

Study of Viscosity Modeling of Coronal Mass Ejection

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Abstract

In Coronal Mass Ejection (CME) propagation CME-CME is a newly emerging theory reveals some unsolved issues in Astrophysics. A CME-CME interaction is closely related with a enhancement signature (Gopalswamy et al. 2001) and low energy proton acceleration in >10 Mev (Gopalswamy et al. 2002). The present study analyzed the change in momentum of pre and primary CME for a CME-CME interaction event (23 Jan 2012 day halo CME event) with respect to elastic coefficient. The study suggests that the increase in momentum change of pre CME and decrease in momentum change of primary CME for the function of elastic coefficient. It confirms the momentum transfer effect on pre CME from primary CME. A new dynamic viscosity model is developed to estimate CME viscosity.

Keywords: - Coronal Mass Ejection - Momentum - Viscosity .

INTRODUCTION

CMEs are the most important phenomena that can change the space weather activities. Coronagraphs can give the propagation information (speed, width, height, mass) of a CME. Interaction between CMEs can also be detectable by a coronagraph if they propagate in from

same active region and within field of view. LASCO and STEREO coronagraphs are now available to study CME-CME interaction. CME – CME interactions and its radio signature features was first investigated by Gopalswamy et al. (2001) using white light coronagraph images from Solar and Heliospheric Observatory/

Large Angle Spectrometric Coronagraph (SOHO/LASCO) and type II spectra at long wavelengths from the Radio and Plasma Wave Experiment (WAVES) on board the Wind spacecraft. Gopalswamy et al. (2001) suggested that the observed radio enhancement was generated due to the increased density in the upstream medium provided by the pre CME that increase in density reduced the Alfvén speed, thereby increasing the Mach number of shock (Gopalswamy et al. 2001, Shanmugaraju et al. 2014, Temmer et al. 2014, Mujib Rahman et al., 2013). The radio signature feature was a non-thermal type radio feature. Sometimes CME-CME interaction can enhance proton acceleration in lower energy range >10 MeV (Gopalswamy et al. 2002, Joshi et al. 2013) Manoharan et al. (2004) found that CME-CME interaction events took longer arrival time due to larger drag by pre CME to reach 1 AU than non-interacting events. The kinematics of CME-CME interaction have been studied by several groups (Temmer et al. 2012, Maricic et al. 2013, Shanmugaraju et al. 2014, Temmer et al. 2014, Misra et al. 2014). Maricic et al. (2013) found the changes in velocities of pre and primary CME after CME-CME interaction for an event occurred during 15 February 2011. All the kinematical studies suggests that

after CME-CME interaction the pre CME speed would increase and primary CME would decrease. However there is need of understanding the change in momentum of pre and primary CME based on elastic coefficient. The need of dynamic viscosity estimation of a CME within coronagraph field of view (FOV) and flow pressure estimation is still an unsolved issues.

To resolve above issues, the important aim of the present study is

- to find the momentum variation of pre and primary CME with respect to elastic coefficient by developing a new model based on kinematics for a CME-CME interaction event
- to estimate the viscosity and flow pressure of a CME event by developing a new dynamic viscosity model.

EVENT SELECTION

The study deals with the kinematical analysis of some CME-CME interaction events during 2011-2013 period of solar cycle 24. These events were studied by several groups [Joshi et al. 2013, Shanmugaraju et al. 2014, Temmer et al. 2014, Misra and Srivatsava 2014, Prasanna, Shanmugaraju and Vrsnak

2016]. The CME information (including Speed, width, mass etc.) are considered from LASCO CME online catalog. The flare details (flare onset time, intensity, location and active region) are taken from GOES spacecraft data catalog. Even a large set of CME-CME interaction events are available in solar cycle 24, the present study considered a CME-CME interaction event on 23 Jan 2012 studied by Joshi et al. (2013) for the kinematical change in momentum analysis. A Type II radio burst associated CME event on 22 May 2013 is considered for the viscosity measurement. It is also a CME-CME/shock interaction event (Prasanna et al. 2016). However, the present study considers only the CME propagation part to estimate CME viscosity.

RESULTS

In this part the CME-CME interaction observation details, the newly developed momentum model and discussion are given.

VISCOSITY MODELING OF CME PROPAGATION

Dynamic viscosity is applicable for both gas and liquid. The CME is also a movement of large plasma magnetic gas cloud. The present study deals with the dynamic viscosity theory application in the

propagation of a CME. The essential condition to apply for a dynamic viscosity measurement the material should be in moving liquid or gas; it has variation of speed in flow in the specific area. The dynamic viscosity is expressed as,

$$\text{Viscosity}(\eta) = \frac{\text{Force}}{\text{Area (velocity gradient)}} \quad (1)$$

The CME propagation is a moving MHD gas object. It has expansion behavior and which is perpendicular to the propagating direction. It has some classical mechanical properties such as mass, linear speed, acceleration, expansion speed. The propagating CME at the solar wind background medium is considered for the study.

$$\text{Viscosity}(\eta) = \frac{m(v_2 - v_1)}{dt * A \left(\frac{dv}{dy} \right)} \quad (2)$$

Here m is the mass of CME, $v_2 - v_1$ is the velocity difference of the CME at different times. A is the surface area of the CME in the semi sphere shaped region. The term dv/dy is the velocity gradient and the term dt is the time difference.

Let us consider most suitable ice cream cone model to solve this analysis. The Figure 1 shows the propagation of a CME

in ice cream coned shape. Now consider the green colored semi sphere shaped part. The height AB is the expansion of the CME. It is considered term y for the

whole analysis. The CME leading edge height is considered as h from the solar disc in STEREO COR-2 coronagraph image.

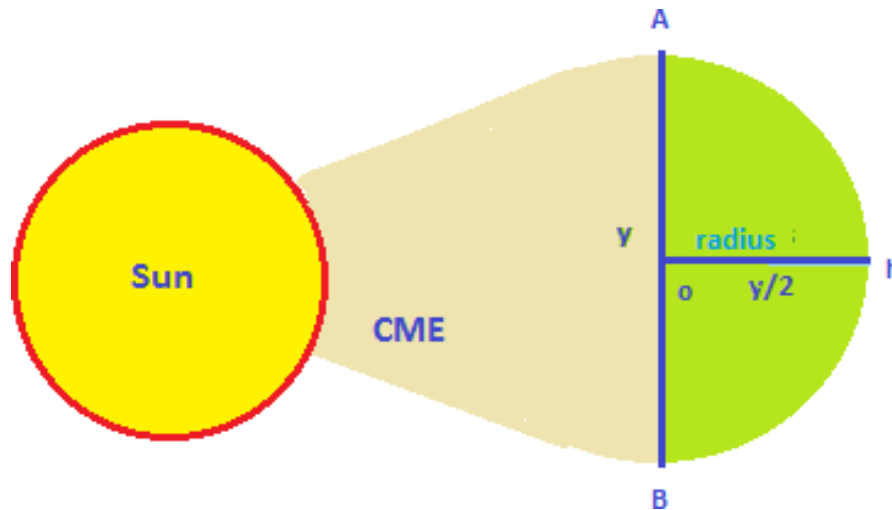


Fig-1 The propagation of a CME with expansion based on ice cream cone model

Table-1 The dynamic viscosity and expansion measurement of the CME

Time	CME height at Leading edge	Expansion height (y)	Velocity	f	A	dv/dy	Viscosity
hh:mm	Rs	Rs	km/s	N	m^2	s^{-1}	Pa s
13:39	4.35	5.82	-	-	-	-	-
14:09	7.47	8.88	1205	$5.71E+15$	$6.00E+19$	$2.7E+14$	$4.07E-19$
14:39	10.6	13.00	1228	$2.23E+14$	$1.28E+20$	$3.8E+12$	$2.56E-19$
14:54	11.4	14.82	591	$7.20E+15$	$1.67E+20$	$2.4E+14$	$1.74E-19$
15:09	12.6	16.12	955	$3.85E+15$	$1.97E+20$	$2E+14$	$1.05E-19$
15:24	13.5	16.65	682	$3.15E+15$	$2.10E+20$	$3.6E+14$	$4.01E-20$

A CME-CME/shock interaction event on 22 May 2013 was studied by Prasanna et al. 2016 and they estimate the expansion speed, radial speed. The study first deals with the loss of KE between CME-CME interaction. Using the pre CME speed = 687 km/s and primary CME speed = 1466 km/s, the pre CME mass = 31×10^{12} kg and primary CME mass = 33×10^{12} kg of LASCO CME data, the change in KE is estimated to be 4.84×10^{24} J using equation 3. The primary CME is a fast and wide halo CME event. A CME driven shock propagated at speed ~ 1500 km/s got interaction with the pre CME. To validate the viscosity model of CME, the present study excludes the shock and interaction part. The viscosity study considers only CME part of the primary CME.

Table 2 shows the details of primary CME and its viscosity measurement. The column 1 gives the time observation of the

event; column 2 shows the leading edge height at position h in Rs and coloumn 3 shows the expansion height at position AB in Rs. The CME velocity in km/s, estimated force in N, surface area A in m² and velocity gradient dv/dy in s⁻¹ and viscosity are given in columns 4-8. It shows that the velocity of the CME, force and viscosity decreased from maximum to minimum, while the surface area of the semi spherical part and change in velocity gradient increased gradually. The Figure 2 shows the viscosity profile of the CME with respect to the time of observation on STEREO COR-2 coronagraph. The declining linear type response is shown in figure. The mean viscosity is calculated as 1.96×10^{-19} Pa s. The mean flow pressure is estimated by taking the ratio between force and surface area, which is calculated as, 3.5×10^{-5} Pa. Generally solar wind has flow pressure ~ 1 nPa and ICME has ~ 10 nPa at 1 AU.

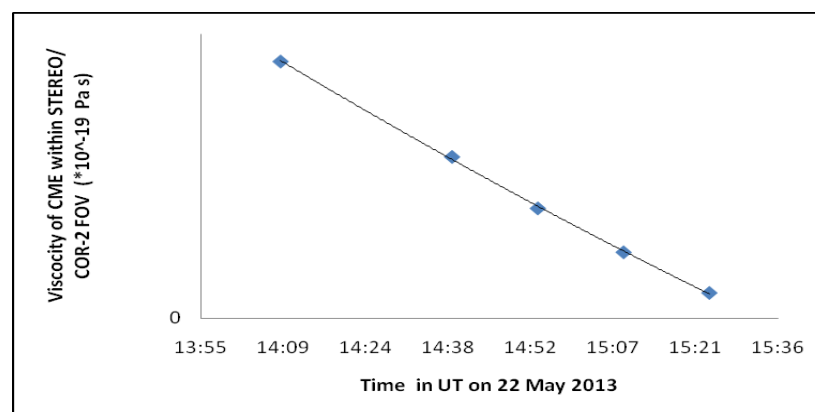


Fig-2 The viscosity-time profile of the CME on 22 May 2013 day event

MOMENTUM TRANSFER MODELING OF CME-CME INTERACTION

By considering e as elastic coefficient Shanmugaraju et al. (2014) have given the loss of KE expression, which is applicable for CME-CME interaction events as,

$$\Delta E = m_1 m_2 [1 - e^2] [u_1 - u_2]^2 / [2 (m_1 + m_2)] \quad (3)$$

The coefficient of restitution is given as,

$$v_1 - v_2 = -e (u_1 - u_2) \quad (4)$$

The suffix terms 1 and 2 refer the pre and primary CME. The term u and v denote the magnitude of velocity of a CME before and after interaction. Their study also found the change in momentum, impulse force and acceleration of primary CME. The kinematic model importantly suggests the interaction overlapping angle. The limitation of their model is to need of primary CME velocity before and after interaction as well as exclusion of elastic coefficient. Hence to resolve these issues, the present study extended their analysis for change in momentum as a function of CME initial velocities based on conservation of momentum and

conservation of energy as followed by Shanmugaraju et al. (2014)

The change in momentum of primary CME is expressed as,

$$\Delta P = m_1 m_2 [1 + e] [u_1 - u_2] / (m_1 + m_2) \quad (5)$$

The change in momentum of pre CME is expressed as,

$$\Delta P = m_1 m_2 [1 + e] [u_2 - u_1] / (m_1 + m_2) \quad (6)$$

A CME-CME interaction mechanism is classified into complete inelastic, partial elastic, super elastic mechanism. The complete inelastic type interaction denotes $e = 0$ for which the loss of KE should be maximum for a CME-CME interaction event as suggested by Shanmugaraju et al. (2014).

On 23 Jan 2012, at 02:03 UT Geostationary Operational Experimental Satellite/X-Ray Sensor (GOES/XRS) detected a start of a M class flare in higher wavelength channel ($1 \text{ \AA} - 8 \text{ \AA}$) and it attained peak at 03:13 UT. Then a partial halo type CME was detected in LASCO C2 and C3 coronagraph during 03:12 –

04:00 UT. The linear speed of the CME was listed as 684 km/s. At 03:35 UT, another M class flare was detected by GOES spacecraft. A fast and energetic halo type CME was detected by LASCO C2 and C3 coronagraph during the period 04:00 – 06:06 UT. The linear speed of the CME was 2175 km/s. The primary CME interacted with the ongoing pre CME 04:18 UT – 05:00 UT at the height range 6.5 Rs – 9 Rs as found from C3 coronagraph. Joshi et al. (2013) found the merged CMEs due to CME-CME interaction from 04:24 – 04:48 UT for the interaction event. The change in KE or

Loss of KE due to CME-CME interaction is given by Shanmugaraju et al.(2014) for a CME-CME interaction event occurred on 15 Feb 2011. Their model is based on CME masses and their velocity.

By considering the LASCO CME speed and mass values as, $u_1 = 684$ km/s, $u_2 = 2175$ km/s, $m_1 = 5.3 \times 10^{12}$ kg, $m_2 = 2.6 \times 10^{13}$ kg and $e = 0$ (for complete inelastic), the loss of KE is found as 4.89×10^{24} J using Kinematic model given by Shanmugaraju et al.(2014). By considering the above mass and velocity values in

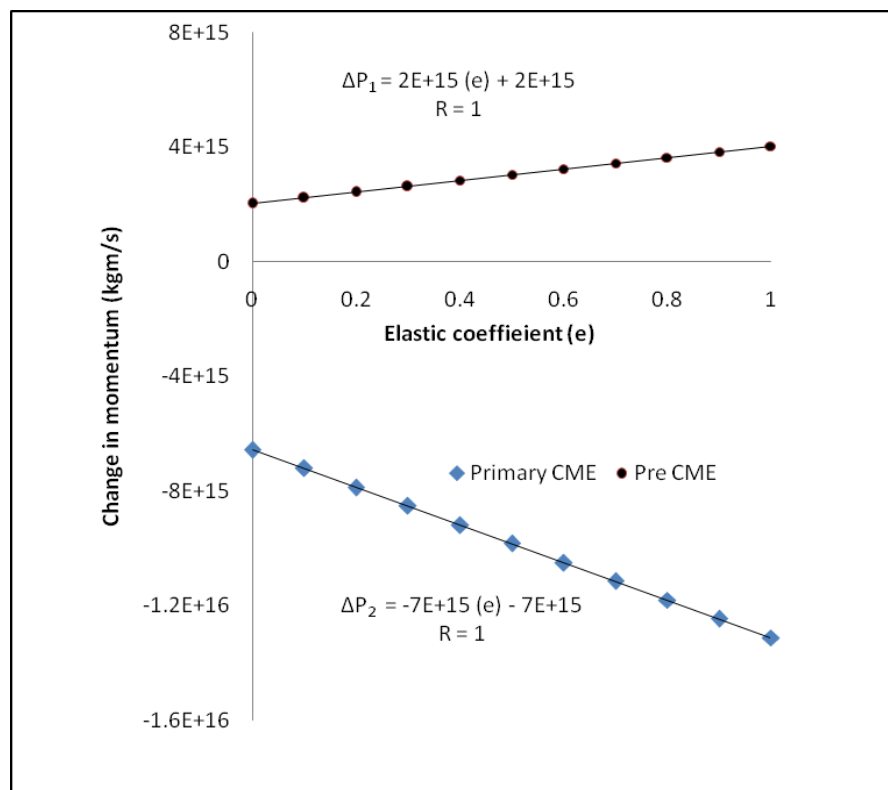


Figure-3 The change in momentum due to CME-CME interaction with respect to elastic coefficient

momentum equations 5 and 6, the change in momentum are calculated for pre and primary CMEs. The change in momentum of pre CME is found as 2×10^{15} kgm/s and the same is for primary CME is found as -6.5×10^{15} kgm/s. As mentioned earlier, the kind of CME-CME interaction is partial inelastic, complete inelastic and complete elastic. Hence the study obtained the change in momentum of pre and primary CMEs for intermediate values of the elastic coefficient between 0.1 to 1.0 is shown in Figure 3. It shows that the change in momentum is in positive magnitude and increases linearly with respect to e for pre CME. The change in momentum on the other hand is completely negative magnitude and decreases linearly with respect to e for primary CME. It also suggests that for complete inelastic collision at $e = 0$ the pre CME momentum change attained very low value and inversely the primary CME momentum change attained very high value.

The first order best fit plot to the above plot gives the change in momentum for pre CME as a function of elastic coefficient and it is given by,

$$\Delta P_1 = 2 \times 10^{15} (e) + 2 \times 10^{15} \quad (7)$$

The change in momentum for primary CME as a function of elastic coefficient is given by,

$$\Delta P_2 = -7 \times 10^{15} (e) - 7 \times 10^{15} \quad (8)$$

The negative values of change in momentum of primary CME suggests that the CME would have declining speed after interaction and that CME would be decelerated one. Inversely, the positive value of change in momentum of pre CME suggests that the CME would have increasing speed after interaction and that CME would be accelerated one. This confirms the previous results of Shanmugaraju et al.(2014), Temmer et al. (2014).

DISCUSSION AND SUMMARY

In any interaction studies, the momentum should be transferred and the velocities should be changed before and after interaction. In CME-CME interaction cases, the velocity of pre CME is found to be increased and the same of primary CME be decreased. Hence the momentum transfer and elastic coefficient are more valid in CME-CME interaction studies. The momentum transferred between the CMEs confirmed the previous results of Temmer et al. (2012), Maricic (2014), Misra and Srivatsava (2014). The radio

enhancement features generally have higher density than the fundamental type II band. This increase in density in the interaction segment reveals the reason for decreasing Alfvén speed in the upstream pre CME medium that enhances electron acceleration much faster than a non-interacting shock acceleration.

Generally fast CMEs are decelerated by ambient solar wind due to aerodynamic drag effect. The decreasing dynamic viscosity of the CME is found to be due to either/both ongoing pre CME medium and/or solar wind medium and it act as aerodynamic drag. Prasad et al. (2012) suggested that solar wind causes aerodynamic drag for propagating CME in the IP medium.

The main results of this study are summarized as follows,

- The study confirms the momentum transfer between the CMEs.
- The momentum transfer modeling is studied in terms of elastic coefficient and CME initial velocities.
- The dynamic viscosity model is studied for a CME event. The

CME-viscosity is high at close to the Sun. The viscosity of the CME decreases with respect to CME expansion. The study confirms the aerodynamic drag influence by solar wind or pre CME (Prasad et al. 2012)

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REFERENCES

- I. Gopalswamy, N., Yashiro, S., Kaiser, M.L., Howard, R.A., Bougeret, J.-L.: 2001, Radio signatures of coronal mass ejection interaction: coronal mass ejection cannibalism? *Astrophys. J. Lett.***548**, L91.
- II. Gopalswamy N, Yashiro S., Michałek, G., Kaiser, M. L., Howard, R. A. Reames, D. V. Leske, R. and Von Rosenvinge, T : 2002, Interacting Coronal mass ejections and SEPs *Astrophys. J.*, **572**, L103.

- III. Gopalswamy N, Yashiro S., Makela, P., Davila, J.M.: 2011, The relationship between expansion speed and radial speed of CMEs confirmed using Quaderate observations of the 15 Feb 2011 day event, Sun and Geosphere., ISSN 1819-0839.
- IV. Joshi, N.C., Uddin, W., Srivatsava, A.K. Chandra, R., Gopalswamy, N., Manoharan, P.K., Aschwanden, M.J., et al. : 2012, A multi wavelength study of an eruptive event on January 23. 012Ad.Space Res. 2013.
- V. Manoharan, P.K., Gopalswamy, N., Yashiro, S., Lara, A., Howard, R.A.Michalek, G.: 2004, Influence of Coronal mass ejection interaction on propagating of IP shocks J. Geophys. Res. 109, A06109.
- VI. Maricic, D., Vrsnak, B., Dumbovic, M., et al : 2013, Kinematics of Interacting ICMEs and related forbush decreases, Solar Phys. DOI/0.1007/s 11207-013-0314-8.
- VII. Mishra, W., Srivastava, N.: 2014, Morphological and kinematic evolution of three interacting coronal mass ejections of 2011 February 13 – 15. Astrophys. J.794, 64.
- VIII. Mujiber Rahman, A., Shanmugaraju, A., Umapathy, S.: 2013, Propagation of normal and faster CMEs in the interplanetary medium, Adv. Space Research, 52, 1168-1177.
- IX. Prasad S., Lara, A., Borgazzi, A: 2012 Journal of Geophysical Res. Lett. Can solar wind viscous drag account for CME deceleration ?, Doi, 10.1029
- X. Prasanna Subramanian, S., Shanmugaraju, A., Vrsnak, B.: 2016, Central Eruopean Astrophysical Bulletin, A study on the kinematics of shock-CME interaction event associated with flares and radio bursts on 22 May 2013, 40, 163.
- XI. Shanmugaraju, A., Prasanna Subramanian, S., Vrsnak, B., Ibrahim, M.S.: 2014, Interaction between two CMEs during 14 – 15

February 2011 and their unusual radio signature. *Solar Phys.***289**, 4621.

- XII. Temmer, M., Veronig, A.M., Peinhart, V., Vršnak, B.: 2014, Asymmetry in the CME–CME interaction process for the events from 2011 February 14–15. *Astrophys. J.***785**, 85.