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Possible Detection of Torsional Alfvén Waves within an Interplanetary Magnetic Cloud

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Abstract

Although it is believed that Alfvén waves can be present in the form of torsional modes in interplanetary magnetic flux ropes, convincing observational evidence remains elusive. In this Letter, we report the detection of Alfvén waves embedded within an interplanetary magnetic cloud (MC) on 2003 March 20, which exhibited features quite different from those upstream and downstream. The magnetic field inside the MC underwent alternate rotations along an arc through a relatively small angle in the plane perpendicular to the minimum variance direction, which seems consistent with the appearance of torsional modes. A significant poloidal motion of plasma existed in the MC, thus it is possible that the field-aligned helical plasma flow was mixed with Alfvén waves exhibiting high correlation between plasma velocity and the magnetic field.

Key words: magnetohydrodynamics (MHD) – solar wind – waves

1. Introduction

In uniform plasmas, Alfvén waves are incompressible transverse oscillations that propagate along magnetic field lines with magnetic tension as the restoring force. In field-aligned plasma structures (e.g., magnetic flux tubes), Alfvén waves could manifest acting as torsional oscillations, i.e., azimuthal perturbations of the magnetic field and plasma velocity, with different phases at different magnetic surfaces. These waves propagate along plasma structures at the local Alfvén speed and are called torsional Alfvén waves (e.g., Spruit 1982; Edwin & Roberts 1983). In the solar atmosphere, magnetic field lines generally clump together to form magnetic flux tubes (Jess et al. 2009; Mathioudakis et al. 2013; Shestov et al. 2017), where Alfvén waves are expected to be present in the form of torsional modes (e.g., Doorsselaere et al. 2008; Vasheghani et al. 2011) and kink modes (e.g., He et al. 2009a, 2009b). The torsional modes can carry significant energy from the lower atmosphere to the corona and solar wind (Ruderman 1999; Copil et al. 2008), and hence receive great attention. However, convincing observational evidence of such modes has been rarely reported, owing to the intrinsic difficulties in their identification (i.e., their nearly incompressible nature). Their possible observational signature would be spectral line broadening due to the Doppler effect. Jess et al. (2009) observed FWHM oscillations coupled with the chromospheric line-of-sight Doppler velocities. This is currently accepted as the unequivocal evidence of torsional modes in solar plasma structures.

The proposed generation mechanisms for torsional modes in solar plasma structures include vortices related to convective motions at magnetic footpoints (Hollweg et al. 1982; Velli & Liewer 1999), magnetic restructuring at all levels from the photosphere to the corona (Copil et al. 2008), and a magnetic twist gradient from the interior portion of the flux tube to the expanded coronal portion (i.e., producing an axial torque; Longcope & Welsch 2000; Fan 2009). The solar corona is structured into various magnetic flux ropes, typically including prominences and filaments. When flux ropes undergo eruption, a magnetic twist gradient is generally established. As a result, torsional waves might be produced, and thus it is possible to detect the torsional waves along the flux ropes in interplanetary space. Nevertheless, identifying torsional oscillations through in situ observations is incredibly difficult. The possible manifestations within interplanetary flux ropes have been reported only once by Gosling et al. (2010). They observed Alfvén waves embedded within a small-scale magnetic flux rope at 1 au and interpreted them in terms of torsional modes produced by distortions within a pre-existing coronal flux rope. Nevertheless, Alfvén waves of such nature have not been repeatedly detected within small-scale flux ropes. One may speculate that many flux ropes observed in the solar wind are not ejections of pre-existing flux ropes. Instead, they are dominantly formed from coronal arcades through converging motion and magnetic reconnection. However, it is known that Alfvén waves could also be generated in the newly formed flux ropes during the reconnection process. It has been simulated that the three types of magnetohydrodynamics waves, including Alfvén waves, can be simultaneously generated and launched from the event of reconnection between the open magnetic field and a closed loop, between which there exist relative convergence and shear motions (Yang et al. 2015). Emission of bidirectional Alfvén waves was also identified in the center of reconnection exhaust in the solar wind (He et al. 2018). Signatures of Alfvén waves were indeed detected to exist throughout large-scale flux ropes, i.e., interplanetary magnetic clouds (MCs; e.g., Yao et al. 2010; Liang et al. 2012), but they are more likely to be arc-polarized Alfvén waves that have been frequently observed in the solar wind (Barnes & Hollweg 1974; Wang et al. 2012). To date, the basic causes of the rarity of torsional modes within interplanetary flux ropes remain unclear. Note that torsional Alfvén waves could possibly exist in the ambient solar wind (Marubashi et al. 2010), but they are beyond the scope of this article.

In this Letter, we report the detection of Alfvén waves throughout the interval of an MC on 2003 March 20, which are likely to appear in the form of torsional modes. The observations could provide an important clue to the manifestations of torsional modes within interplanetary flux ropes.

2. Observation and Analysis

Figures 1 and 2, respectively, show the solar wind plasma and magnetic field data acquired by the *WIND* and *ACE* spacecraft during 2003 March 19–21 encompassing an MC. The MC was clearly indicated by the enhanced magnetic field strength $|B|$, the large, smooth rotation of the magnetic field direction, bidirectional streaming of suprathermal electrons, the low proton temperature T_P, and a low proton β ($\sim$0.1) (Burlaga et al. 1981). The MC was encountered by *WIND* from 12:40 UT to 21:58 UT on 2003 March 20, when *WIND* was located upstream from Earth at about (1.37, 0.51, 0.028) $\times$ 10^6 km in geocentric solar ecliptic (GSE) coordinates. The MC was encountered by *ACE* from 12:30 UT to 22:15 UT, when *ACE* was located upstream from Earth at about (1.4, 0.004, $-$0.077) $\times$ 10^6 km in GSE coordinates. The shock driven by the MC could be discerned around 04:25 UT on March 20 at *WIND* and around 04:20 UT on March 20 at *ACE*. The MC exhibited quite similar features at both spacecraft, except that the MC duration at *WIND* ($\sim$9 hr and 18 minutes) was slightly less than that at *ACE* ($\sim$9 hr and 45 minutes). It is interesting to note that outward propagating Alfvénic-like fluctuations, characterized by the correlated fluctuations in magnetic field B and velocity V_P, were present in the entire interval of the MC. To confirm that the fluctuations are Alfvén waves in nature, we conduct a Walén test (Sonnerup et al. 1987) and a dispersion relation analysis (Shi et al. 2015) using the 3 s resolution data from *WIND*.

In general, to examine whether the fluctuations satisfy the Walén relation, a deHoffman–Teller (HT) frame needs to be found. Given that flux ropes expand during their propagation in interplanetary space, we divide the MC interval into multiple segments with a duration varying from 20 to 30 minutes for the HT frame search. The result suggests that good HT frames indeed exist in all segments. For each segment, the HT frame electric field ($E_{\mathrm{HT}} = -V_{\mathrm{HT}} \times B$) agrees well with the corresponding convection electric field ($E_c = -V \times B$) in the x-, y-, and z-components, and thus the convection electric field in the HT frame becomes extremely small, although it does not disappear. Then we calculate the plasma velocity in the HT frame ($V_{\mathrm{GSE}} - V_{\mathrm{HT}}$) and the Alfvén velocity, i.e., $V_{\mathrm{A}} = \frac{\delta B}{\sqrt{\mu_0 m N_p}}$, where δB, μ_0, m, and N_p refer to the changes in magnetic field, permeability of free space, proton mass, and proton number density, and show the scatter plots of $V_{\mathrm{GSE}} - V_{\mathrm{HT}}$ versus V_{A} to evaluate the Walén relation. Figure 3 displays the scatter plots for four selected segments in the leading, middle (two intervals), and trailing portions of the MC. The slopes of the linear regression fitting are 0.79, 0.87, 0.83, and 0.75, and the correlation coefficients are all greater than 0.75. For all segments, the correlation coefficients are found to be larger than 0.70, indicating that the fluctuations within the MC are primarily Alfvénic (e.g., Guo et al. 2016; Wang et al. 2018).

We further conduct a comparison analysis of the observational and theoretical results of the wave dispersion relations. A cross wavelet analysis is first applied to magnetic field B and electric field E_c to extract the frequency information. Then the singular value decomposition (SVD) method developed by Santolík et al. (2003) is used to calculate the wavevector k for each frequency by solving Faraday's law. (Note that only one wavevector can be searched and solved for one frequency via the SVD method. If there is more than one branch of waves at the same frequency, there is no way to find out all of the wave branches using this method.) The top panels of Figures 4(a)–(d) illustrate the comparisons between observed and theoretical dispersion relations for the same four segments as shown in Figure 3. The middle panels show the comparisons between observed phase speed and theoretical phase speed. The bottom panels show the angles between wavevector k and magnetic field B. As suggested by Shi et al. (2015), the comparisons should be better made in the limited range of $2/t \leqslant f \leqslant 0.1 f_{ci}$, $kd_i \leqslant 0.025$, where t is the duration of the segment, f_{ci} is the ion gyrofrequency, and d_i is the ion inertial length. In this frequency range, the observed dispersion relation and phase speed better match the theoretical expectations for Alfvén waves. The angles between wavevector k and magnetic field B are generally less than 45°. We examine all of the segments and find that the observed dispersion relation matches well with the theoretical Alfvén wave dispersion relation. This suggests that outwardly propagating Alfvén waves dominated the fluctuations within the MC. It should be mentioned that Alfvénic-like fluctuations characterized by correlated changes in the solar wind are not always Alfvén waves (see Shi et al. 2015).

3. Discussion

We have identified the existence of Alfvén waves in the whole interval of the MC on 2003 March 20. Alfvénic-like fluctuations with correlated changes in magnetic field B and velocity V_P were also present both upstream (i.e., sheath region) and downstream of the MC, as shown in Figures 1 and 2. It is interesting to note that the fluctuations within the MC exhibited two features quite different from those upstream and downstream: (1) the timescales of the magnetic field and velocity variations were much larger, and (2) the amplitudes of the magnetic field and velocity variations were relatively small. Note that the large amplitude fluctuations in the sheath region were partly due to the compression of the high-speed plasma. To further investigate the physical properties of the waves within the MC, we apply a minimum variance analysis (MVA) to the magnetic field data at ten-minute intervals, during which the inherent twists of the magnetic field lines inside the MC were very weak. For comparison purposes, a similar MVA is carried out on the downstream magnetic field data. Figure 5 shows the hodograph of the $B_l - B_m$ magnetic field components (maximum and intermediate eigenvector directions) for three selected intervals within the MC and three intervals downstream. It is clearly visible that the downstream magnetic field underwent smooth rotations, interspersed by sudden jumps, along an arc through a large angle, which is well

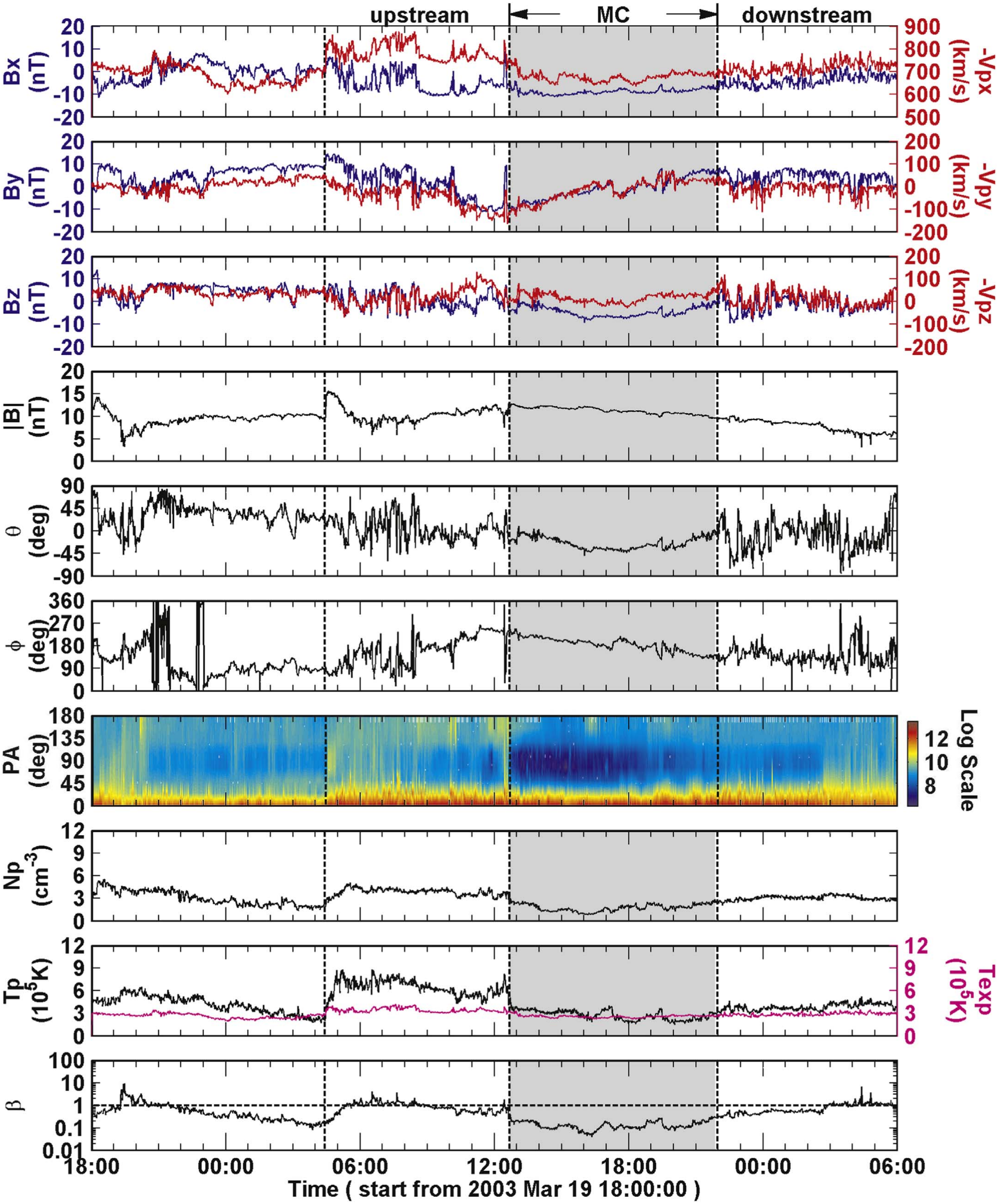

Figure 1. Solar wind parameters observed by *WIND* with a time resolution of 60 s during 2003 March 19–21. From top to bottom: magnetic field and proton velocity components in GSE coordinates, magnetic field magnitude ($|B|$), elevation angle (θ) and azimuthal angle (ϕ) of field direction, pitch angle (PA) of the suprathermal electron ($\sim$300 eV), proton density (N_p), proton temperature (T_p) overlaid with the expected temperature ($T_{\rm exp}$) from the observed speed, and proton β. The vertical black dashed line shows the location of the shock, and the shaded region shows the MC structure.

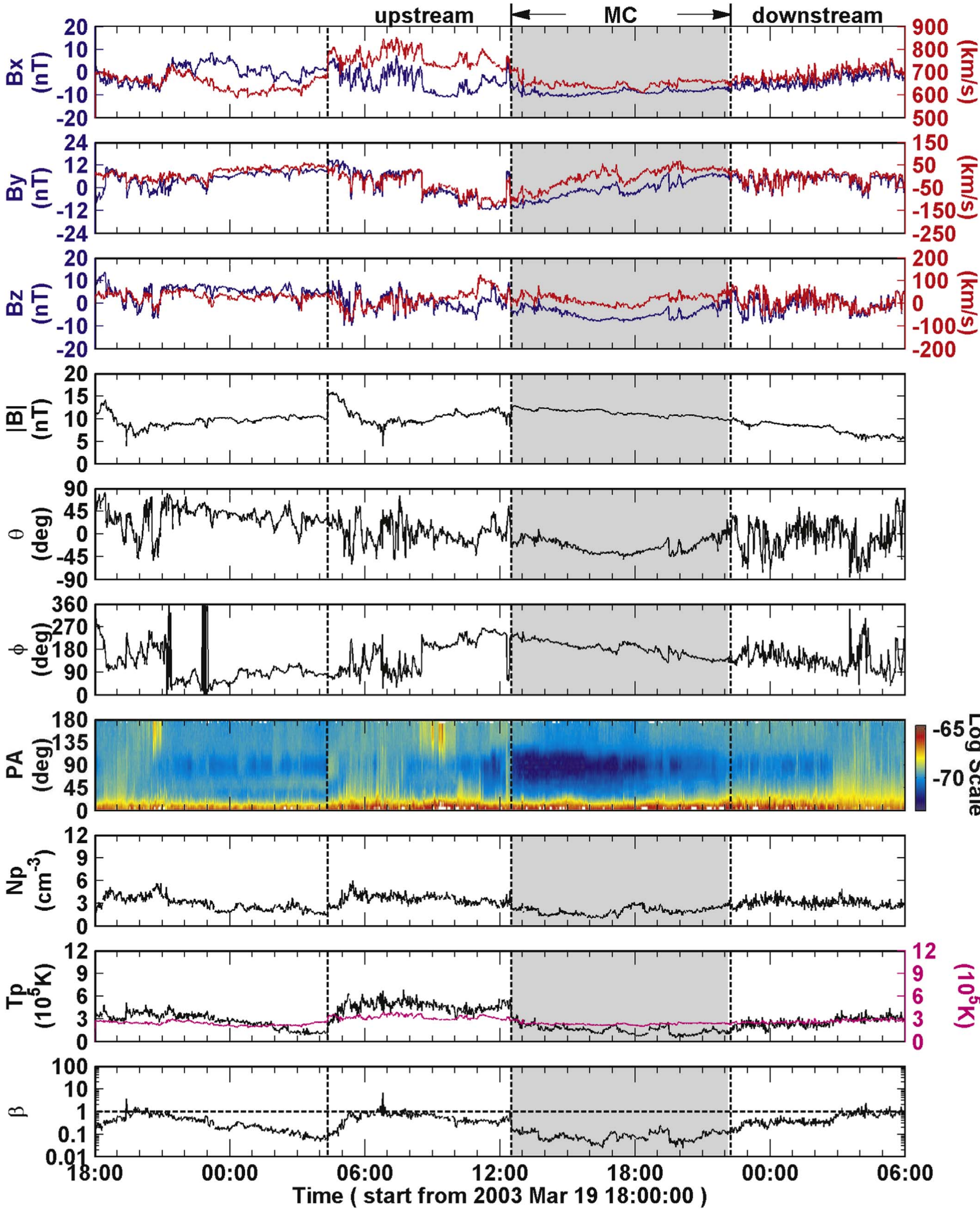

Figure 2. Solar wind parameters observed by *ACE* with a time resolution of 64 s during 2003 March 19–21. Same format as Figure 1, except pitch for the angle (PA) of the suprathermal electron (∼272 eV).

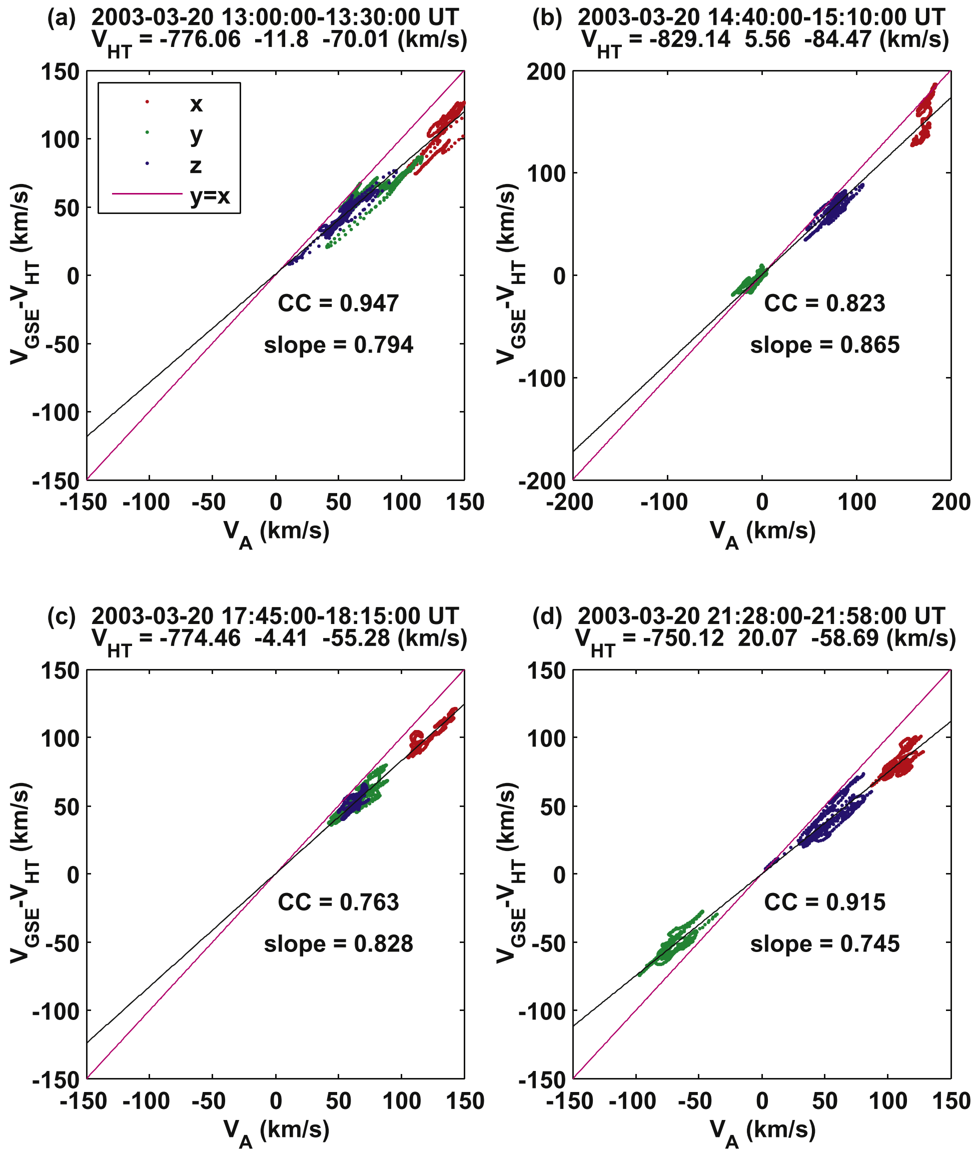

Figure 3. (a) Plasma velocity in the HT frame ($V_{\mathrm{GSE}} - V_{\mathrm{HT}}$) vs. Alfvén velocity ($V_{\mathrm{A}}$) of all three components for a segment in the leading portion of the MC. The HT frame velocity, correlation coefficient, and the linear regression fitting slope are shown. Panels (b), (c), and (d) are the same as (a), but for segments in the middle leading, middle trailing, and trailing portions of the MC, respectively.

consistent with the characteristic of the arc-polarized Alfvén waves. In contrast, the magnetic field within the MC underwent irregular alternate rotations along an arc through a relatively small angle (around 20°–30°), which seems consistent with the appearance of phase-mixed torsional waves that consist of alternate azimuthal perturbations of the magnetic field and plasma velocity. If this is the case, one possible explanation for the irregular rotations is that the neighboring flux surfaces across the MC oscillated with different phases and frequencies (e.g., Heyvaerts & Priest 1983). Presently we have no knowledge of how large the azimuthal angles of torsional Alfvén waves within MCs should be. Jess et al. (2009) observed a twist of ±22° produced by torsional Alfvén waves in the lower solar atmosphere, which may provide a reference for the torsional perturbations occurring in interplanetary flux ropes. These results inspire us to further examine whether similar magnetic field rotations happened in the torsional Alfvén wave event identified by Gosling et al. (2010). Specifically, the torsional Alfvén waves were embedded within a small-scale magnetic flux rope on 2003 January 12. As expected, alternate magnetic field rotations through a small angle are indeed seen. Even so, there is no direct observational evidence for the oscillations of the azimuthal component of the magnetic field inside the MC, and thus the interpretation in terms of arc-polarized Alfvén waves cannot be ruled out.

Wang et al. (2015) found that a significant poloidal motion of plasma existed in some MCs, including the MC of interest on 2003 March 20 with a poloidal speed of $\sim 58\ \mathrm{km\,s^{-1}}$. This implies that there might exist helical plasma motions following the helical magnetic field lines inside the MC, which could give rise to fluctuations in plasma velocity and the magnetic field in good correlation. To evaluate this possibility, a velocity-modified cylindrical force-free flux rope model is applied to the MC. The fit values of plasma velocity show strong correlation ($r \sim 0.93$) with the observed velocity (see Wang et al. 2015, their Figure 13).

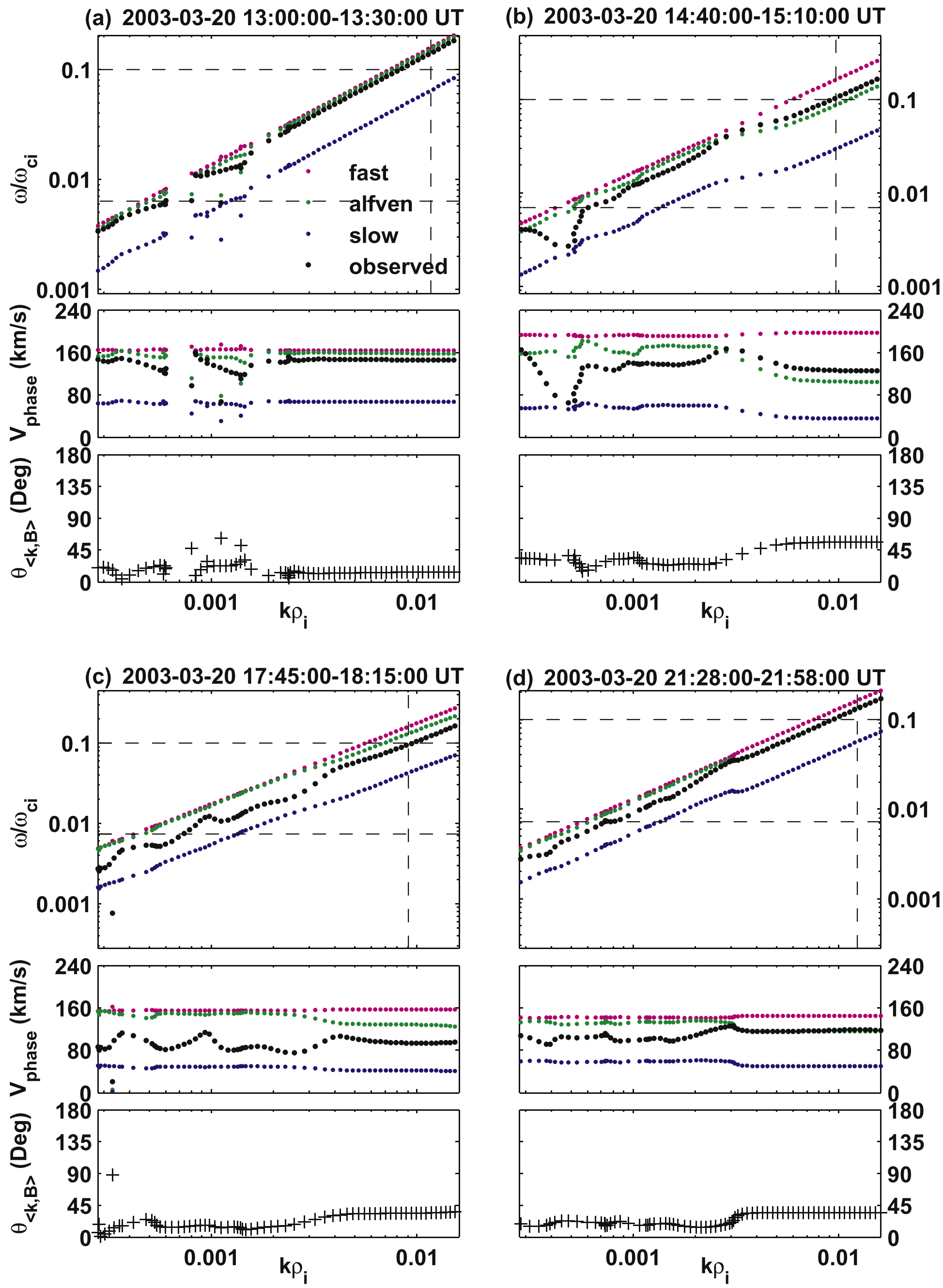

Figure 4. (a) From top to bottom: dispersion relation comparisons between observed and theoretical MHD waves, phase speed comparison between observed and theoretical MHD waves, and the angle between the wavevector and magnetic field for a segment in the leading portion of the MC (see the text for details). The three dashed lines in the top panels mark the range for comparison. Panels (b), (c), and (d) are the same as (a), but for segments in the middle (two intervals) and the trailing portions of the MC.

However, this does not mean that the fluctuations within the MC are more likely to be associated with helical plasma flow rather than Alfvén waves. First, the microscale fluctuations within the MC have not been effectively captured by the flux rope model. Second, the helical plasma flow is unable to account for the good match degree between the observed dispersion relations and the theoretical dispersion relations of Alfvén waves, as well as the alternate magnetic field rotations through a small angle. Of course, it is possible that the field-aligned helical plasma flow was mixed with Alfvén waves exhibiting the signatures of the Alfvénic-like fluctuations.

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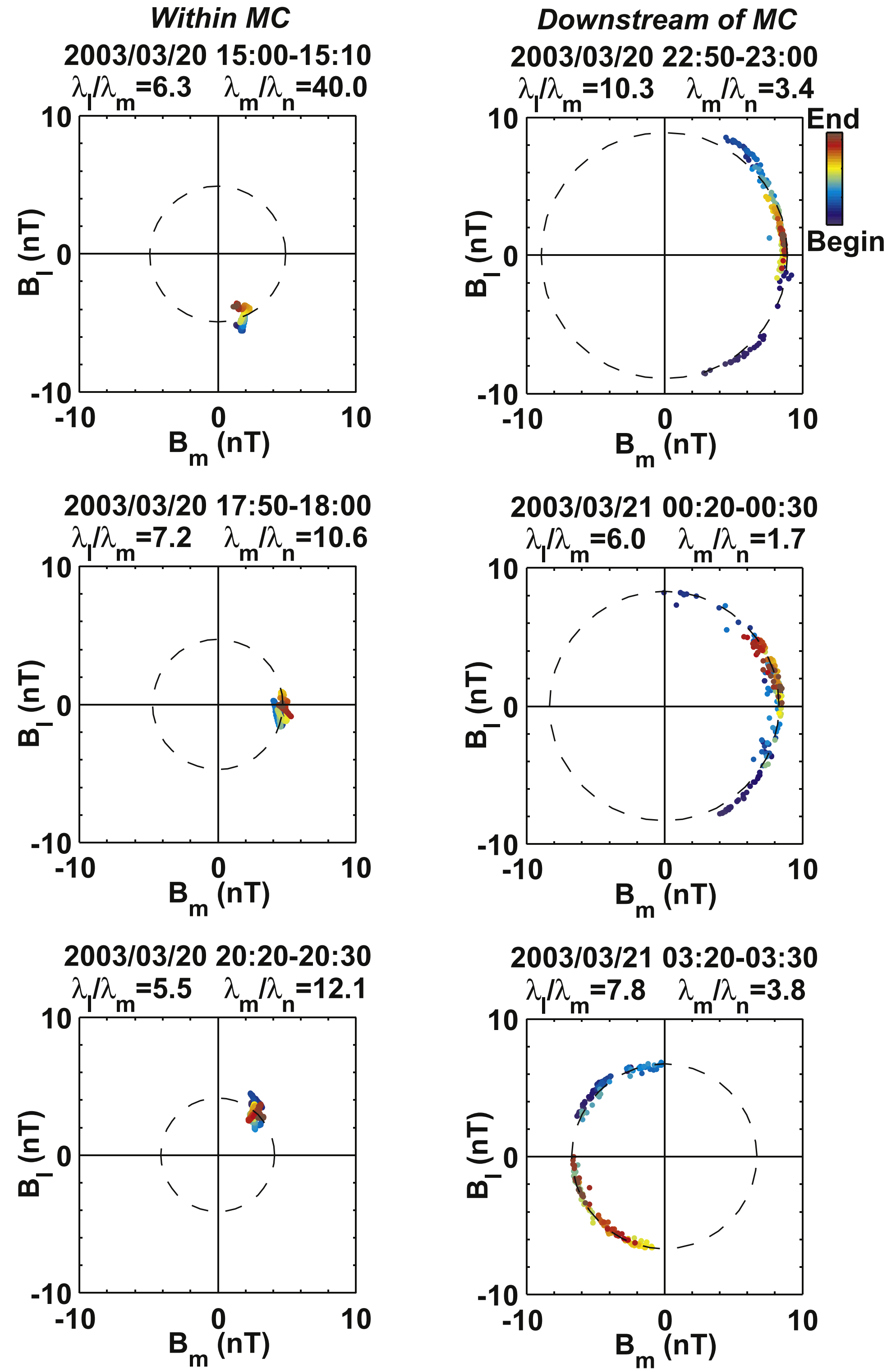

Figure 5. Hodogram of the magnetic field B_l and B_m components (along the maximum and intermediate variance directions, respectively) in the plane perpendicular to the n direction (the minimum variance direction) during ten-minute intervals within the MC (left) and the downstream of the MC (right). The ratio of the maximum to the intermediate eigenvalue (λ_l/λ_m) and that of the intermediate to the minimum eigenvalue (λ_m/λ_n) are shown.

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