Postprint: Study on the Deflection Characteristics of Coronal Mass Ejections

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Abstract

A Coronal Mass Ejection (CME) is a process in which enormous bubble-like plasma carrying magnetic field lines is ejected from the Sun over a period of several hours. CMEs are accompanied by the release of substantial amounts of charged particles and radiation, which propagate into the heliospheric space and cause significant disturbances to the magnetic field therein; upon reaching the vicinity of Earth, they severely impact Earth' s magnetosphere, generating geomagnetic storms, and also interfere with both space-borne and ground-based electronic equipment. Deflection of a CME during its propagation will affect its geo-effectiveness. Therefore, investigating the deflection characteristics of CMEs is of significant importance for forecasting their influence on the heliospheric environment. This study primarily employs CME observational data from the STEREO satellite on October 8, 2007, in conjunction with magnetic field extrapolation using the Global Linear Force-Free Field (GLFFF) model, to analyze the relationship between CME deflection and the energy density distribution of the background magnetic field, and to calculate the trajectory of the CME. By varying the force-free factor a, it is found that when a = 0.15, the calculated CME trajectory exhibits the best fit with the actually observed CME trajectory.

Full Text

A Study on the Deflection Characteristics of Coronal Mass Ejections

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Abstract

Coronal Mass Ejection (CME) is the process in which huge amounts of foam-like gas carrying magnetic field lines are ejected from the Sun over a few hours. CMEs release large quantities of charged particles and radiation that cause significant disturbances to the interplanetary magnetic field when they propagate into the Sun-Earth space. When reaching Earth’ s vicinity, they severely affect Earth’ s magnetic field, generating geomagnetic storms and interfering with space-based and ground-based electronic equipment. If a CME deflects during propagation, its geo-effectiveness will be affected. Therefore, studying the deflection characteristics of CMEs is important for forecasting their impact on the Sun-Earth space environment. This work primarily utilizes STEREO satellite observations of a CME event on October 8, 2007, combined with the Global Linear Force-Free Field (GLFFF) model for magnetic field extrapolation. We analyze the relationship between CME deflection and the distribution of background magnetic field energy density, and calculate the CME’ s trajectory. By varying the force-free parameter , we find that when   = 0.15, the theoretically calculated CME trajectory best fits the actual observed trajectory.

Keywords: CME; deflection; background magnetic field; trajectory

1. Introduction

Coronal Mass Ejection (CME) is a solar activity phenomenon closely related to space weather. In a few minutes to several hours, a mass of coronal material is ejected outward from the Sun [1]. This ejected material enters interplanetary space, causing significant disturbances to the interplanetary magnetic field. When propagating to Earth’ s vicinity, CMEs severely affect Earth’ s magnetic field, producing geomagnetic storms and interfering with communication equipment and satellite operations [2]. The propagation speed of CMEs may be one reason for differences in associated radio bursts [3]. Changes in CME propagation direction determine whether a CME can reach Earth, making the study of CME deflection important for forecasting space weather events.

Due to limitations of single-point observations, only the projection of CMEs in the meridional plane could be obtained. Many scholars have studied CME deflection in the meridional plane. Studies of CMEs observed by Skylab found that CME deflection could affect geomagnetic effects. Research on CME deflection in the meridional plane during solar minimum years (1997-1998) showed that CMEs symmetrically deflect toward the equator during solar minimum but show no such deflection during solar maximum. Further studies of all CME events during solar minimum years obtained similar results.

Scholars have proposed several factors that may affect CME deflection: collisions and interactions between CMEs, high-speed solar wind from coronal holes, and the background coronal magnetic field.

Regarding collisions and interactions between CMEs, numerical simulations of two interacting CMEs found that both experienced latitudinal deflection, with east-west deflection occurring after collision. Analysis of observed CME data confirmed that both the speed and direction of CMEs can change due to interactions between them.

Regarding high-speed solar wind from coronal holes, studies have shown that CMEs can be deflected by the influence of Parker spiral solar wind in interplanetary space. Some researchers suggest that CMEs may experience longitudinal deflection during interplanetary propagation, primarily due to interaction between CMEs and background solar wind. Others believe some CMEs may be influenced by high-speed solar wind from coronal holes near their source region, causing them to deviate from the Sun-Earth line.

Regarding the background magnetic field, studies have found that the background magnetic field B is another factor affecting CME deflection. When the magnetic field direction is parallel to the CME propagation direction, the magnetic energy density B^2 can better represent the factor causing CME deflection. More in-depth studies have examined the relationship between CME deflection and the gradient of background magnetic field energy density. However, there is no direct physical correlation between background magnetic field density gradient and CME trajectory. Therefore, this paper quantitatively describes the relationship between CME deflection and the distribution of background magnetic field energy density gradient, calculates CME trajectories, and seeks better agreement between theoretically extrapolated CME deflection and actual observations by varying the force-free parameter .

2. Observations and Magnetic Field Extrapolation

2.1 CME Event Observations The selected case is the CME event on October 8, 2007. This event occurred during solar minimum when solar wind influence was relatively small, and has been studied by many researchers [17]. Therefore, this study does not consider the influence of solar wind on CME deflection. The characteristic of this CME event is its clear and complete process, which facilitates studying the entire deflection process.

STEREO satellite observations provide images within the COR1 and COR2 fields of view. The CME event first appeared at the upper edge of the COR1-B field of view at 08:46 UT. STEREO satellite has sufficiently high resolution to clearly observe its deflection process in the meridional plane. The CME remained in the COR1 field of view for 0-4 Rs and in the COR2 field of view for 4-6.5 Rs.

[Figure 1: see original paper] shows the temporal evolution of the CME projection in the meridional plane. Panels (a)-(f) show the CME in the COR1 field of view, with crosses indicating the leading edge position points. Panels (g)-(i) show the CME in the COR2 field of view, with crosses indicating the lower edge position points. During early propagation (COR1), the CME propagated essentially radially without latitudinal deflection. During later propagation (COR2), its propagation direction continuously approached the solar equatorial plane, showing obvious deflection in latitude.

[Figure 2: see original paper] shows the variation of the CME’ s central position angle (CPA) with leading edge height in the meridional plane. The CPA changed from approximately 55.0° to 27.5°. During early propagation, the CME’ s propagation direction continuously changed to lower latitudes. However, due to dispersion causing measurement errors, there is a data gap in the 4-6.5 Rs range. Based on the leading edge height, we infer that the event continued to deflect toward lower latitudes during this propagation process. At greater heights, the central position no longer changed significantly, indicating approximately radial propagation.

3. Influence of Background Magnetic Field on CME Deflection

CME deflection in the latitudinal direction has been studied by many scholars. The background coronal magnetic field is considered a key factor affecting CME deflection [13,15,19]. This paper quantitatively describes the relationship between CME deflection and the distribution of background magnetic field energy density gradient, and calculates CME trajectories.

3.1 CME Deflection Model in Background Magnetic Field When a CME propagates, the background magnetic field it passes through becomes compressed, creating magnetic energy accumulation. This accumulated magnetic energy produces a restoring force that acts on the CME, causing deflection. If the CME occupies a sufficiently small region, the net force from the background magnetic field acting on the CME is the magnetic energy density gradient force at the CME’ s location.

Assuming the upper and lower parts of the CME occupy regions of equal volume and scale, the net force acting on the CME depends only on the magnetic energy density difference between the upper and lower boundaries. The magnetic energy density = $B^2/2$, where B is the background magnetic field strength and is the magnetic permeability.

[Figure 3: see original paper] provides a sketch of the background magnetic field perturbed by a CME. The magnetic energy density of the background field disturbed by the upper part of the CME is _up, with restoring force F_up acting on the upper part. Similarly, the restoring force acting on the lower part is F_down. The net force is determined by the magnetic energy density difference between the boundaries.

3.2 CME Deflection and Background Magnetic Energy Density Gradient Distribution To study the influence of background magnetic field energy density gradient on CME deflection, we first need to obtain the distribution of the background coronal magnetic field. Since direct measurement of coronal magnetic fields is extremely difficult, we can only extrapolate using photospheric magnetic field measurements. This paper uses the Global Linear Force-Free Field (GLFFF) model to calculate the background magnetic field energy density distribution. This extrapolation method calculates the global coronal potential or linear force-free field based on photospheric magnetograms, offering better applicability for analyzing local solar activity phenomena such as CME deflection than potential field models.

[Figure 4: see original paper] shows the background magnetic field energy density distribution at 3 Rs for Carrington rotation 2061 corresponding to the October 8, 2007 CME event. The ellipse represents the CME’ s projection on the Carrington magnetogram, with dashed and solid lines indicating the upper and lower boundaries of the CME, respectively. The cross marks the CME’ s position at this height. The background magnetic energy density distribution is non-uniform, with greater magnetic energy density at the CME’ s upper boundary than at its lower boundary. There are significant differences in magnetic energy density at different latitudes, so the net restoring force points downward toward lower latitudes, with magnitude determined by the magnetic energy density difference at the boundaries.

[Figure 5: see original paper] shows the variation of CME deflection and magnetic energy density difference with height. Triangles represent the variation of magnetic energy density difference with leading edge height, while crosses represent the variation of CPA with leading edge height. The trends of CME propagation direction change and magnetic energy density difference are basically consistent. At lower heights (COR1), CME deflection is more obvious. At higher heights (COR2), the CME no longer shows significant deflection.

4. CME Trajectory Calculation

From previous work, we established the relationship between CME deflection and background magnetic field energy density gradient distribution. Since the restoring force F is proportional to the magnetic energy density difference between the CME’ s upper and lower boundaries, and assuming the CME mass m remains constant during propagation, we can calculate the CME’ s deflection trajectory using the formula _i = $\frac{1}{2}at^2$, where acceleration $a = F/m$.

[Figure 6: see original paper] compares the theoretical CME trajectory with the observed trajectory when   = 0.15. The solid line represents the theoretically calculated trajectory, while asterisks (*) represent the actually observed trajectory. The theoretical trajectory matches the observed trajectory well.

5. Results Analysis and Discussion

We now search for better agreement between theoretically calculated CME deflection and actual observations by varying the force-free parameter . The units of   are Mm ^{1}. [Figure 7: see original paper] shows the theoretical CME trajectories versus observed trajectories for different   values. Symbols represent the observed CME propagation direction variation with time: “+” for   = 0.0, “×”

for = 0.10, “ ” for = 0.15, and “*” for = 0.20. When the background magnetic field is a linear force-free field, the theoretical trajectories obtained with = 0.15 and = 0.20 fit the actual observed CME trajectory better.

Table 1 shows the absolute error (average) between theoretical and observed CPA for different values:

	Absolute Error (°)
0.05	13.3
0.10	55.0
0.15	12.6
0.20	92.1
0.30	(value missing)
0.40	(value missing)
0.50	(value missing)
0.60	(value missing)

The results show that when = 0.15, the theoretically calculated CME trajectory fits the actual observed trajectory best. When exceeds this value, the error becomes large.

This study of a CME event observed by STEREO satellites demonstrates that CMEs are deflected toward lower latitudes during early propagation due to the influence of background magnetic field energy density gradient, and propagate essentially radially during later stages. When the background magnetic field is a linear force-free field with = 0.15, the theoretically calculated trajectory matches observations best. These results further confirm the close relationship between CMEs and the background magnetic field, and indicate that forecasting CME trajectories based on the relationship between CMEs and background magnetic field energy density gradient is feasible to some extent.

However, there are areas for improvement. The main limitation is that when calculating the magnetic energy density difference between the CME’ s upper and lower boundaries, we assumed the CME maintains a constant shape (a circle with angular width as radius) during propagation, which introduces some error. Future work will use actual observational data to select points on the CME’ s upper and lower boundaries for calculating the background magnetic field energy density gradient, which will reduce theoretical estimation errors and improve forecast accuracy.

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Note: Figure translations are in progress. See original paper for figures.