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The Relationship of Magnetic Twist and Plasma Motion in a Magnetic Cloud

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Abstract

Our recent investigations indicate that interplanetary magnetic clouds (MCs) have a high-twist core and a weak-twist outer shell. Utilizing the velocity-modified uniform-twist force-free flux rope model, we further investigate the relationship between the twist profile of magnetic field lines and the distribution of the plasma poloidal angular velocity inside an MC. The poloidal velocity in the MC is 11 km s^{-1}. There are evidently positive correlations between the absolute value of the twist and the plasma poloidal angular velocity in peeled flux ropes or flux rope layers, although the correlation coefficients in flux rope layers are less than those in peeled flux ropes. This finding suggests that plasma flows are frozen-in magnetic field lines as we expected for interplanetary medium, of which the magnetic Reynolds number is large. Furthermore, based on this picture, we infer the axial velocity in the MC frame, which is less than 10 km s^{-1} and almost uniform in the cross section of the MC. Besides, it is inferred that the plasma flows velocity in the MC is much less than the local Alfvén speed.

Unified Astronomy Thesaurus concepts: Interplanetary magnetic fields (824)

1. Introduction

Magnetic flux ropes (MFRs), as one of fundamental magnetic structures in the universe, consist of helical magnetic field lines collectively winding around a central axis. The twist of magnetic field lines in an MFR is described as $T = \frac{B_\varphi}{rB_z}$, in units of radians per unit length in the local cylindrical coordinate (r, φ, z), where z is aligned with the central axis. The interplanetary manifestations of coronal mass ejections, called interplanetary coronal mass ejections (ICMEs), play a vital role in solar–terrestrial interaction. Magnetic clouds (MCs), a subset of ICMEs, clearly present an MFR structure detected by in situ spacecraft at 1 au, which possess an enhanced magnetic field strength, a large and smooth rotation of the magnetic field vector, and low proton beta compared to ambient solar wind (Burlaga et al. 1981; Klein & Burlaga 1982). In particular, MCs are the main drivers for many space-weather events (e.g., Tsurutani et al. 1988; Huttunen et al. 2002; Wu & Lepping 2002; Cane & Richardson 2003; Zhang et al. 2007), and therefore they are the most widely studied complex flux rope in the solar wind in the past four decades.

Owing to a close relationship of magnetic field lines that twist with magnetic free energy and stability (Dungey & Loughhead 1954; Kruskal et al. 1958; Hood & Priest 1979; Mikic et al. 1990; Baty 2001; Fan & Gibson 2004; Török & Kliem 2005), the twist distribution of magnetic field lines inside MCs have been studied by various methods, for example, solar energetic electron probes (Larson et al. 1997; Kahler et al. 2011a, 2011b), the Grad–Shafranov (GS) reconstruction technique (Hu & Sonnerup 2002; Hu et al. 2014, 2015; Wang et al. 2017), and multiple-spacecraft observations utilizing force-free model (Wang et al. 2018). The main feature of the GS reconstruction method is that the structure is not assumed as a force-free state and has an arbitrary two-dimensional (2D) cross section (Hu et al. 2013). Hu et al. (2014) found that the magnetic field lines' twist distribution in the MFRs is more consistent with a nonlinear force-free model. Furthermore, Hu et al. (2015) utilized the GS reconstruction and a constant-twist nonlinear force-free flux rope model to infer the field line twist distribution, in which they found that the twist is inconsistent with the Lundquist model. Recently, with the aid of a velocity-modified uniform-twist (nonlinear) force-free flux rope model (Wang et al. 2016), Zhao et al. (2018) concluded the twist profile in the cross section of an interplanetary MC and it showed an almost monotonous decreasing trend from the axis to the periphery of the MC. If we can further obtain the relationship between the twist of magnetic field lines and the rotational motion of plasma flows in the MC, perhaps whether or not plasma move along the magnetic field lines can be concluded.

The rotational motion of plasma flows, v_p, is the motion of a velocity component along the poloidal direction, i.e., around the axis of the MC (hereafter called poloidal motion). This motion was first reported and studied by Farrugia et al. (1992, 1995). Wang et al. (2015) made a statistic study and found that about 51% MCs detected by the *Wind* spacecraft during 1995–2009 had evident plasma poloidal motion with a rotation velocity of $|v_p| \geqslant 10$ km s^{-1}. For this motion, the authors raised three possible producing mechanisms: (1) the local interaction with the solar wind, (2) the rotational component separated from kinetic energy coming from the magnetic energy during the expansion of MCs, and (3) the initial eruption of the corresponding CME that are carried all the way to 1 au. Utilizing multi-spacecraft observations, Zhao et al. (2017a) studied the same MC and found that the interaction with local solar wind may be the major cause of the poloidal motion inside the MC, in which viscosity might be one of the local causes. Based on the statistic study of the MCs detected by the *Wind* spacecraft during 1995–2012, it was found that the viscosity did play a role on the poloidal motion (Zhao et al. 2017b). According to current magnetohydrodynamic theory, plasmas will be frozen-in magnetic field lines when the magnetic Reynolds number is large; therefore, a certain correlation between the plasma poloidal motion and the twist of magnetic field lines inside MCs may exist. Our previous work mainly focused on the reason that causes plasma poloidal motion inside MCs, but the correlation of poloidal motion with magnetic twist was not studied, so we will study it here.

The event and the calculation methods are introduced in Section 2. In Section 3, the relationship between the magnetic twist and the plasma poloidal motion inside an MC is obtained, and the axial velocity is also referred and discussed. Finally, we give a summary in Section 4.

2. Event and Method

In this work, the selected event is the same as that one in Zhao et al. (2018), and the reason is that this event satisfies two necessary conditions: (1) the spacecraft path is close to the axis of the MC, and (2) the azimuthal magnetic flux is balanced around the axis in the cross section of the MC in the MC frame, suggesting that the MC did not experience erosion process with ambient solar wind (Dasso et al. 2006; Tian et al. 2010; Gosling 2012). Thus, it is an ideal event.

The twist distribution of magnetic field lines in the cross section from the axis to the periphery of the MC had been obtained in Zhao et al. (2018). Here, we need to further acquire the distribution of the plasma poloidal velocity in the cross section through the similar method that was used by Zhao et al. (2018) to obtain the twist. First, we use the velocity-modified uniform-twist force-free flux rope model (Wang et al. 2016) to fit the measurements of the magnetic field and velocity. Utilizing the fitting parameters θ and φ (the elevation and azimuthal angle of the axis orientation), we convert the measurement velocity from GSE coordinates into the MC frame (x', y', z'), in which the z' points along the main axis of the MC, and y' is perpendicular to the observational path of the spacecraft. Second, we separate the poloidal velocity from the observed plasma velocity in the cross section (x', y') of the MC. The observed plasma velocity in the cross section of the MC can be decomposed into two components: the expanding velocity, v_e, and the poloidal velocity, v_p. When peeling off an equal azimuthal magnetic flux layer by layer from the outer shell to the axis of the MC in the x'–y' plane, we call the remaining flux rope the peeled flux rope, and we call the peeled layer the flux rope layer, as depicted in Figure 1. Here, a step of 10% of the peak azimuthal magnetic flux is used to peel off the flux rope layer by layer from both the front and rear boundaries. Finally, we calculate the average plasma poloidal angular velocity in every peeled flux rope and flux rope layer by the function of $\omega = \frac{v_p}{r}$, where r is the average radial distance from the axis of the flux rope.

3. The Relationship between Twist and Plasma Motion

Here, 10 peeled flux ropes and five flux rope layers for 0%–20%, 20%–40%, 40%–60%, 60%–80%, and 80%–100% are obtained, in which $\overline{\omega}$ and ω denote the averaged poloidal angular velocity in every peeled flux rope and flux rope layer, respectively. By applying the two error tests, including the randomized noise and axis orientation (see more details in Zhao et al. 2018), the corresponding poloidal angular velocity, $\overline{\omega}/\omega$, can also be obtained (panels (b/e) and (c/f); Figure 2), respectively. The relationship between the absolute value of the twist, $\overline{\tau}/\tau$, and $\overline{\omega}/\omega$ for the MC are presented in Figure 2. Figures 2(a)–(c) show strong positive correlations between the average twist and the average plasma poloidal angular velocity in peeled flux ropes, for which all the correlation coefficients (cc) are larger than 0.76, with a confidence level (CL) of nearly 1. By comparison, Figures 2(d)–(f) show a little weak positive correlations between the twist and the poloidal angular velocity in flux rope layers, with the correlation coefficients 0.78, 0.73, and 0.64 of confidence levels 0.91, 0.88, and 0.61, respectively. These results indicate that the twist of the magnetic field lines is almost positively correlated with plasma poloidal motion in the MC, suggesting that the plasma flows are probably frozen-in magnetic field lines as we expected for large magnetic Reynolds number medium.

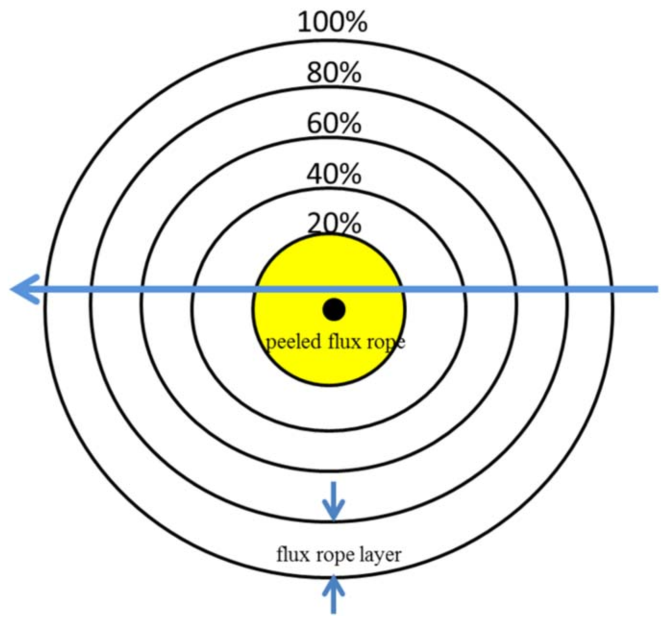

Figure 1. Schematic diagram showing different peeled flux ropes and flux rope layers in the cross section of the MC, as adapted from Zhao et al. (2018). The long blue arrow denotes the spacecraft path, the yellow region indicates a peeled flux rope, and the interval marked by the short blue arrows shows a flux rope layer.

Based on this picture, the magnetic field, B, and plasma velocity, v, in the MC should be correlated as

$$\frac{v_p}{B_{\varphi'}} = \frac{v_{z'}}{B_{z'}} \tag{1}$$

in which v_p and $v_{z'}$ are the poloidal and axial velocity, respectively, in the MC cylindrical coordinates (r', φ', z'). Based on Equation (1), the twist can be written as

$$\tau = \frac{T}{2\pi} = \frac{B_{\varphi'}}{2\pi r B_{z'}} = \frac{v_p}{2\pi r v_{z'}} = \frac{\omega_p}{2\pi v_{z'}}. \tag{2}$$

Then, the axial velocity could be given as

$$v_{z'} = \frac{\omega_p}{2\pi\tau}. \tag{3}$$

Using the obtained values of $\overline{\omega}_p/\omega_p$ and $\overline{\tau}/\tau$, we approximately calculate the average axial velocity, $\overline{v}_{z'}$, in every peeled flux rope and the axial velocity, $v_{z'}$, in each flux rope layer. The uncertainty in $\overline{v}_{z'}/v_{z'}$ is propagated from the uncertainties in the $\overline{\omega}_p/\omega_p$ and $\overline{\tau}/\tau$. Figure 3 shows the variation of the axial

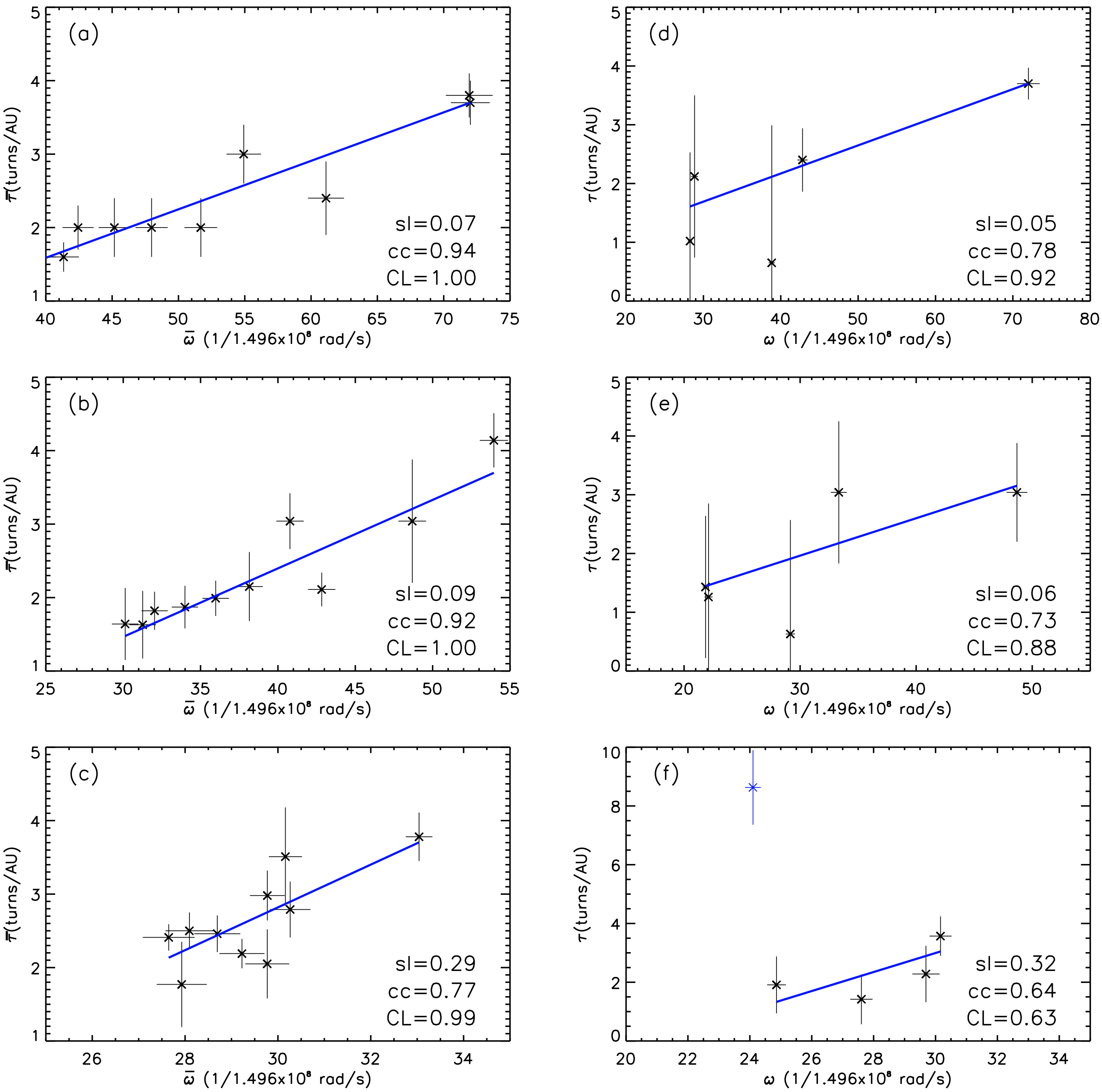

Figure 2. Average twist vs. average plasma poloidal angle velocity in a peeled flux rope (panels (a)–(c)) and the twist vs. plasma poloidal angular velocity in the flux rope layer (panels (d)–(f)) for the MC, in which the blue lines indicate the linear fitting results. sl, cc, and CL are the slope of linear fitting, the correlation coefficients, and the confidence level by a permutation test, respectively. Panels (b) and (e) show the test results for adding 5% average randomized noise, and panels (c) and (f) show the test results for changing the orientation of the MC axis to the mean value of the 10 orientations (see more details in Zhao et al. 2018).

velocity, $\bar{v}_{z'}/v_{z'}$, with the different peeled flux rope/flux rope layer, in which the axial velocity is almost less than 10 km s^{-1}. Furthermore, the distribution of axial velocity looks flattened, meaning that plasma flows are almost uniform in the cross section of the MC.

The local Alfvén speed can be calculated by $V_A^2 = \frac{B^2}{4\pi\rho}$, where B is the magnetic field strength and ρ is the local density. For this MC, the proton number density is about 10 cm^{-3} and magnetic field strength is about 12 nT, on average. Thus, the local average Alfvén speed is about 85 km s^{-1}. The poloidal velocity of the plasma in the MC is about 11 km s^{-1}. It is reasonable that both the poloidal and axial velocity and their combination, i.e., the helical velocity, are much smaller than the local Alfvén speed, and no strong disturbance, e.g., shock waves, can be produced.

4. Summary and Discussion

In this work, based on the velocity-modified uniform-twist force-free flux rope model, we studied the relationship between the twist of magnetic field lines and plasma poloidal motion in an MC. The clear positive correlations between the twist and the plasma poloidal angular velocity in peeled flux ropes or flux rope layers of the MC are exhibited, suggesting that the twisted degree of magnetic field lines is related to plasma poloidal motion and that plasmas move along the magnetic filed lines. We further infer the axial velocity in the MC frame and find that it is almost uniform from the axis to the periphery of the

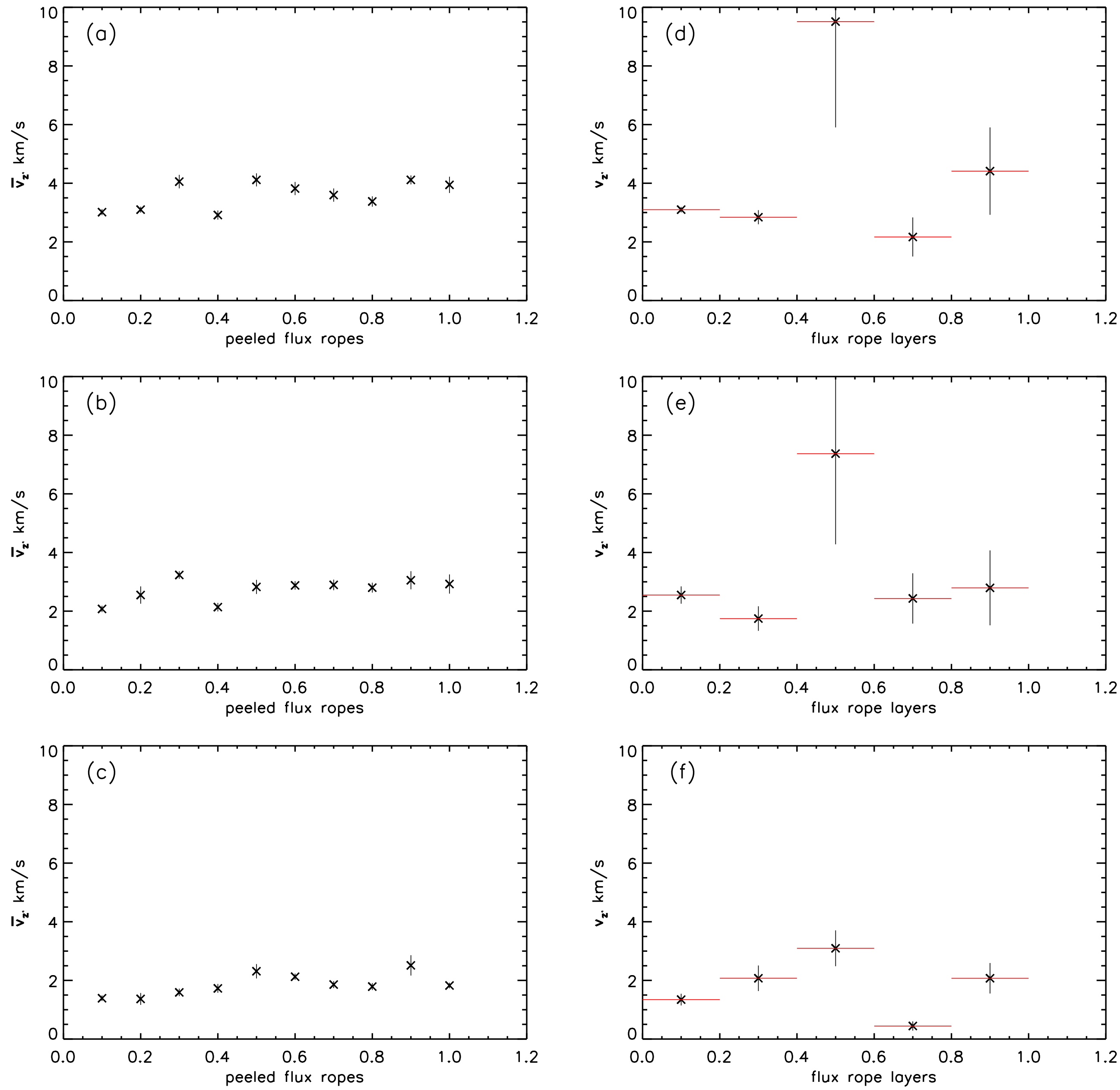

Figure 3. Distribution of the average axial velocity in peeled flux ropes (panels (a)–(c)) and the axial velocity in flux rope layers (panels (d)–(f)). The red horizontal lines indicate the corresponding layer of the azimuthal magnetic flux, i.e., 0%–20%, 20%–40%, 40%–60%, 60%–80%, and 80%–100%. The results of the randomized noise test are shown in panels (b) and (e), and the test results for orientation of the MC axis are shown in panels (c) and (f).

MC. In comparison with the local Alfvén speed in the MC, the axial velocity is less than it.

Noted that the force-free condition is probably not strictly satisfied for MCs as the presence of more or less of the pressure gradient. However, the β value inside the MC of interest is less than 0.1. Thus, the magnetic field structure in the MC can be approximately regarded as a force-free state.

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