# Dynamic Evolution of CME in Interplanetary Medium.

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# Acknowledgement

I take the opportunity to acknowledge all those who have helped me throughout my project in the Department of Physics (Autonomous), University of Mumbai. I would like to express my gratitude to Dr. Anil Raghav, University of Mumbai. I would thank Dr. Prasad Subramanian, IISER Pune, for providing us with the data used in my project. I would also like to thank my colleagues who have helped me during this project work.

# Contents

# 1 INTRODUCTION

1,1 Top Coronal Mass Ejection (CME) are large eruption of plasma and magnetic field from solar corona. The mass of CME can range between $10^{11}$-$10^{12}$ kg and the speed can be in between 400-1000 km/s. CMEs can erupt from any region of corona but it manily erupts from low latitude regions, particularly near solar minimum. Druing solar minimum the ejection of CME can be once in a day, whereas during the solar maximum the elimination can be as frequent as four to five times a day. CMEs are the major source of space weather disturbances. Some CMEs are directed towars the Earth, they are called as 'Halo CME'. Halo CMEs causes disturbances in Earth's atmosphere causing Geomagnetic storms. Hence, CMEs not only effect the sapce satellites but also have it's effect on gound-based technologies. For the predictions of space weather, the travel time of CME in Sun-Earth line is very important. CMEs are detected by white-light coronagraphs. CMEs at 1AU can be detected by spacecraft Ace situated at L1 position. CMEs after travelling a particular heliospheric distance ( 50Ro) is known as Interplanetary Coronal Mass Ejection (ICME). ICMEs are known by various names like driver gas, ejecta and plasma cloud. The magnetic field of ICMEs are enhanced with respect to the ambient solar wind. When the ICME has a flux rope staructure it is called as Magnetic Cloud. Studies of CME are basically divided into two parts; Initiation and propagation. Initiation part deals with the initial eruption mechanism of CME, while the propagation issue is corcerned about the forces acting on CME when it is traveling the distance from Sun to Earth. Fast CMEs, with the speed >=1000 kms$^{-1}$ gets initially accelerated due to Lorentz self-force and are mostly decelerated because of Aerodynamice drag from the surrounding solar wind. Slow CMEs, with the speed 100 kms$^{-1}$ gets accelerated by solar wind.

The forces acting on CMEs just after it's eruption are:-

1. Buoyancy
2. Lorentz force
3. Sun's gravitational pull
4. Lorentz self-force

These are the forces acting on the flux rope CME and are responsible for powering the CME upto $2 - 30Ro$. Buoyancy arises because of the pressure gradient between CME and the surrounding solar wind. Lorentz force is beacuse of the current inside the flux rope and the magnetic field outside it.

For understanding Lorentz self-force, consider a current carrying tube. The current is along the axis and generates a toroidal magnetic field. Now, if the tube is bent in a circular form, the toroidal field lines gets bunched up at the bottom and is very less on the top, which means magnetic pressure will be more on bottom than on top. This results in an outwardly force.

The buoyancy and the gravitationalpull by the Sun, both depends on the cross-sectional area of CME, but the mechanical forces acting on CME is independent of it's cross-sectional area. Hence, with regard to this argument, both the forces can be neglected. Also the external magnetic field decreases with the distance and can be negligible after $2Ro$. Hence the Lorentz force can too be neglected.

Hence, according to this argument, it's only Lorentz self-force responsible for driving the flux rope. However, it acts only on the topmost, curved part of the flux rope. This force arise due to the misalignment of current and magnetic field inside the evolving flux rope. The magnitude of the Loentz self-force depends on the magnitude of current density and the magnetic field as well as the angle in between them. The excess magnetic energy inside the CME flux rope helps in translating and expanding the CME. On an average, 74 percent of the required energy to travel the Sun-Earth distance is because of the magnetic energy conatained by the CME.

It is observed that the flux rope CMEs expands in nearly self similar way, that is, the ratio of their minor radius to major radius (k) remains approximately constant with time. Self similar expansion is a consequence of the assumption that both the axial magnetic field and the helicity remains conserved.

For Lorentz self-force, CME needs to be non force-free, whereas at 1AU, CME flux ropes are force-free. The actual nature of Lorentz self-force is not yet understood. The idea of momentum coupling is raised by the findings that when a CME is launched with the speed exceeding the ambient solar wind speed, it gets decelerated, while CME whose speed is less than the ambient solar wind was accelerated. Hence, Cme tries to be in equilibrium with the surrounding solar wind. These observations have awaken the research on Drag-based model. An important parameter in this model is the Drag Coefficient which is used to characterize the interaction between the CME and the ambient solar wind. Solar wind drag can decelerate as well as can accelerate the CME. There are three phases in the propagation of CME: the initiation acceleration phase which is due to Lorentz self-force, the second phase is, when the equilibrium is attained by Lorentz and Drag forces acting on CME and the third phase is when the CME gets decelerated by the Aerodynamic drag.

The momentum coupling between the CME and ambient solar wind is given by the equation;

$$F_{drag} = m_{cme}\frac{dV_{cme}}{dR} = -\frac{1}{2}C_D N_i m_p A_{cme}(V_{cme} - V_{sw})|(V_{cme} - V_{sw})| \quad (1)$$

where, $m_{cme}$ is the CME mass, $V_{cme}$ is the CME speed, $C_D$ is the all-important dimensionless drag coefficient, $N_i$ is the proton number density in the ambient solar wind, $m_p$ is the proton mass, $A_{cme}$ , is the cross-sectional area of the CME and $V_{SW}$ is the solar wind speed.
$C_D$ tells about the strength of momentum coupling between the CME and the ambient solar wind.
Equation (1) can also be written as,

$$\frac{F_{drag}}{m_{cme}} = a_d = -\gamma(V_{cme} - V_{sw})|(V_{cme} - V_{sw})| \quad (2)$$

where,

$$\gamma = \frac{C_D N_i m_p A_{cme}}{m_{cme}} \quad (3)$$

For slower CMEs,it is observed that, formits initial part of the trajectory Lorentz self-force is dominant, whereas, aerodynamic drag taks over at larger heights. Slower CMEs are draggeed up by the solar wind. The Drag-based model gives reasonable result for fast CMEs.
In the Drag-based model (Drag model), the drag coefficient is taken to be unity (conmstant). Taking $C_D$ equal to 1 maks the modelled data to agree well with the observations. $C_D$ equal to unity infers that the CME attains equilibrium wiht the ambient solar wind. However, CME will hardly attain equilibrium as soon as it gets ejected. Cargill 2004, through simulations showed that the value of $C_D$ depends upon the ICME density and the velocity of the solar wind. The value of $C_D$ changes and hence increases from 1 for dense ICME. For very weak ICME, it is much greater than 1. In most cases $C_D$ remains roughly constant as the ICME travels from Sun to Earth. Very weak ICME shows a significant dependence on radius.
The all-important drag coefficient has ben taken as unity in Subramanian et al 2015. However, one can question about its variation. Drag coefficient variation with respect to heliospheric distance is the aim of this report. Can $C_D$ incraese up to some distance and then become constant or decrease and then reach equilibrium? These are the questions answered in this report.

| Event Number | Date | $v_0$ (kms$^-1$) | $n_{wind}$(cm$^{-3}$) | $v_{wind}$(kms$^-1$) | log$m_o$ | $h_{occ}$ ($Ro$) | log$\Delta m$ |
|---|---|---|---|---|---|---|---|
| 1 | 2010 Mar 19-23 | 162 | 3.60 | 380 | 14.7 | 3.65 | 14.3 |
| 2 | 2010 Apr 03-05 | 916 | 7.15 | 470 | 15.1 | 3.46 | 14.6 |
| 3 | 2010 Apr 08-11 | 468 | 3.60 | 440 | 15.4 | 3.55 | 14.7 |
| 4 | 2010 Jun 16-20 | 193 | 3.50 | 500 | 14.9 | 4.37 | 14.1 |
| 5 | 2010 Sep 11-14 | 444 | 4.00 | 320 | 15.2 | 3.84 | 14.7 |
| 6 | 2010 Oct 26-31 | 215 | 3.80 | 350 | 15.2 | 5.66 | 14.7 |
| 7 | 2011 Feb 15-18 | 832 | 2.50 | 440 | 15.6 | 3.85 | 13.9 |
| 8 | 2011 Mar 25-29 | 47 | 3.00 | 360 | 15.4 | 4.43 | 14.3 |

Table 1: Observed Parameters

## 2 Data

We took the well fited Graduated Cylindrical Shell modelled data (Colaninno 2012 and Colaninno, Vourlidas and Wu 2013) from Dr. Prasad Subramanian. It is an eight enormously studies, Earth-impacting CMEs during the rising phase of solar cycle 24 from March 2010 to June 2011. These CMEs are observed by SOHO LASCO, SECCHI coronagraphs and HI (Heliospheric Imagers) onboard STEREO. Near Earth parameters of these CMEs are obtained from WIND spacecraft (in-situ measurement).
The table above contains the important observed quantites of CME and the Solar wind.
The quantity $v_o$ is the initial speed of CME. We can see that CMEs 1,2,4,8 starts out a bit slowly with the initial speed less than 200 kms$^{-1}$. CMEs 3,5,7 starts with relatively faster with the speed greater than 400 kms$^{-1}$. CME 2 starts with the initial speed of 916 kms$^{-1}$ and is comparatively the fastest event in this sample.

## 3 Models and Observations

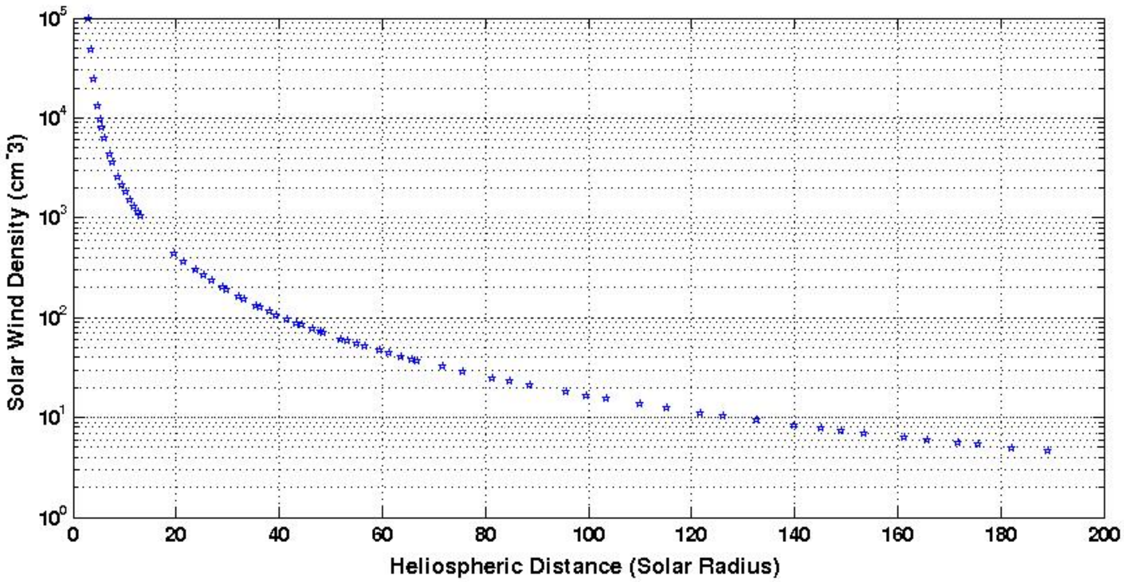
The Drag model is given by equation is given by equation (1).
The data-based models for finding the parameters in drag model can be explained as follows;
The plots shown will be of event three.

### 3.1 Solar wind density (Leblanc 1998, Sachdeva 2015)

The quantity $n_{wind}$ in the table denotes the proton number density at Earth one or two days before the arrival of CME and the shock. The assumption is, the proton number density and the electron number density are equal. The electron number density as a fucntion of heliospheric distance is given by;

$$n(R) = \frac{n_{wind}}{7.2}[3.3 * 10^5 R^{-2} + 4.1 * 10^6 R^{-4} + 8 * 10^7 R^{-6}] \tag{4}$$

The quantity n(R) represents the number density of the solar wind in which the CME propagates. The priginal model of Leblanc observes that at 1AU the number density is 7.2 $cm^{-3}$. The factor $n_{wind}/7.2$ makes sure that the electron number density given by the above equation matches the proton number density ($n_{wind}$) measured by WIND spacecraft (in-situ measurement) near the Earth.
The graph of solar wind density as a function of heliospheric distance is shown




### 3.2 Model for the Area of CME. (Thernisien 2011)

Dividing the CME in two portions, Curved front and foot legs as cones. We found the area of CME by adding the area of curved front and cone.
To find Area of the Cone.
From GCS model (Colaninno 2012), the data we have is, aspect ratio ($k$), half angle ($\alpha$), height of CME front ($h_f$)
The height of the cone (h) can be found using GCS model,

$$h = \frac{(h_f * (1 - k) * cos(\alpha))}{1 + sin(\alpha)} \tag{5}$$

Hence, the equation for the Area of Cone,

$$A_{cone} = \pi * (\frac{h}{k})^2 * \sqrt{k * k + 1} \tag{6}$$

To find the Area of Curved front,
Minor radius of the ellipse,

$$b = \frac{h}{cos(\alpha)} \tag{7}$$

$$rho = h * tan(a) \tag{8}$$

$$R_{bb} = \frac{(k * (b + \rho))}{(1 - k^2)}; \tag{9}$$

Major radius of the ellipse

$$X_o = \frac{\rho + b * k^2}{1 - k^2} \tag{10}$$

$$R = \sqrt{(}X_o^2 + \frac{((b^2 * k^2) - (\rho)^2)}{1 - k^2} \tag{11}$$

$$R_{aa} = X_o + R \tag{12}$$

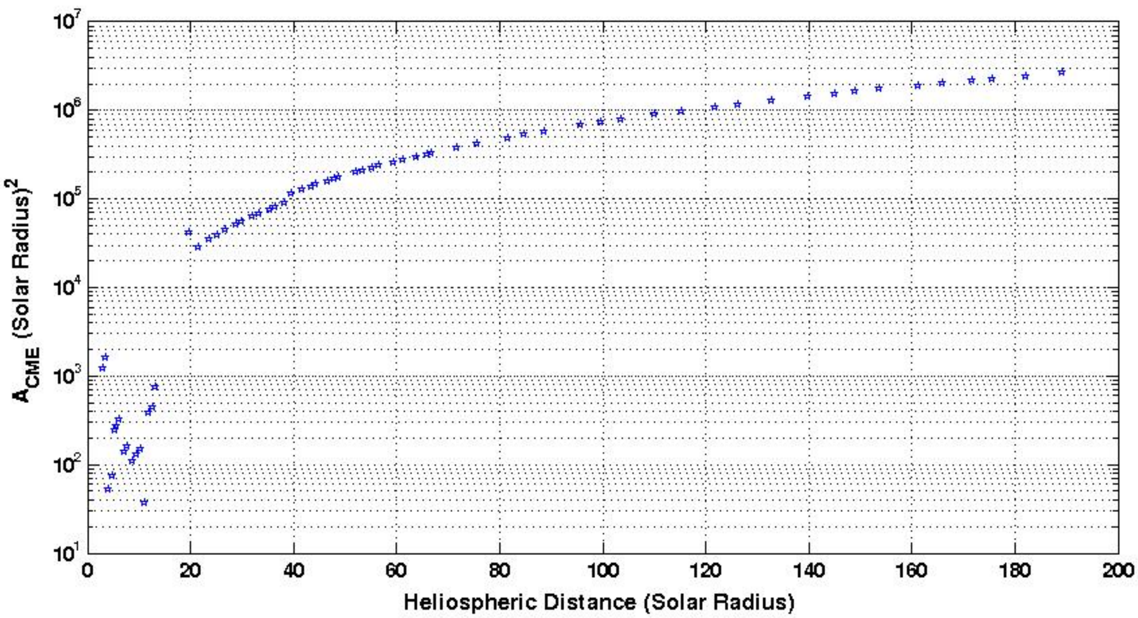
Total Area of the curved front,

$$A_{cf} = \pi * R_{aa} * R_{bb}; \tag{13}$$

The final total area of the CME is the given by,

$$A_{CME} = A_{cf} + A_{cone}; \tag{14}$$

The graph of area of CME as a fucntion of heliospheric distance is shown as follows,

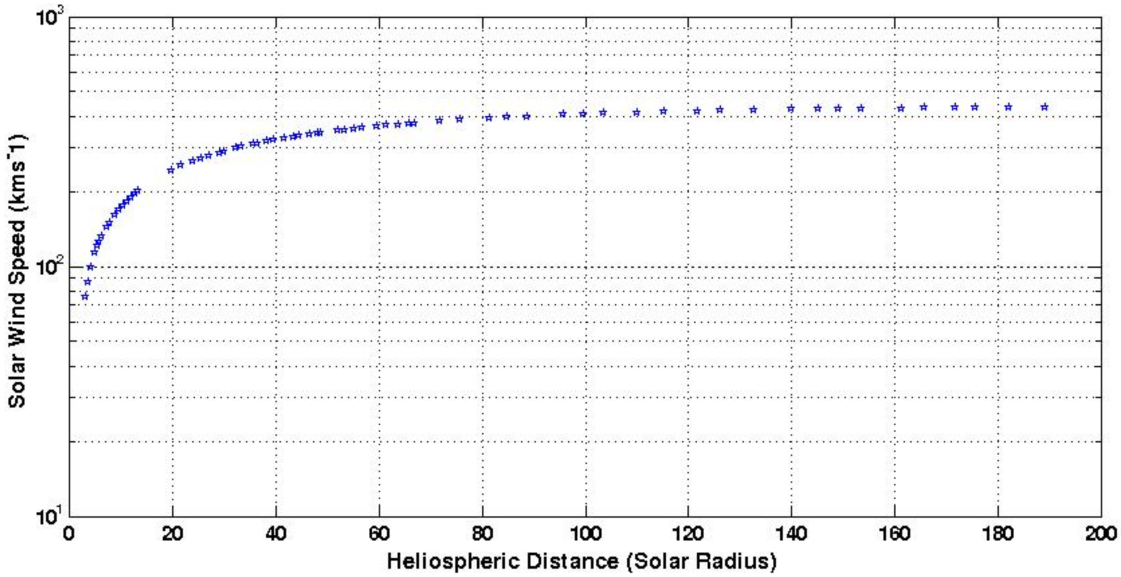



## 3.3 Solar wind speed estimation. (Sheeley et al 1997. Subramanian 2015)

The quantity $v_{wind}$ in the table is the spped of solar wind by in-situ measurement using WIND spacecraft. The equation to estimate the solar wind speed is given by,

$$V_{SW}^2(R) = v_{wind}^2[1 - \exp\frac{-(R - r_o)}{r_a}] \tag{15}$$

The quatity $r_o$ denotes the heliocentric distance where the solar wind speed is zero and is taken to be 1.5Ro and $r_a$ is e-folding distance, is taken to be 50Ro. The graph of solar wind speed as a function of heliospheric distance is shown as follows

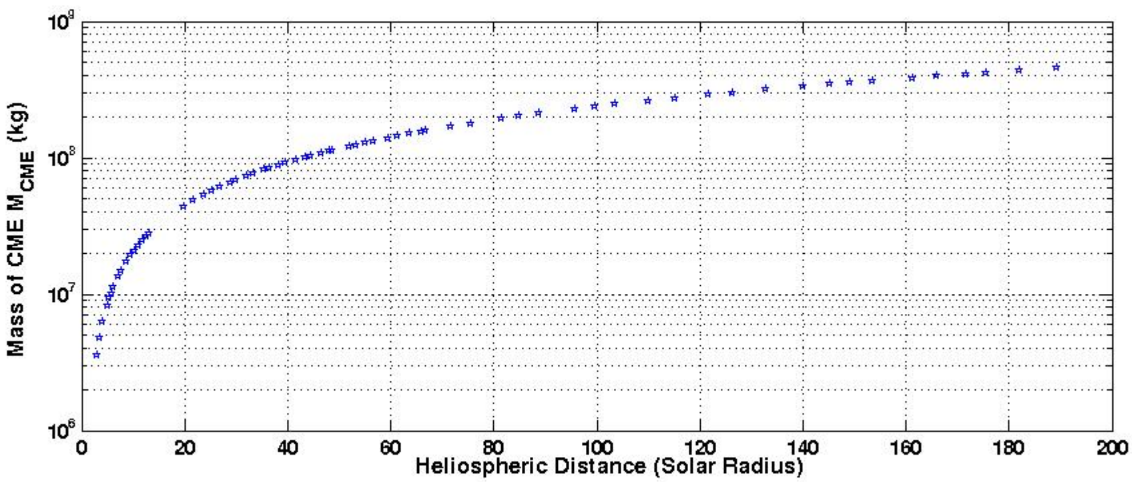



## 3.4 Mass of CME estimation. (Bein et al. 2013. Subramanian 2015)

The Thomson scattering geometry (Billings 1966) relates the observed brightness with the coronal electron density. The mass of CME is derived by assuming that all mass is concentrated in a plane at the longitude which is derived from GCS model. The correction for the effect of occulter is give by Bein et al. (2013) who suggest the equation of mass of CME as follows,

$$m_{CME} = m_o + \Delta m(R - h_{occ}) \tag{16}$$

where, $m_0$ is the true mass of CME when it is first observed from the occulter, $\Delta m$ is the increase of mass with height and $h_{occ}$ is the radius of the occulter. The graph of mass of CME as a function of heliospheric distance is shown as follows,



## 3.5 Kinematic viscosity of solar wind. (Subaramanian 2012. Subramanian 2015)

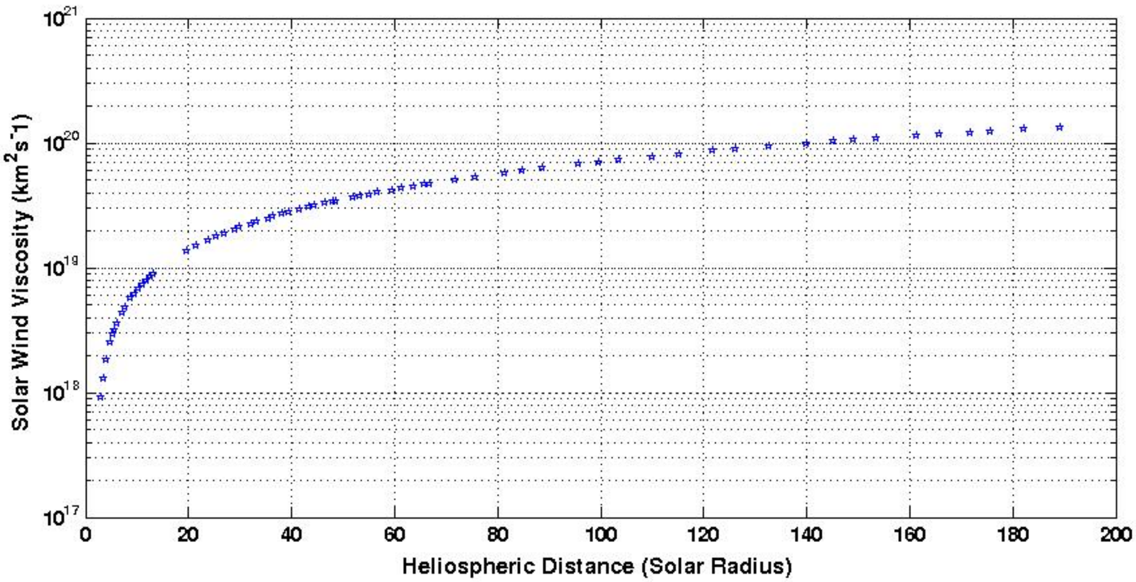
The viscosity ($\nu$) of the collisionles ambient solar wind is due to resonant scattering of solar wind protons and can be expressed with a fluid expression guven by,

$$\nu_{SW} = \sqrt{6}\frac{2}{15}v_{rms}\lambda \tag{17}$$

where v$_r ms$ is the root mean square speed of solar wind protons and $\lambda$ is the mean free path and can be written as,

$$\lambda = 228n^{-0.5} \tag{18}$$

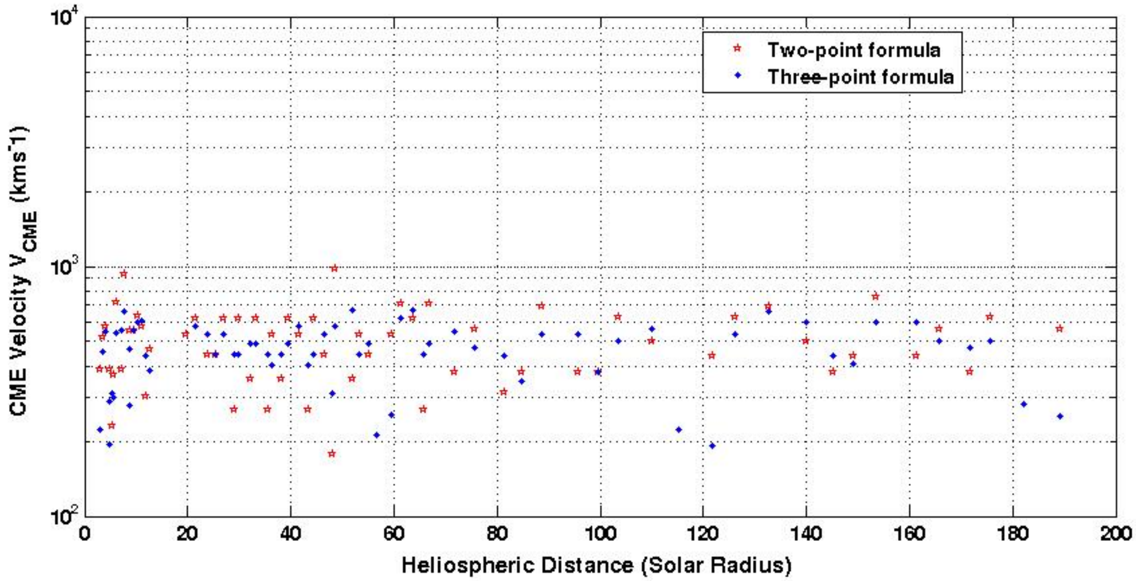
The graph of Kinematic viscosity as a fucntion of heliospheric distance can be shown as follows,




## 3.6 Velocity and Acceleration of CME.

The velocity of the CME can be found using Two-point and Three-point difference formula. Although the three-point difference formula gives a better and smooth graph as compared to two-point formula and this can be seen from the plot of velocity as a function of heliospheric distance.

The acceleration of the CME is found using the two-point and three-point velocity. Like in velocity, in acceleration too by using the three-point velocity we get a better and smooth plot than two-point. This can be seen from the plot below, which is a plot of CME acceleration as a function of heliospheric distance. The red stars denote the plot using two-point formula, whereas the blue stars denote that of using three-point formula.

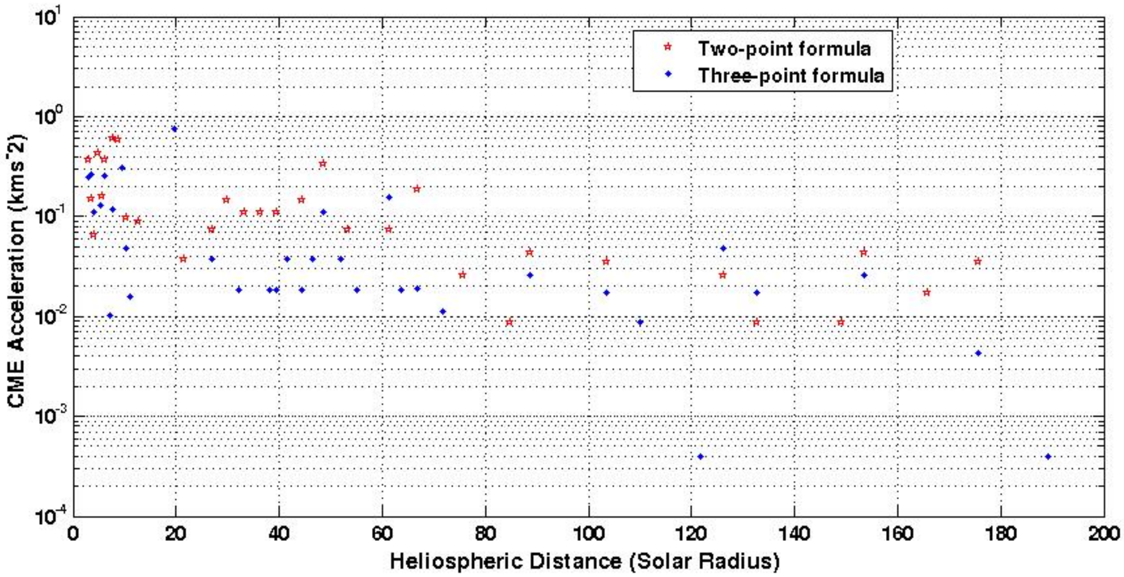



### 3.7 Inverse deceleration length, $\gamma$ (Subramanian 2015)

The inverse deceleration legth ($\gamma$) can be derived using equation (2).

$$\gamma = \frac{a_d}{V_{CME} - V_{SW}|VCME - V_{SW}|} \tag{19}$$

Three-point velocity and acceleration has been used. $\gamma$ as a fucntion of heliospheric distance can be shown as follows




### 3.8 Drag Coefficient $C_D$. (Subramanian 2015)

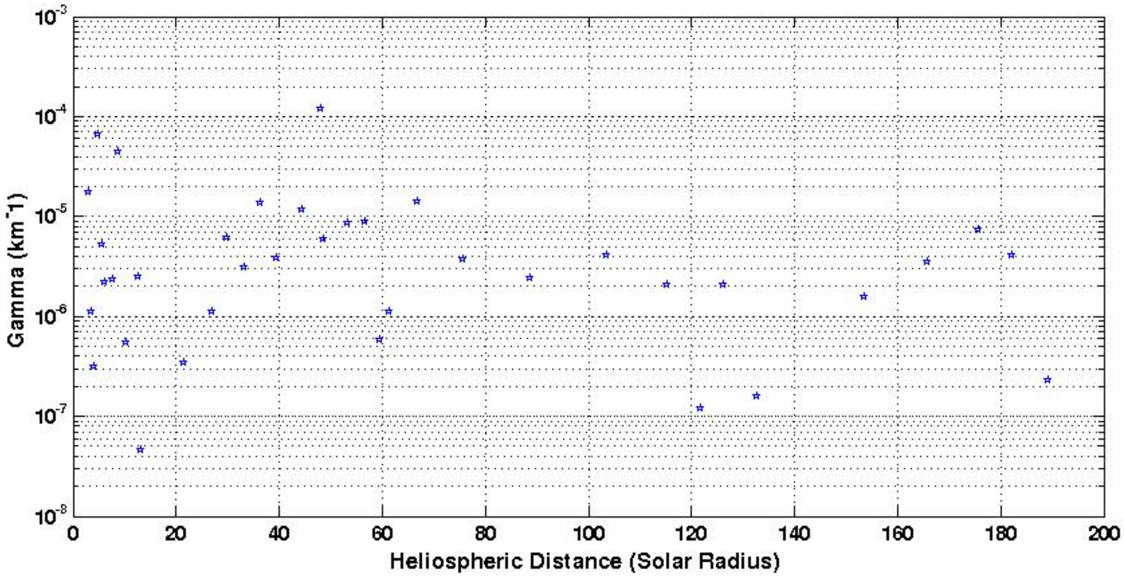
The Drag coefficien $C_D$ is an important parameter in the drag model. $C_D$ variation with heliospheric distance can be estimated from the formula

$$C_D = \frac{\gamma * M_{CME}}{A_{CME} * n * m_p}(6.65^2 * 10^{-25}) \tag{20}$$

The parameter in the paranthesis is for making the $C_D$ dimensionless. $m_p$ is the mass of proton.

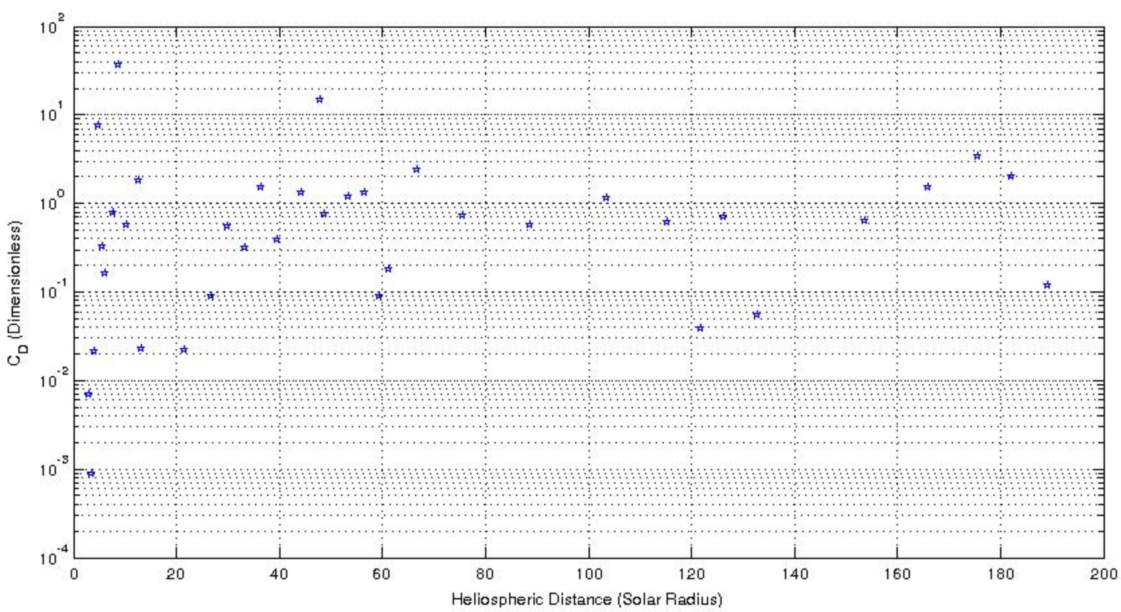
From the below shown plot, it can be seen that $C_D$ varies with heliospheric distance. Initially it increases or decreases depending on the history before its ejction. The drag coefficient increase or decrease depending on whether another CME is ejcted after the concerned one or before it. It can also be observed that after traveling some distance (near to 1AU) it reaches the said constant value, that is, unity.

Similar observations can be made for the drag coefficient plots of other events and similar result can be seen.

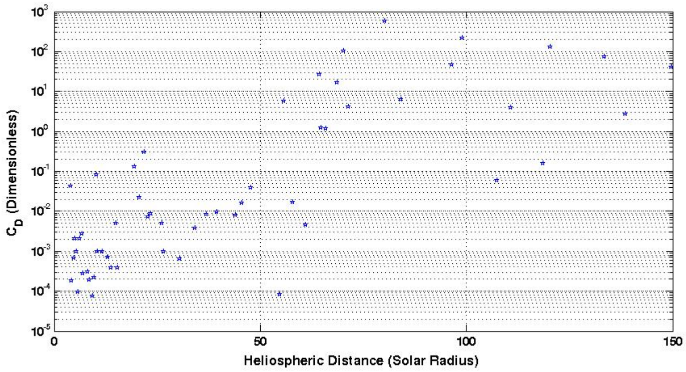



# 4 Discussion

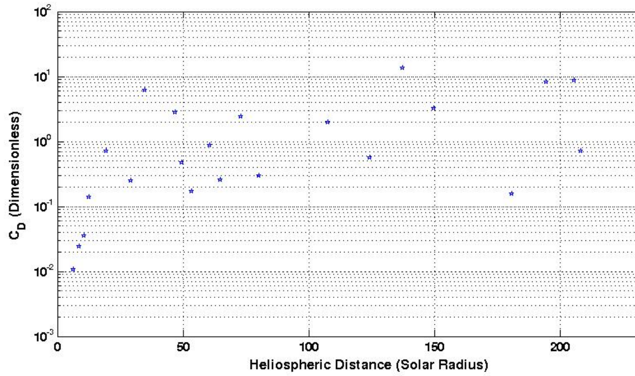
We have studied eight extensively studies CMEs covering a range of velocity varying between the slowest to fastest CMEs.CMEs accelerate or decelerate by momentum coupling with the solar wind. The Drag-based model have been used to study about this phenomena. In this model only the aerodynamic drag force is considered and the other forces like lorentz self-force, Sun's gravitational pull has been neglected since its effect is only upto few solar radius. The important parameter in this model is the drag coefficient $C_D$. Until now, this emperical fitting parameter was taken to be unity. Here we have tried to see whether $C_D$ varies or remains constant. From the analysis done above, it can be seen that $C_D$ varies with the heliospheric distance. It either goes above unity or below depending on the history of its ejection.



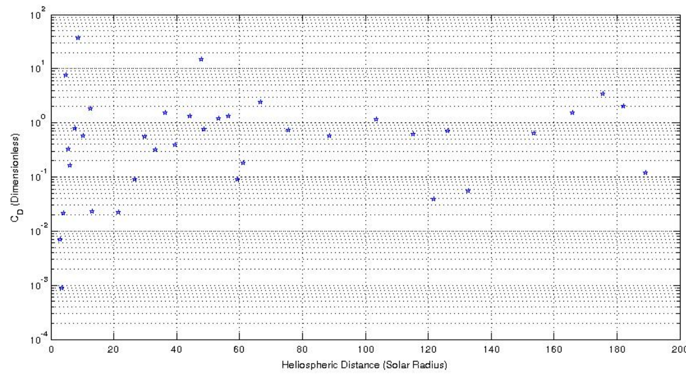
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$C_D$ (Dimensionless)
0
20
40
60
80
100
120
140
160
180
200
Heliospheric Distance (Solar Radius)



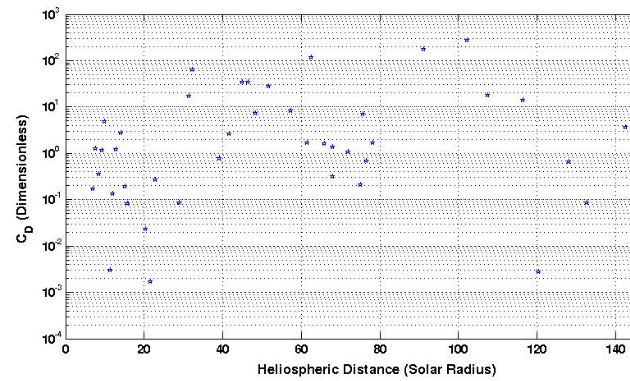

(a) Event one



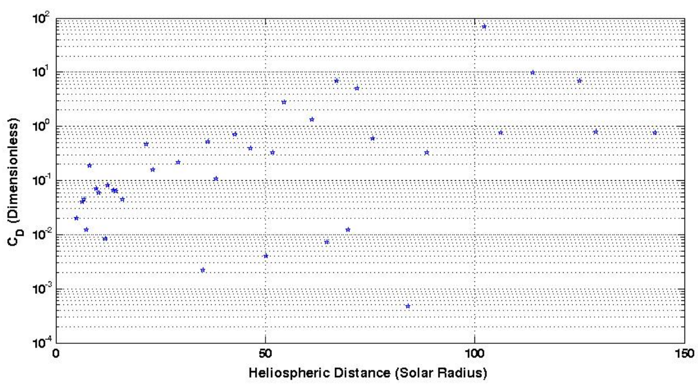

(b) Event two



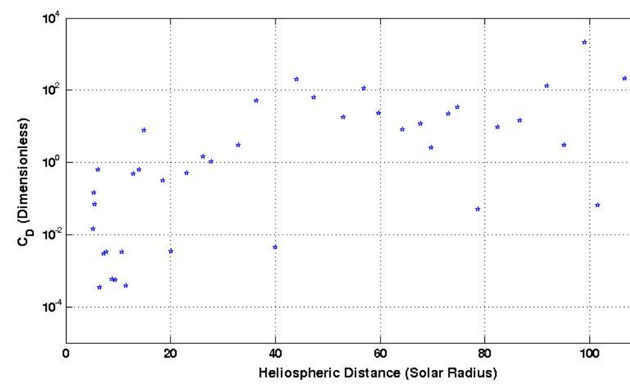

(c) Event three



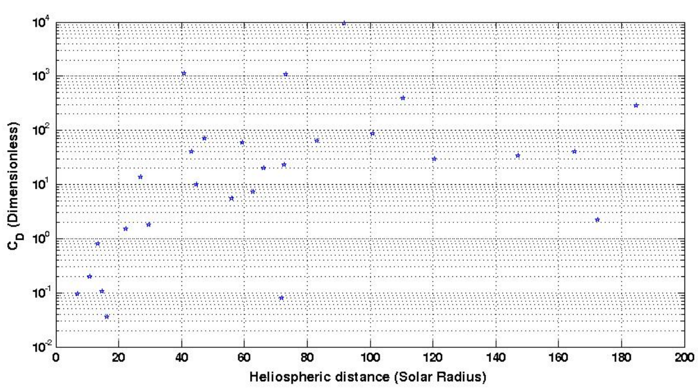

(d) Event four



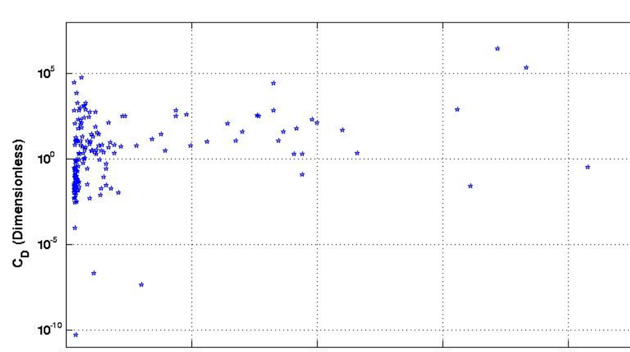

(e) Event five




(f) Event six




(g) Event seven




(h) Event eight