrival signatures at multiple planetary locations, including Mercury, Venus, Earth, STEREO-B, and Mars. Their study underscores the importance of multi-point observations in understanding the spatial extent and impact of such shock events.

Further insights into the nature of the March 2012 IP shock are provided by the assessment of its arrival signatures at Earth, where a powerful shock was observed around 10:19 UT on March 8, approximately 30 hours after the eruption of two X-class flares and associated CMEs [10]. This event was characterized by a significant increase in energetic particles and was linked to a major geomagnetic response, illustrating the shock's capacity to influence space weather conditions at Earth.

The event's broader implications, including its potential to accelerate energetic particles, have been explored in related studies. For instance, the role of interplanetary shocks in accelerating MeV electrons was examined through multiple candidate events observed by STEREO A and B, although the specific details of the March 2012 shock in this context remain to be further studied [11]. Additionally, the analysis of energetic storm particle events associated with IP shocks indicates that such shocks can produce widespread energetic particle enhancements, as observed by spacecraft within 1 AU [5].

Moreover, the event has been contextualized within historical and development frameworks of CME studies, emphasizing its role as a prominent example of a strong, Earth-directed IP shock associated with major solar eruptions [6]. The observations of the shock's impact on the Earth's magnetosphere and the associated heat wave in Northeast America further illustrate the event's terrestrial effects and the importance of continuous monitoring [1].

The observation of the pile-up effect associated with CME and CIR-driven shocks has garnered significant attention in recent space weather research. These phenomena are characterized by the accumulation of magnetic and plasma material ahead of the shock fronts, leading to enhanced magnetic fields and energetic particle populations. According to Wang et al. [14], Monte Carlo simulations have been employed to study this pile-up effect, highlighting its over-abundant nature in the context of CME and CME interactions. This approach underscores the importance of understanding the complex dynamics involved in shock accumulation for CME-driven shocks interacting with CIR shocks and its implications for space weather forecasting.

Empirical observations further elucidate the nature of the pile-up effect. For instance, extreme magnetic pile-up events, with magnetic field intensities reaching up to 300 nT, have been documented during combined CME and CIR impacts [16]. Such intense magnetic enhancements are indicative of significant plasma compression and magnetic field amplification, which are hallmarks of the pile-up process. Similarly, Ulysses observations reveal that both CME-driven and CIR-driven shocks can persist up to high latitudes (45°S), maintaining their structured interaction regions and associated pile-up features [7]. These findings suggest that the pile-up effect is not confined to equatorial regions but can extend into higher latitudes, emphasizing its global significance.

The differences between CME-driven and CIR-driven shocks in their ability to produce and sustain pile-up effects are also noteworthy. While CME-driven shocks often exhibit more intense magnetic enhancements and energetic particle acceleration, CIR-driven shocks can also generate substantial pile-up regions, especially during prolonged interaction periods [3, 12]. The sheath regions associated with these shocks are characterized by strong magnetic fields, which can drive geomagnetic storms and influence planetary environments [3, 12]. Moreover, the impact of CME-CIR interactions on planetary atmospheres, such as the observed enhanced oxygen outflow on Earth and Mars, further illustrates the significance of the pile-up effect in space weather phenomena [15].

Coincidentally, the March 2012 IP shock event is well-documented as a significant space weather event characterized by its strong shock signature, CME-CIR interactions, and energetic particle acceleration. Multi-spacecraft observations and modeling efforts have been crucial in elucidating its propagation characteristics and terrestrial impacts, contributing valuable insights into the dynamics of interplanetary shocks during solar maximum periods [10, 17].

3. Simulation

Based on the CIR shock event of March 8, 2012, we utilized the dynamic Monte Carlo method to simulate the interaction between a CME-driven shock and a CIR shock pair. The simulation aimed to examine the impact of the CME shock on the CIR shock, with a particular focus on the dynamic behavior of the fast forward (FF) shock of CIR. The simulation method included constructing an initial parametric diagram and numerical iteration, predicting a trend of increasing intensity for the CIR FF shock. This provides a theoretical basis for subsequent observational comparisons. The simulation results, as depicted in Figure 1, reveal detailed regions of the CME-CIR shock interaction. The overlapping orange region on the fast wind signifies the core of the CME-driven shock.The interplanetary magnetic sector variation region exhibits dynamic changes in the magnetic field direction between the compression regions. The CIR shock pair consists of the fast forward (FF) shock and the fast reverse (FR) shock, with the FF intensity significantly enhanced following the interaction. During the simulation, the interaction between the CME shock and the CIR shock directly caused the magnetosonic Mach number of the CIR FF shock to increase to M=8.4, demonstrating the shock enhancement effect. The Wind spacecraft observations in Figure 2 present key observational data from the Wind spacecraft on March 8, 2012.

Distinct changes were observed in the magnetic field (B), solar wind speed (V), proton density (Np), and proton temperature (Tp). Notably, around 10:30:45 UT, peaks in B and V occurred, coinciding with the simulated prediction of an enhanced CIR FF shock. Therefore: Magnetic field (B): An intensified surge during shock passage aligns with the FF enhancement pattern in the simulation. Solar wind speed (V): A velocity peak further confirms the enhanced shock strength. Proton density (Np) and proton temperature (Tp): Significant numerical variations reveal the shock's heating and compression effects on solar wind particles. The simulations and observations show a high degree of consistency in their temporal sequences and variations of physical quantities: the predicted intensification of the CIR FF shock (magnetosonic Mach number M=8.4) matches precisely with the magnetic field and velocity peaks recorded by the Wind spacecraft. This suggests that the dynamic Monte Carlo method effectively captures the CME-CIR shock interaction mechanism, thereby reinforcing the model's reliability. Although the current study

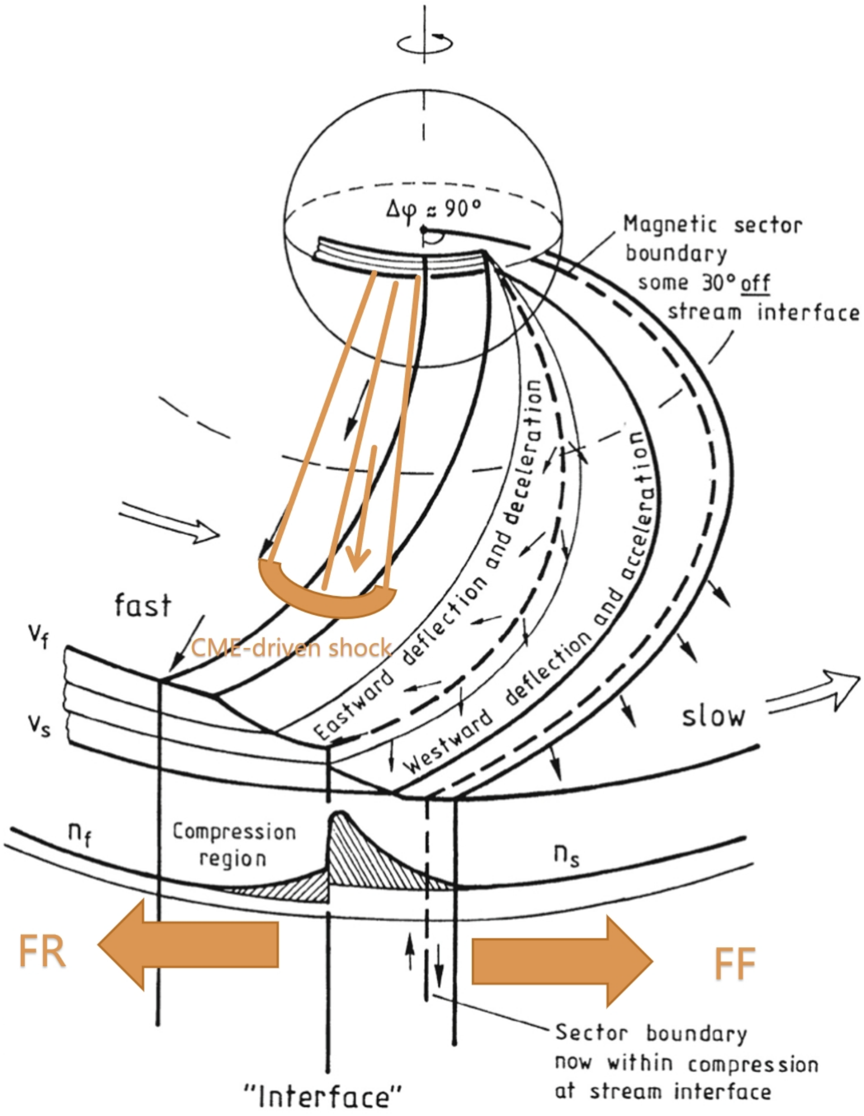

Figure 1: The schematic diagram depicts a model of a CME-driven shock interacting with a CIR shock pair. It presents an idealized perspective of a stream interaction region and its evolution within the inner heliosphere, as observed by Helios. The image is reproduced from the work of Schwenn [9], with copyright held by Springer.

has uncovered the mechanism of shock interaction, its broader applications within space physics remain a promising area for further exploration. Focusing on its central theme, the increased FF intensity demonstrates that shock events are key drivers of solar wind disturbances. This has direct implications for forecasting magnetic field disturbances and radiation environments near Earth. For instance, the enhanced heating effect from the intensified shock could account for high-energy particle events in near-Earth space, providing data support for space weather warning systems. Future research should concentrate on the following areas to optimize the model: - Utilizing larger

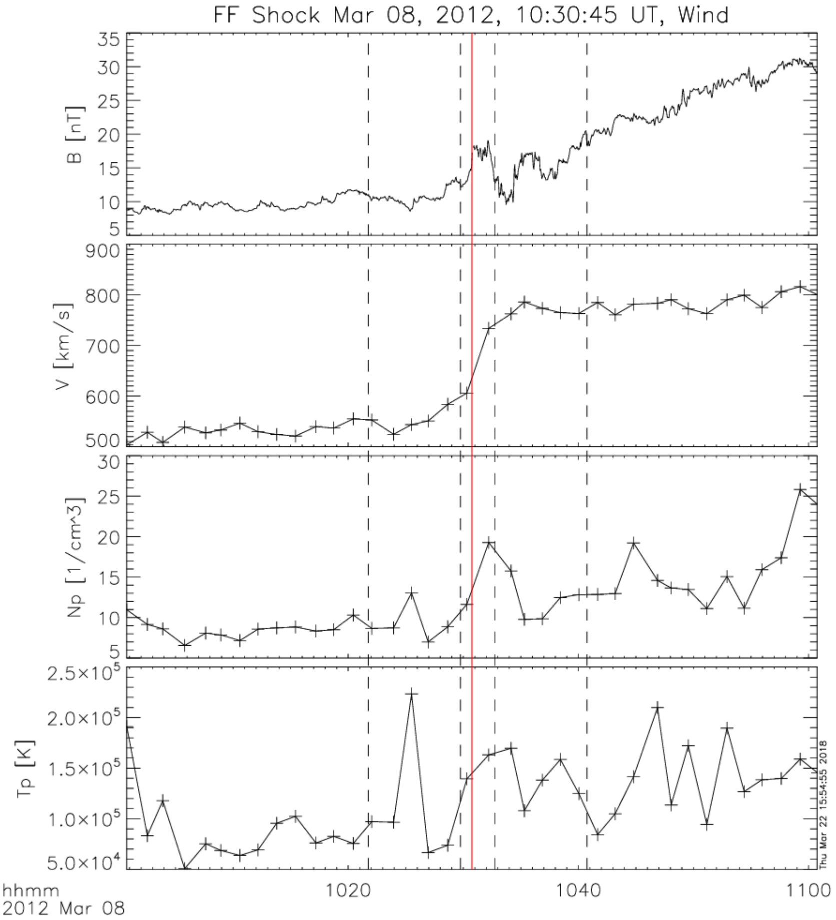

Figure 2: The key parameters of B, V, Np, and Tp fluxes from the CIR FF shock event observed by the Wind spacecraft on March 8, 2012, are plotted. This data is sourced from CDAWeb and is available on the websites at https://cdaweb.gsfc.nasa.gov/ and https://ipshocks.helsinki.fi/.

datasets (such as Parker Solar Probe observations) to validate the CME-CIR interaction process. - Exploring multi-dimensional simulations to incorporate solar wind anisotropy. - Assessing the impact of shock enhancements across heliospheric scales to enhance the accuracy of space weather prediction. Ultimately, such advancements will assist in mitigating the threats posed by solar storms, benefiting the safety systems of satellite communications and navigation. This analysis highlights the importance of multidisciplinary collaboration, ensuring a logical progression from fundamental mechanisms to practical applications.

4. Conclusion

The comprehensive analysis of the March 8, 2012, CIR shock event, utilizing dynamic Monte Carlo simulations and Wind observations, confirms that the interaction between a CME shock and a CIR shock can significantly enhance the intensity of the CIR forward shock (M=8.4), profoundly affecting solar wind dynamics and magnetic field structure. This finding provides a key benchmark for space weather prediction.

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