First Detection of Radial and Azimuthal Oscillations in Halo CMEs

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Introduction

- There have been many observations on the oscillations of prominence/filaments [Oliver & Ballester 2002; Lin et al. 2007; Tripathi et al. 2009] and coronal loops [Aschwanden et al. 2003; Nakariakov & Verwichte 2005; Ruderman & Erdelyi 2009; Terradas 2009].

- The interest in MHD oscillations is connected with MHD seismology - diagnostics of plasma parameters and physical processes operating in the plasma by means of MHD oscillations.
Introduction

- Krall et al. [2001] found that the projected velocities varied with the period of about 4 - 6 hours for 11 CME events.
- Shanmugaraju et al. [2010] found that the periods of quasi-periodic oscillations range between 48 and 240 minutes for 15 CME events.
Data

- We consider well-observed 9 HCMEs by LASCO from 2011 February to June.

- The running difference images of the propagation of the HCME (5:42-07:42 UT) on 2011 June 21. The radial white lines (every 15°) show the given direction and black dots show the measured front edge of the HCME.
Spherical harmonics

Laplace's equation in spherical coordinates

\[ \nabla^2 f = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial f}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial f}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 f}{\partial \varphi^2} = 0 \]

\[ r^2 \nabla^2 Y_{\ell}^m(\theta, \varphi) = -\ell(\ell + 1)Y_{\ell}^m(\theta, \varphi) \]

Is called spherical harmonic function of degree \( \ell \) and order \( m \)

\( \ell \) : degree, the total number of node circles on the sphere

\( m \) : longitudinal order, the number of node circles through the poles

\( \ell = 1, m = 0 \quad \ell = 3, m = 2 \quad \ell = 10, m = 5 \quad \ell = 3, m = 2 \quad \ell = 5, m = 2 \)
Results

\[ V_{\text{ins}} = \Delta V \sin(\omega(t - K)) + b \]

- **\( V_{\text{ins}} \):** instantaneous speed
- **\( \Delta V \):** speed amplitude
- **\( \omega \):** cyclic frequency
- **\( K \):** phase
- **\( b \):** mean value

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Maximum amplitude

Harmonic function

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Results (wave mode : m=1)

- Oscillation direction (arrow) : 75°
- Oscillation period : 24 mins
- Speed amplitude : 400 km/s
- Projection speed : 800 km/s
Results (wave mode: m=1)

- Oscillation direction (arrow): 135°
- Oscillation period: 48 mins
- Speed amplitude: 300 km/s
- Projection speed: 800 km/s
Results (wave mode : m=2)

- Oscillation direction : 15°, 105°
- Oscillation period : 24 mins
- Speed amplitude : 800 km/s
- Projection speed : 1500 km/s
Results  (complex wave pattern)

- Oscillation direction: 30°, 90°
- Oscillation period: 24 mins
- Speed amplitude: 700 km/s
- Projection speed: 1300 km/s
Results

- Correlation between (a) the observed maximum projected speed ($V_{pro}$) and the oscillation amplitude ($2\Delta V$). (b) the oscillation period and amplitude.

![Graph showing correlation between $V_{pro}$ and $2\Delta V$ with CC = 0.92 and RMSE = 230 km s$^{-1}$]

![Graph showing correlation between Period (min) and $2\Delta V$]

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Discussions

- One interpretation is connected with the natural oscillations of the plasmoid displaced from its equilibrium.

- In particular, estimations performed by Cargill et al. [1994] and Filippov et al. [2001] showed that a curved magnetic rope could perform oscillations with a period up to several tens of minutes.
These models accounted for the restoring force caused by the perturbations of the magnetic field and also the aerodynamic drag force.

These results would be consistent with the observed coincidence of the m=1 oscillation polarization with the direction along the HCME position angle.
Discussions

- Another possibility is connected with the typical zigzagging trajectory of an emerging body, connected with shedding of vortices.

- This mechanism belongs to the class of self-oscillations that appear because of the nonlinear conversion of DC energy (e.g. of the steady flow) in AC energy (e.g. the transverse oscillatory motion).

- $B_e$: external magnetic field
  - $F$: MHD force

Nakariakov et al. [2009]
Summary

- We present the **first observational detection** of radial and azimuthal oscillations in full HCMEs.

- The oscillations in seven events are found to be associated with distinct azimuthal wave modes with the azimuthal wave number \( m=1 \) for six events and \( m=2 \) for one event.

- We find that the development of all these HCMEs is accompanied with **quasi-periodic variations** of the instantaneous radial velocity with the periods ranging from **24 to 48 minutes**.
Summary

- The amplitudes of the instant speed variations reach about a half of the projected speeds. The amplitudes are found to anti-correlate with the periods and correlate with the HCME speed, indicating the nonlinear nature of the process.

- The polarization of the oscillations in these seven HCMEs is broadly consistent with those of their position angles with the mean difference of 43 degrees.

- The oscillations may be connected with natural oscillations of the plasmoids around a dynamical equilibrium, or self-oscillatory processes, e.g. the periodic shedding of Alfvénic vortices.