Supplementary Information for

Direct Evidence for Cross-scale Energy Transfer in Mars's Space

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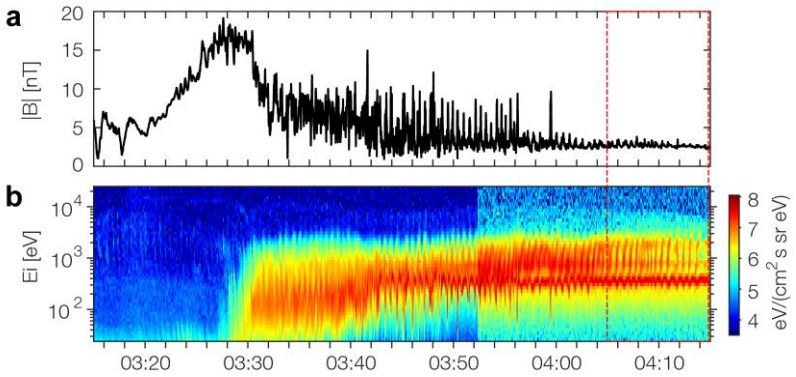
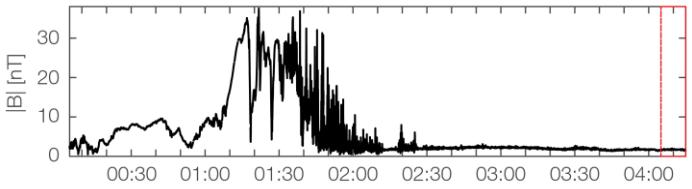
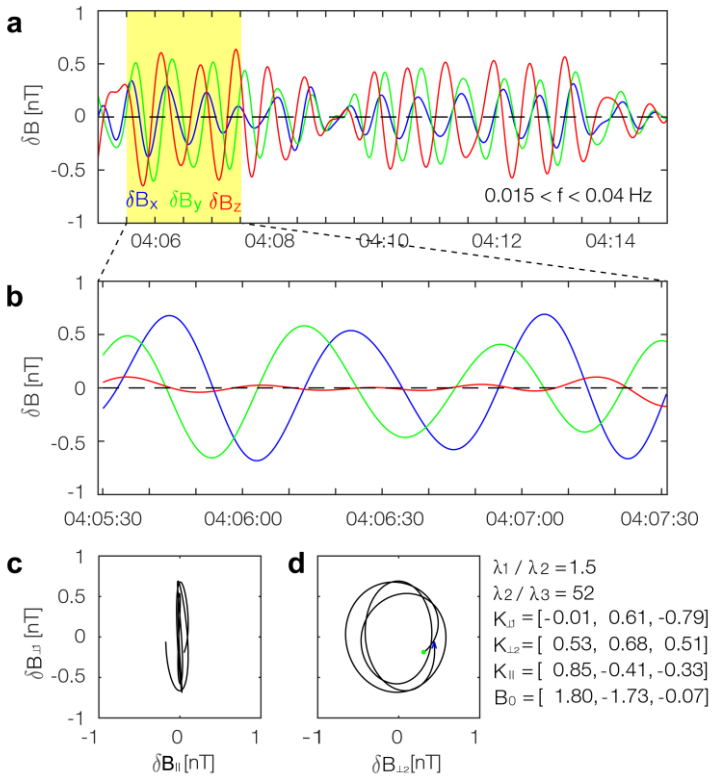


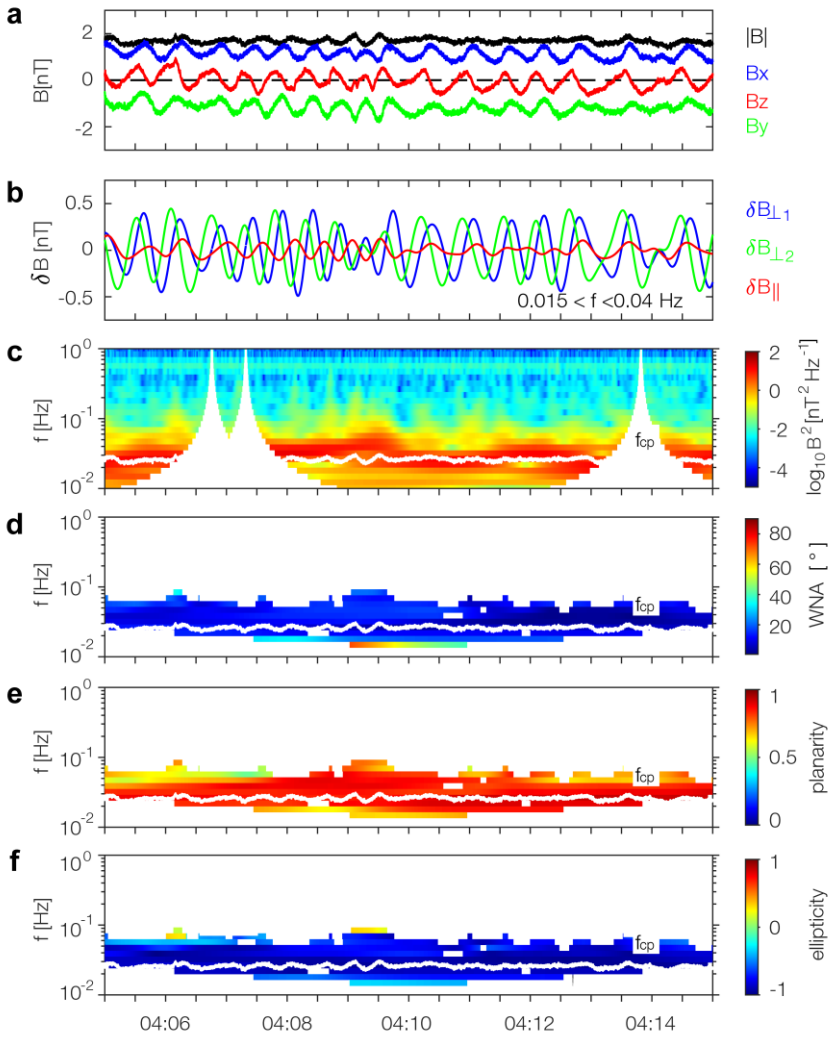
Supplementary Fig. 1. MAVEN crossing a quasi-parallel bow shock. **a** Magnetic field strength. **b** Ion differential energy flux. Approximately 35 minutes prior to the interval of interval (marked by red dashed box), MAVEN's passage across the bow shock into the solar wind detected a broad shock transition region characterized by intense magnetic field fluctuation—a signature indicative of a quasi-parallel bow shock.



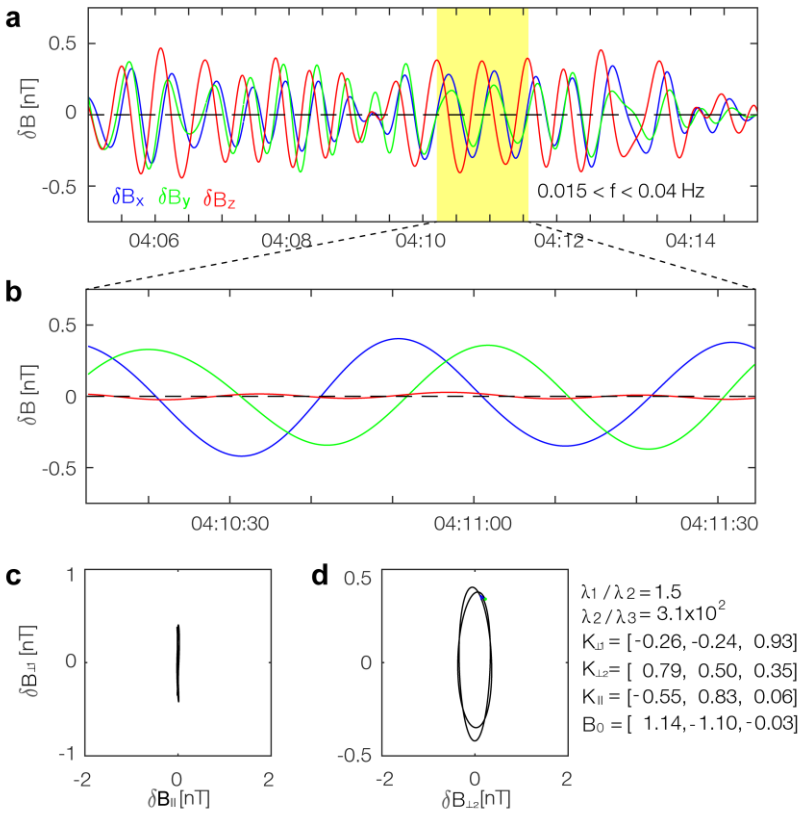
Supplementary Fig. 2. Tianwen-1 crossing a quasi-parallel bow shock. Approximately 150 minutes prior to the interval of interval (marked by red dashed box), **Tianwen-1**'s passage across the bow shock into the solar wind detected a broad shock transition region characterized by intense magnetic field fluctuation—a signature indicative of a quasi-parallel bow shock.



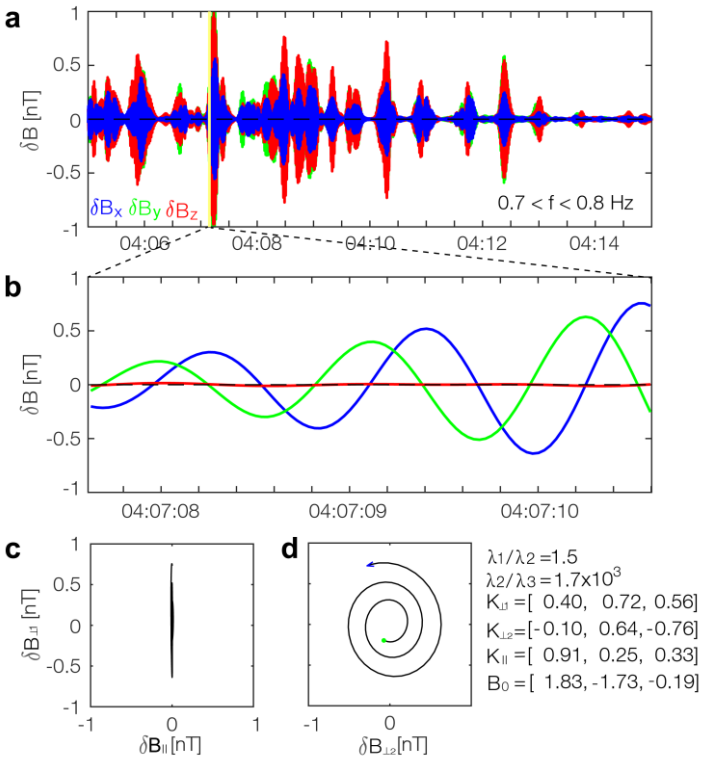
Supplementary Fig. 3. Minimum variation analysis (MVA) on low-frequency waves observed by MAVEN. a Waveform $\delta \boldsymbol{B}$ of the low-frequency wave obtained by a band-pass filtering between 0.015–0.04 Hz during the interval of interest (04:05:00–04:15:00 UT). **b** A Zoom-in view of this waveform $\delta \boldsymbol{B}$ between 04:05:30.044 and 04:07:30.060 UT. Vector quantities in panels **a–b** are shown in the Mars solar orbital (MSO) coordinates. **c–d** Hodograph of $\delta B_{\parallel} - \delta B_{\perp 1}$ (**c**) and $\delta B_{\perp 2} - \delta B_{\perp 1}$ (**d**) obtained from MVA on this waveform $\delta \boldsymbol{B}$ between 04:05:30.044 and 04:07:30.060 UT. $K_{\parallel}$, the minimum variation direction, represents the wave propagating direction in MSO coordinate. Both $K_{\perp 1}$ and $K_{\perp 2}$ are perpendicular $K_{\parallel}$, completing the right-hand coordinate system. Therefore, the waveform ($\delta B_{\perp 1}$, $\delta B_{\perp 2}$, $\delta B_{\parallel}$) in the ($K_{\perp 1}$, $K_{\perp 2}$, $K_{\parallel}$) coordinate can be transformed from that in MSO coordinate. The ratio of intermediate to minimum eigenvalue is 52, large enough to ensure the reliability of the MVA result. The green dot in panel **d** represents start point, while the blue arrow in panel **d** denotes end point. Hodograph of $\delta B_{\perp 2} - \delta B_{\perp 1}$ exhibit a left-handed polarization characteristic.



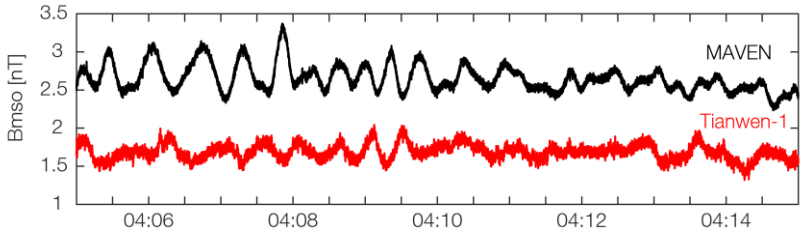
Supplementary Fig. 4. Polarization analysis of low-frequency waves observed by Tianwen-1 spacecraft. a–f Polarization analysis of low-frequency waves, including magnetic field B_x , B_y and B_z components (**a**), waveform δB_x , δB_y and δB_z components obtained by a band-pass filtering between 0.015 and 0.04 Hz (**b**), power spectral density of magnetic field (**c**), wave normal angle (**d**), planarity (**e**), and ellipticity (**f**). The white lines in panels **c–f** denotes proton cyclotron frequency (f_{cp}). This polarization analysis is obtained by conducting the well-established singular value decomposition (SVD) method of the magnetic fields.



Supplementary Fig. 5. Minimum variation analysis (MVA) on low-frequency waves observed by Tianwen-1 spacecraft. a Waveform $\delta \boldsymbol{B}$ of the low-frequency wave obtained by a band-pass filtering between 0.015–0.04 Hz during the interval of interest (04:05:00–04:15:00 UT). **b** A Zoom-in view of this waveform $\delta \boldsymbol{B}$ between 04:10:12.572 and 04:11:34.572 UT. Vector quantities in panels **a–b** are shown in the Mars solar orbital (MSO) coordinates. **c–d** Hodograph of $\delta B_{\parallel} - \delta B_{\perp 1}$ (**c**) and $\delta B_{\perp 2} - \delta B_{\perp 1}$ (**d**) obtained from MVA on this waveform $\delta \boldsymbol{B}$ between 04:10:12.572 and 04:11:34.572 UT. $K_{\parallel}$, the minimum variation direction, represents the wave propagating direction in MSO coordinate. Both $K_{\perp 1}$ and $K_{\perp 2}$ are perpendicular $K_{\parallel}$, completing the right-hand coordinate system. Therefore, the waveform ($\delta B_{\perp 1}$, $\delta B_{\perp 2}$, $\delta B_{\parallel}$) in the ($K_{\perp 1}$, $K_{\perp 2}$, $K_{\parallel}$) coordinate can be transformed from that in MSO coordinate. The ratio of intermediate to minimum eigenvalue is 310, large enough to ensure the reliability of the MVA result. The green dot in panel **d** represents start point, while the blue arrow in panel **d** denotes end point. Hodograph of $\delta B_{\perp 2} - \delta B_{\perp 1}$ exhibit a left-handed polarization characteristic.



Supplementary Fig. 6. Minimum variation analysis (MVA) on whistler-mode waves observed by MAVEN. a Waveform $\delta\boldsymbol{B}$ of the low-frequency wave obtained by a band-pass filtering between 0.7–0.8 Hz during the interval of interest (04:05:00–04:15:00 UT). **b** A Zoom-in view of this waveform $\delta\boldsymbol{B}$ between 04:07:07.624 and 04:07:10.606 UT. Vector quantities in panels **a–b** are shown in the Mars solar orbital (MSO) coordinates. **c–d** Hodograph of $\delta B_{\parallel} - \delta B_{\perp 1}$ (**c**) and $\delta B_{\perp 2} - \delta B_{\perp 1}$ (**d**) obtained from MVA on this waveform $\delta\boldsymbol{B}$ between 04:07:07.624 and 04:07:10.606 UT. $K_{\parallel}$, the minimum variation direction, represents the wave propagating direction in MSO coordinate. Both $K_{\perp 1}$ and $K_{\perp 2}$ are perpendicular $K_{\parallel}$, completing the right-hand coordinate system. Therefore, the waveform ($\delta B_{\perp 1}$, $\delta B_{\perp 2}$, $\delta B_{\parallel}$) in the ($K_{\perp 1}$, $K_{\perp 2}$, $K_{\parallel}$) coordinate can be transformed from that in MSO coordinate. The ratio of intermediate to minimum eigenvalue is 1700, large enough to ensure the reliability of the MVA result. The green dot in panel **d** represents start point, while the blue arrow in panel **d** denotes end point. Hodograph of $\delta B_{\perp 2} - \delta B_{\perp 1}$ exhibit a left-handed polarization characteristic.



Supplementary Fig. 7. Comparison between oscillation amplitude of low-frequency waves detected by MAVEN and Tianwen-1. The black and red curve represents oscillation amplitude of low-frequency waves detected by MAVEN and Tianwen-1, respectively. They are band-passed magnetic strength between 0.015 Hz and 0.04 Hz.