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Three-part Structure Formation & Interplanetary Rotation of Mars-Directed Coronal Mass Ejection on 2021 December 4

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In this work, we use multispacecraft observations and a high-resolution numerical simulation to understand the coronal mass ejection (CME) event on 2021 December 4, with an emphatic investigation of its three-part structure and rotation. This event is observed as a partial halo CME from the back side of the Sun by coronagraphs and reaches the BepiColombo spacecraft and the MAVEN/Tianwen-1 as a magnetic flux-rope-like structure.

The typical structure of a CME was identified as a three-part morphology, which includes a bright front, a dark cavity, and a bright core, with the cavity and the core generally regarded as flux rope and eruptive prominence. However, there are three-part CMEs that are not associated with prominences. It is disclosed that the CME, with no signatures of prominence at the beginning, evolves into a high-low-high-density structure, which appears in a coronagraph image as a bright front immediately followed by a dark cavity with a bright core behind. The moving and expanding spheromak flux rope sweeps up the solar wind plasma and meanwhile, the plasma at its utmost edge is compressed, which produces the high-density front overlying the flux rope. It is also found that the expansion of the flux rope is uneven, with strong expansion at its outlying area and weak expansion at its central and rear parts. The differential expansion rates lead to the distinct rarefaction rates of the plasma, which results in the formation of the low-density cavity and the high-density core within the flux rope.

The magnetic orientation of CMEs is of great importance to understand their space weather effects. Although plenty of evidence suggests that CMEs can undergo significant rotation during the early phases of evolution in the solar corona, there are few reports that CMEs rotate in the interplanetary space. Our simulation discloses that in the solar corona the CME is approximately a translational motion, while the interplanetary propagation process evidences a gradual change of axis orientation of the CME ' s flux-rope-like structure. It is also found that the downside and the right flank of the CME moves with the fast solar wind, and the upside does in the slow-speed stream. The different parts of the CME with different speeds generate the nonidentical displacements of its magnetic structure, resulting in the rotation of the CME in the interplanetary space. Furthermore, at the right flank of the CME exists a corotating interaction region, which makes the orientation of the CME alter and also deviates from its route due to the CME.

Our three-dimensional study for the first time demonstrates that the evolution of the flux rope can self-consistently generate the three-part density structure, which improves the understanding of CME ' s morphologies in coronagraph images. Our results also provide new insight into interpreting CMEs' dynamics and structures during their traveling through the heliosphere.