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The Role of Viscosity in Causing the Plasma Poloidal Motion in Magnetic Clouds

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Abstract

An interesting phenomenon, plasma poloidal motion, has been found in many magnetic clouds (MCs), and viscosity has been proposed as a possible mechanism. However, it is not clear how significant the role of viscosity is in generating such motion. In this paper, we conduct a statistical study of the MCs detected by the *Wind* spacecraft during 1995–2012. It is found that, for 19% of all the studied MCs (186), the poloidal velocities of the MC plasma near the MC boundaries are well correlated with those of the corresponding ambient solar wind plasma. A non-monotonic increase from inner to outer MCs suggests that the viscosity does play a role, albeit weak, on the poloidal motion in the MC statistically. The possible dependence on the solar wind parameters is then studied in detail for the nine selected crossings, which represent the viscosity characteristic. There is an evident negative correlation between the viscosity and the density, a weak negative correlation between the viscosity and the turbulence strength, and no clear correlation between the viscosity and the temperature.

Key words: solar wind – Sun: coronal mass ejections (CMEs)

1. Introduction

Coronal mass ejections (CMEs) are expulsions of solar plasma and magnetic field that rapidly release a huge amount of energy into the heliosphere. Magnetic clouds (MCs) as a subset of the interplanetary manifestations of CMEs are recognized by relatively strong magnetic field magnitude, a smooth magnetic field rotation through a large angle, and low proton temperature and proton plasma beta compared to ambient solar wind in in situ measurements (Burlaga et al. 1981; Klein & Burlaga 1982; Burlaga 1988). Owing to their extremely important role in the Earth's environment (Farrugia et al. 1997), the dynamical evolution of MCs in interplanetary space has been paid much attention for several decades.

An interesting phenomenon, the plasma rotation around the MC's axis (called poloidal motion hereafter), was first reported and analyzed by Farrugia et al. (1992, 1995). They derived a magnetohydrodynamic solution to model a rigidly rotating cylindrical symmetric MC and proposed that transit time from the Sun to 1 au might be related to rotating velocities. However, no explanation of the cause of such poloidal rotating motion in MCs has been given in the past 25 years. The recent statistical study by Wang et al. (2015) showed again that 51% of MCs during 1995–2009 were evidently experiencing such poloidal motion with a poloidal speed $v_p \geqslant 10\,\mathrm{km\,s^{-1}}$. The authors proposed three possible speculations for the cause: (1) the local interaction with solar wind, (2) the release of internal magnetic energy, and (3) the generation during the eruption at the Sun and the angular momentum is being carried to the heliosphere due to angular momentum conservation. Recently, Zhao et al. (2017) utilized the in situ observations from the *Solar Terrestrial Relations Observatory* (*STEREO*) and *Wind* spacecraft to study the same MC, which occurred on 2007 November 19–21, and found that there was an evident rotation at *Wind* and *STEREO-B* but no clear rotation motion at *STEREO-A*. More detailed analysis of the poloidal motion at *Wind* and *STEREO-B* showed that the rotational direction inside the MC is consistent with that of the ambient solar wind at both the front and rear boundaries and the rotational speeds are roughly smaller than the ambient solar wind. These results suggested that the local interaction with solar wind may be the major cause of the poloidal motion inside the MC and the viscosity might be one of the factors. However, it is not clear how significant a role the viscosity plays in causing such poloidal motion.

Since solar wind was first predicted theoretically by Parker (1958), various viscous models of the solar wind have been proposed (e.g., Scarf & Noble 1964, 1965; Whang et al. 1966; Dahlberg 1970). It was found that the thermal energy and heat flow decrease because the accumulated energy is consumed to counteract the resistant force of the viscosity, suggesting that the viscosity plays a significant role in the momentum transformation/energy conservation of the solar wind in the interplanetary medium (e.g., Whang et al. 1966; Coleman 1968; Eisler 1969; Dahlberg 1970; Wolff et al. 1971). Viscosity is an intrinsic property of local media. Although the studies of the mechanism of viscosity are rare, its influence on the dynamic process of large-scale structures is prominent and well-recognized as, e.g., aerodynamic drag force (e.g., Vršnak & Gopalswamy 2002; Cargill 2004; Borgazzi et al. 2009; Maloney & Gallagher 2010; Vršnak et al. 2010). Therefore, the role of viscosity cannot be neglected during the solar wind propagation in the heliosphere. If the viscosity plays a role in the poloidal motion, to what degree does the viscosity cause the plasma poloidal motion in an MC and what is the relation between the viscosity and the solar wind parameters, e.g., density, temperature, and turbulence intensity of the magnetic field? This information will perhaps allow us to better understand the cause of the poloidal motion in an MC as well as the property of the viscosity of solar wind. In Section 2, we represent the basic idea, starting from which the statistical relationship between the poloidal velocities of the MC and solar wind plasma is exhibited. In Section 3, a more detailed analysis about the possible dependence of the viscosity on solar wind parameters is carried out. We summarize and discuss our work in Section 4.

2. Statistical Relationship between the Poloidal Velocities of MCs and Ambient Solar Wind

2.1. Data and Method

The MC list maintained at https://wind.gsfc.nasa.gov/mfi/mag_cloud_S1.html, which collected 169 MCs observed by the *Wind* spacecraft from 1995 to 2012, is used for the statistical study. Here, we exclude three kinds of data: (1) two events because of the large data gaps; (2) one event because it is believed multiple MCs; and (3) those classified as poor fitted events, i.e., the parameter Q in the list is equal to 3. With the aid of the velocity-modified cylindrical force-free flux rope model (Wang et al. 2015), the linear propagation velocity of the MC $\boldsymbol{u}_{\mathrm{mc}}$ in GSE coordinates and the poloidal velocity, $\boldsymbol{v}_{\varphi} = v_p \hat{\varphi}$, in the MC frame ($r$, φ, z), where z is aligned to the axis of the MC, are obtained. The poloidal velocity, otherwise known as the tangential velocity, is along the φ direction.

Since the MC is a large-scale structure, the viscosity between the MC and solar wind at the front and rear boundaries is studied separately, which means that the number of crossings of the MC boundaries is 186, two times the number of MCs. If the viscosity is the main cause of the plasma poloidal motion in MCs, the tangential velocities of plasma in the MC frame should gradually increase from inside to outside of the MC. To test this picture, we narrow down the sample by applying the following three criteria: (1) the fitting parameter $|v_p|$ obtained from our model is more than or equal to $10\,\mathrm{km\,s^{-1}}$, (2) these events have no large fluctuation, (3) the direction of the tangential velocity $\boldsymbol{v}_{\varphi}$ is consistent with that of the ambient solar wind velocity, $\boldsymbol{u}_{\mathrm{sw}}$, which is an average over 1.5 hr right outside of the MC's boundary, in the MC frame. Finally, the number of crossings meeting the above requirements is 35, which accounts for 19% of all the 186 crossings, suggesting that the role of viscosity is weak if the viscosity is the cause of the poloidal motion in the MC.

For these crossings, we compute the average tangential velocities of ambient solar wind and the MC plasma every 30 minutes beside the boundary, i.e., $v_{\mathrm{psw}i}$ and $v_{\mathrm{pmc}i}$, $i = 1$, 2, and 3, in which the smaller i means the location closer to the boundary, as illustrated in Figure 1. A correlation analysis between the two sets of tangential velocities is performed to look for the signature of the viscosity.

2.2. Results

For the selected 35 events, the pairwise correlations between the $v_{\mathrm{pmc}i}$ and $v_{\mathrm{psw}i}$ ($i = 1$, 2, and 3) are shown in Figure 2. We make a linear fitting to the data set and calculate the slope of the fitting line. The error bars indicate the standard deviation of the tangential velocity in every 30-minute time interval. From this figure, we find that the correlation coefficient is generally higher for the closer pairwise data set and lower for the farther pairwise data set, this result is natural and reasonable. All of the correlation coefficients are more than 0.80. The strong correlations between the tangential velocity of the MC and solar wind plasma suggest that there are some connections between the MC plasma and ambient solar wind. An interesting phenomenon is that the slopes of the fitting lines are all less than 1 and the slope roughly

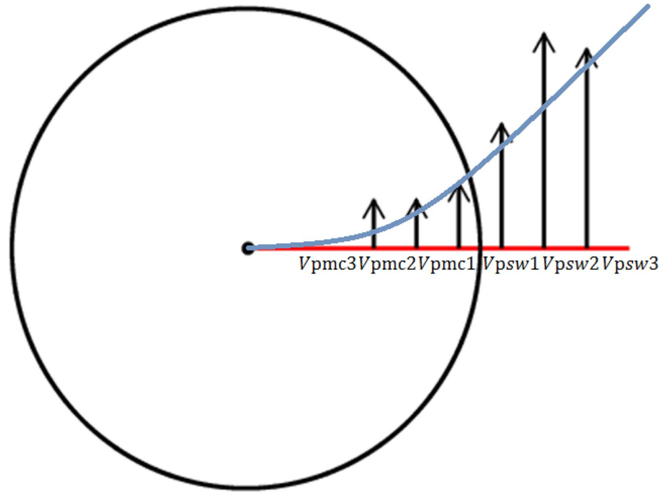

Figure 1. Arrows indicate the average of the normalized tangential velocities of the solar wind ($v_{\mathrm{psw}i}$) and the MC ($v_{\mathrm{pmc}i}$) plasma at each time interval ($i = 1$, 2, 3).

decreases from about 0.87 for the closest paired data set to about 0.75 for the farthest paired data set, suggesting that the tangential speeds of ambient solar wind are overall larger than those of the MC plasma and the difference increases with distance. These signatures indicate that the viscosity might play some role in causing the poloidal motion in the MC from the statistical viewpoint.

The arrows in Figure 1 intuitively show the tangential velocity changing from the inner to the outer an MC based on the fitting results. There is a roughly increasing trend of the tangential velocity away from the axis of the MC that continues in the ambient solar wind. However, this increase is not strictly monotonous, which may be attributed to fluctuations.

3. Possible Dependence of the Viscosity on Solar Wind Parameters

3.1. Data and Method

The above analysis has shown some viscosity signature from a rough statistic. Here we study the role of viscosity further through detailed investigation of the change of the tangential velocity crossing the MC boundaries. By manually checking the change of the 1 minute averaged tangential velocity profile near the front/rear boundaries of the MCs, we further narrow down the sample by selecting the crossings during which the tangential velocity clearly increases from the inner to the outer the MC. Finally, nine crossings that we think represent the picture fairly well in Figure 1 are selected and shown in Figure 3. A few data points indicated by the red symbols in Figures 3(a), (b), and (d) are discarded in the following analysis because they deviate significantly away from the main trend of the crossings due to inevitable fluctuations.

It is not clear how to obtain the viscous coefficient in the solar wind. Alternatively, we use the following formula to roughly assess the strength of the viscosity between the ambient solar wind and MC plasma

$$f_{\mu_\nu} = \frac{\bar{v}_{\mathrm{pmc}}}{\bar{v}_{\mathrm{psw}} - \bar{v}_{\mathrm{pmc}}}$$

in which f_{μ_ν} is assumed to be a function of the viscous coefficient μ_ν, and $\bar{v}_{\mathrm{pmc}}$ and $\bar{v}_{\mathrm{psw}}$ are averaged tangential speeds

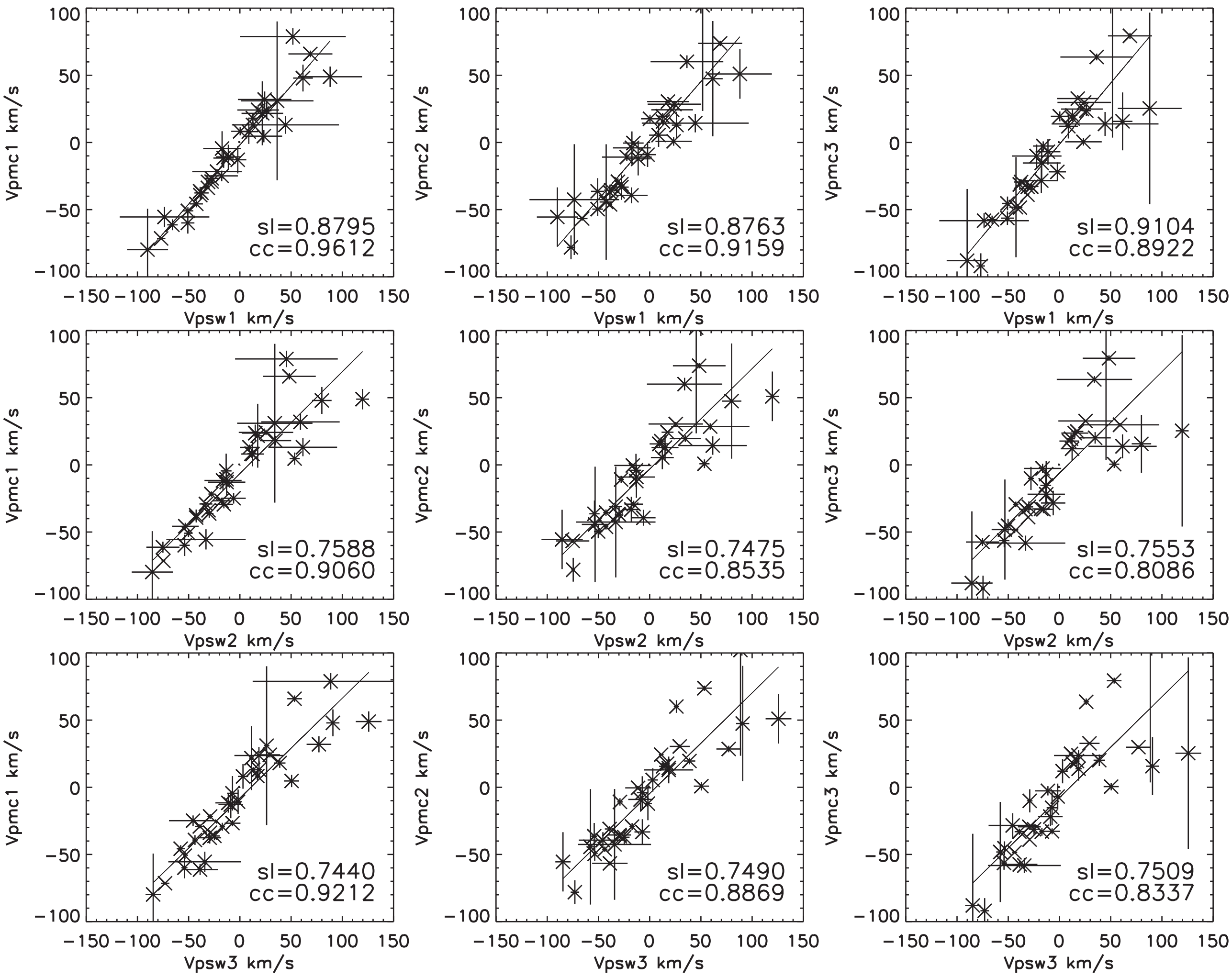

Figure 2. Relationship between the plasma tangential velocities of the MC $v_{\mathrm{pmc}i}$ and those of the ambient solar wind $v_{\mathrm{psw}i}$ ($i = 1, 2, 3$), where cc is the correlation coefficient and sl is the slope of the fitting line.

in MC and solar wind, respectively. The formula follows the idea that if there is no viscosity $\bar{v}_{\mathrm{pmc}}$ should approach zero as well as f_{μ_ν}, and if there is a strong viscosity $\bar{v}_{\mathrm{pmc}}$ should be equal to $\bar{v}_{\mathrm{psw}}$, leading f_{μ_ν} to be infinitely large. Considering that there is more or less uncertainty in determining the boundary of an MC, we calculate the values of $\bar{v}_{\mathrm{psw}}$ and $\bar{v}_{\mathrm{pmc}}$ based on the measurements within one and a half hours next to the boundary with the nearest half an hour ignored. The uncertainty in f_{μ_ν} is propagated from the uncertainties in the averaged tangential velocities $\bar{v}_{\mathrm{psw}}$ and $\bar{v}_{\mathrm{pmc}}$. The averaged solar wind parameters, e.g., density, temperature, and turbulence intensity of the magnetic field, inside and outside of the boundary are also calculated within the same intervals to investigate the possible dependence of the strength of the viscosity between the ambient solar wind and MC plasma.

3.2. Results

The scatter plots between f_{μ_ν} and solar wind parameters inside and outside of the MC are shown in Figure 4. The turbulence intensity of the magnetic field is estimated based on 96-second averaged data by using the formula

$$\frac{\delta B}{B_0} = \frac{\sqrt{\frac{\sum_{i=1}^{N}(B_i - B_0)^2}{n}}}{B_0},$$

where B_0 is the average magnetic field magnitude. Figures 4(a)–(b) show strong negative correlations between the viscosity and the density inside and outside of MCs, for which the correlation coefficient (cc) is -0.7994 and -0.8091, respectively, with a confidence level (CL) of nearly 1. Weak negative correlations between the viscosity and the turbulence intensity of the magnetic field can be found in Figures 4(e)–(f), in which cc is -0.5862 and -0.6323, respectively, with CLs of 0.9280 and 0.9300. There is no evident correlation between the viscosity and temperature as shown in Figures 4(c)–(d). These results suggest that larger density and/or turbulence may reduce the viscosity. The dependence of the strength of the viscosity on the solar wind parameters found here shows a different trend compared to the theoretical analysis for a collision-dominated plasma medium, in which the viscosity is believed to positively correlate with the density and temperature

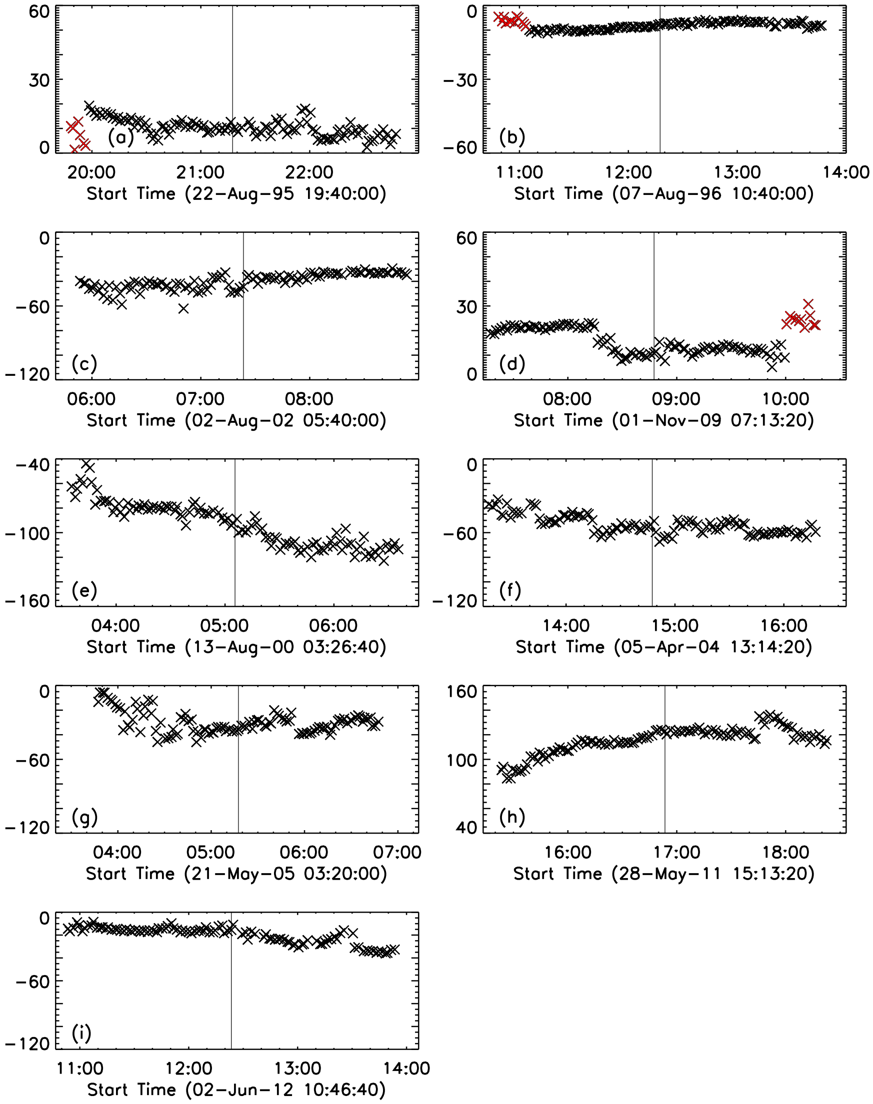

Figure 3. Change of the tangential velocities with time. Panels (a)–(d) show the change of the tangential velocities at the front boundary of the MC, and (e)–(i) at the rear boundary. The verticle solid line indicates the boundary of the MC. The ordinate axis is the tangential velocity, where the positive value means the anti-clockwise rotation and the negative value means the clockwise rotation.

(Hollweg 1985). A possible reason for the difference is that the solar wind is inclined to be collisionless.

4. Summary and Discussion

We statistically studied the role of viscosity on the poloidal motion in the MCs based on the MC events detected by the *Wind* spacecraft during 1995–2012. At first, the crossings satisfying the increasing tendency of the plasma tangential velocity to move from inside to outside of the MC only occupied 19% of all the MCs, suggesting that the viscosity played only a minor role if it is a cause of the poloidal motion in the MC. The further statistical study of the 19% selected MCs shows a strong correlation between the tangential velocity of the MC plasma and that of ambient solar wind plasma, and the tangential velocity generally increases from the inner to the outer MC. Hence, we conclude that the viscosity does play a role on the poloidal motion, though the effect is weak. To further study the dependence of the viscosity on the solar wind parameters, nine crossings representing signatures of the viscosity fairly well are investigated in detail. It is found that there is a clear negative correlation between the viscosity and the density, a weak negative correlation between the viscosity and the turbulence strength, and no evident correlation between the viscosity and the temperature. These results are not consistent with previous theoretical analyses for a collision-dominated plasma, suggesting that the property of the plasma in the collisionless medium probably differs from that of the collisional plasma in terms of viscosity. Although the number of data is small, the correlation between the viscosity and the density is notable with a confidence level close to 1. It is an interesting phenomenon and worthy of further study in the future.

As mentioned in the Introduction, an aerodynamic drag coefficient is believed to be a macro-manifestation of the viscosity. As a preliminary attempt, we study the relationship between the viscosity strength f_{μ_ν} and the drag coefficient C_D for the nine selected crossings. Based on the Equations (2)–(10)

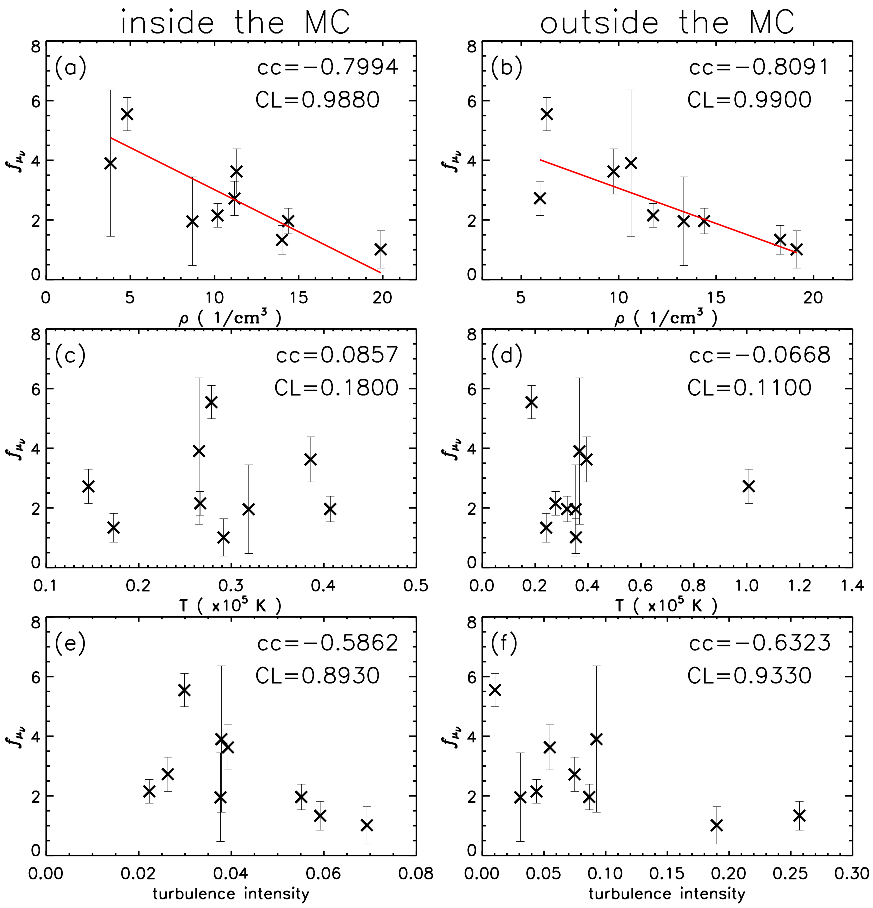

Figure 4. Relationship between the viscous strength f_{μ_ν} and the solar wind parameters, including the density ρ, the temperature T, and the turbulence intensity of the magnetic field. Here cc is the correlation coefficient and CL is the confidence level by a permutation test. The left and right panels show the relation inside and outside of the MC, respectively.

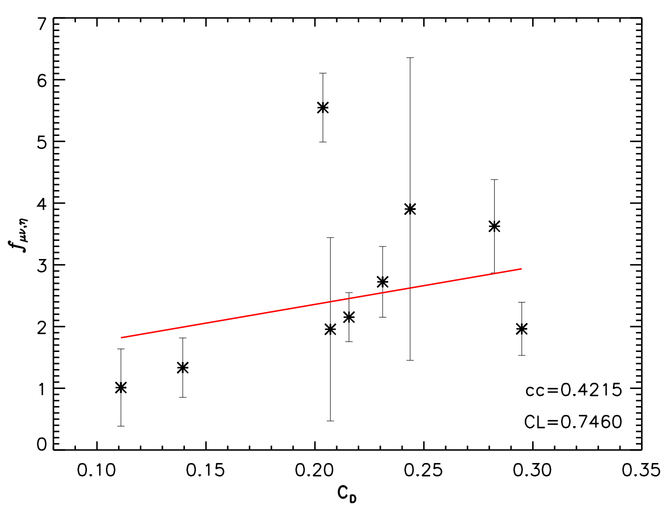

Figure 5. Relationship between the viscous strength f_{μ_ν} and the drag coefficient C_D in aerodynamics. Here cc is the correlation coefficient and CL is the confidence level by a permutation test.

in Subramanian et al. (2012), the dimensionless drag coefficient C_D can be estimated at 1 au for an MC. Figure 5 shows the relationship between the parameters. It is found that, although the correlation coefficient is not too high, which is only 0.42, a

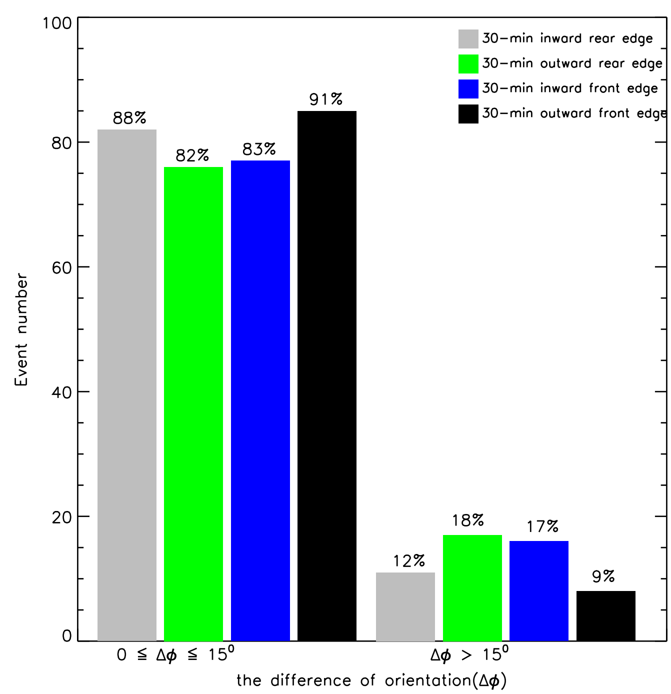

Figure 6. Statistical results of the difference of axial orientation between the unshifted and shifted boundaries.

trend that higher C_D corresponds to larger f_{μ_ν} is roughly established, confirming that the drag coefficient is a macro-manifestation of the viscosity.

It is noted that the above analysis highly depends on the orientation of the MC axis, based on which MC local coordinates are established to analyze tangential velocities. The orientation of an MC axis is derived from the MC fitting technique and may be influenced by choosing different boundaries of MCs. In many events, the boundaries are not clear enough and may suffer from an uncertainty of about an hour. To test the influence of the uncertainty in boundaries on our results, we check the difference of the fitted orientation of the MC axis by shifting the front and rear boundary inward and outward by 30 minutes, respectively. The statistical results of the difference of orientation between the unshifted and shifted boundaries are shown in Figure 6 for 93 MCs. From this figure, we find that the change of the orientation is statistically small. There are 88%, 82%, 83%, and 91% of tests with the angle difference $\Delta\phi$ less than or equal to 15°. For the selected 19% of events, the percentages are similar, which are 89%, 79%, 100%, and 89%, respectively. Hence, we think that the uncertainties in the boundaries will not change our results in this study.

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