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Conditions for the existence of Kelvin-Helmholtz instability in a CME

Andrés Páez[1], Vera Jatenco-Pereira[1], Diego Falceta-Gonçalves[2] and Merav Opher[3]

[1]Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas,
Rua do Matão 1226, São Paulo, SP, 05508-090, Brazil
email: `andresspaez@usp.br`

[2]Universidade de São Paulo, Escola de Artes, Ciências e Humanidades,
Rua Arlindo Bettio 1000, São Paulo, SP, 03828-000, Brazil
email: `dfalceta@usp.br`

[3]Astronomy Department, Boston University,
Boston, MA 02215, USA
email: `mopher@bu.edu`

Abstract. The presence of Kelvin-Helmholtz instability (KHI) in the sheaths of Coronal Mass Ejections (CMEs) has been proposed and observed by several authors in the literature. In the present work, we assume their existence and propose a method to constrain the local properties, like the CME magnetic field intensity for the development of KHI. We study a CME in the initiation phase interacting with the slow solar wind (Zone I) and with the fast solar wind (Zone II). Based on the theory of magnetic KHI proposed by Chandrasekhar (1961) we found the radial heliocentric interval for the KHI existence, in particular we constrain it with the CME magnetic field intensity. We conclude that KHI may exist in both CME Zones but it is perceived that Zone I is more appropriated for the KHI formation.

**Keywords.** Sun, Coronal mass ejection, Kelvin-Helmholtz instability.

1. Introduction

Coronal Mass Ejections (CMEs) are one of the strongest ejections (10^{31} ergs and 10^{15} g), originated at the solar surface. A normal CME has a three-part structure morphology: core, cavity and frontal loop (Illing & Hundhausen 1985). A CME propagates with velocities of 20 to 3200 km/s (Brueckner *et al.* 1995), expands with velocities approximately twice radial velocity (Rigozo, Dal Lago & Nordeman 2011) and deflects in the interplanetary space with magnitude and direction depending mainly on the CME mass and velocity (Kay, Opher & Evans 2015). The CME propagation allows shock wave formation ahead of the ejection, and the CME-sheath formation by the plasma compression behind the shock.

The Kelvin-Helmholtz instability (hereafter KHI), is a fast phenomenon in the boundary interface between two fluids developed mainly by the existence of a velocity gradient or velocity shear. The velocity shear provides kinetic energy to the boundary surface of the fluids allowing the formation of the rolled-up KH vortex. The KHI can be affected by the topology and magnitude of the magnetic field (Chandrasekhar 1961). A magnetic field parallel to the interface of the fluids is critical for the KHI development.

Foullon *et al.* (2011) analyzed the fast CME of November 3 of 2010 occurred near the southeast of the solar limb in the active region (AR) NOAA 11121 where is clear the formation of the flux rope. They considered the development of the KHI in the north flank of the ejection in distances of 150 Mm above the solar surface. Foullon *et al.* (2013)
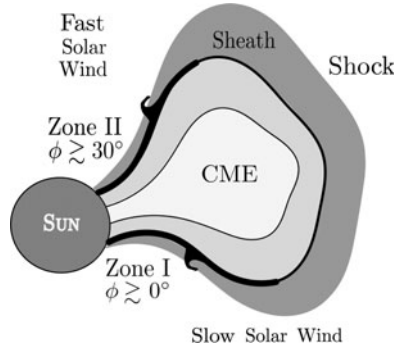
Figure 1. A cartoon showing the CME Zones I and II the regions of our study. Zone I represents the interaction with slow solar wind (latitudes $\phi \gtrsim 0^o$) and Zone II the interaction with the fast solar wind ($\phi \gtrsim 30^o$). The shaded area represents the CME sheath.

44 made a spectral analysis to explore the CME plasma structure to corroborate the features
45 observed by Foullon *et al.* (2011). Nykyri & Foullon (2013) showed with 2.5-D magneto-
46 hydrodynamic (MHD) simulations the development of the KHI in the conditions of the
47 ejecta of November 3 of 2010. With this work they showed the first calculus for determin-
48 ing the magnetic fields appropriated for the KHI development between the sheath and
49 its CME in distances of the low corona. A similar situation observed by Foullon (2011)
50 is shown in Figure 1. The regions of our study are represented by Zones I and II. The
51 first one represents the interaction with slow solar wind (latitudes $\phi \gtrsim 0^o$) and Zone II
52 the interaction with the fast solar wind ($\phi \gtrsim 30^o$). The shaded area represents the CME
53 sheath.
54   In this paper, we implement a method for finding the distances in which heliospheric
55 distances the KHI exists. We study a CME in the initiation phase in interaction with the
56 slow solar wind (Zone I) and with the fast solar wind (Zone II).

57 ## 2. Model

58   We adopt the condition of existence of the magnetic KHI proposed by Chandrasekhar
59 (1961) to the interaction between solar wind and a CME, in an infinitely thin sheath. We
60 assumed a electron-proton plasma, with densities $\rho = \rho_e + \rho_p$, with the approximations,
61 $\rho_e \approx n_e m_e$, $\rho_p \approx n_p m_p$ (m_e, m_p are electron and proton masses), and quasi-neutrality
62 MHD, $n_e \approx n_p \approx n$:

$$\left(U_{SW} - U_{CME}\right)^2 > \frac{n_{SW} + n_{CME}}{m_p\, n_{SW}\, n_{CME}}\left(B_{SW}^2 + B_{CME}^2\right), \qquad (2.1)$$

64 where U_{SW}, U_{CME}, n_{SW}, n_{CME}, B_{SW} and B_{CME} are solar wind and CME velocities,
65 numerical densities and magnetic field, respectively.
66   We have constructed velocity functions for the solar wind slow and fast using a profile
67 hyperbolic tangent, $U_{SW}^{Slow,Fast}(r) = a\,tanh[(r-1)/b] + d$ (km s^{-1}) (Coles *et al.* 1991),
68 with the transformation: $tanh(r-1)$ to initiate at the solar surface. We adjust the
69 constants a, b and d in there different points, the solar surface, $1R_\odot$ with $U_{SW}^{Slow,Fast}$
70 velocities taken from Harra *et al.* (2008), He *et al.* (2010), $3R_\odot$ from Quémerais *et al.*
71 (2007), Antonucci, Dodero & Giordano (2000) and $40R_\odot$, where we assume a constant
72 value for the slow and fast solar wind. For the numerical densities of the slow and fast
73 solar wind, we use mass conservation law where the values at the solar surface were taken
74 from Fludra *et al.* (1999). For the magnetic field of the solar wind we use conservation of

Table 1. Values for slow and fast solar wind velocities in three heliocentric distances $r = 1, 3$ and $40\,\mathrm{R_\odot}$, values for the constants a, b and d, values for the densities and for the magnetic fields at $r = 1\,R_\odot$.

U_{SW}	$r = 1$	$r = 3$	$r = 40$	a	b	d	n_{SW} (cm^{-3})	B_{SW} (G)
U^{Slow}	100	200	400	299.9	5.77	100	$n^{Slow} = 2 \times 10^8$	$B^{Slow} = 2.2$
U^{Fast}	250	400	750	497	6.42	250	$n^{Fast} = 3 \times 10^8$	$B^{Fast} = 6$

magnetic flux law where the values at the solar surface were evaluated from (Manchester *et al.* 2004) see Table 1.

For the existence of the KHI we are interested only in the Zones I and II where both magnetic fields of slow and fast solar wind and CME are parallel. In these situations we have a sheath with higher density, which we suppose to have a constant value of $n_{sheath} = 10^9\,\mathrm{cm^{-3}}$ (Hannah & Kontar 2013).

3. Results and Conclusions

Constraint the intervals of heliocentric distances where de KHI can exists, r_{KH}, we have to find the values of velocities and densities for slow and fast solar wind and CME that satisfies the equation (2.1), linked with the value of CME magnetic field intensity. We found that in the Zone I the KHI can exists in the heliocentric distances of $0.15\mathrm{R_\odot} \leqslant r_{KH}^{Slow} \leqslant 0,61\mathrm{R_\odot}$ linked to $1\mathrm{G} \leqslant B_{CME}^{Slow} \leqslant 1.81\mathrm{G}$. In Zone II the KHI can exists for distances $r_{KH}^{Fast} \leqslant 1.41\mathrm{R_\odot}$ linked to $1\mathrm{G} \leqslant B_{CME}^{Fast} \leqslant 2.88\mathrm{G}$. The interval for r_{KH}^{Slow} is in accordance with the results obtained by Foullon *et al.* (2011) and the values for B_{CME}^{Slow} is in agreement with the work of Möstl, Temmer & Veronig (2013).

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