Ensemble Simulations of Coronal Mass Ejections in Interplanetary Space with Elliptical Cone Models

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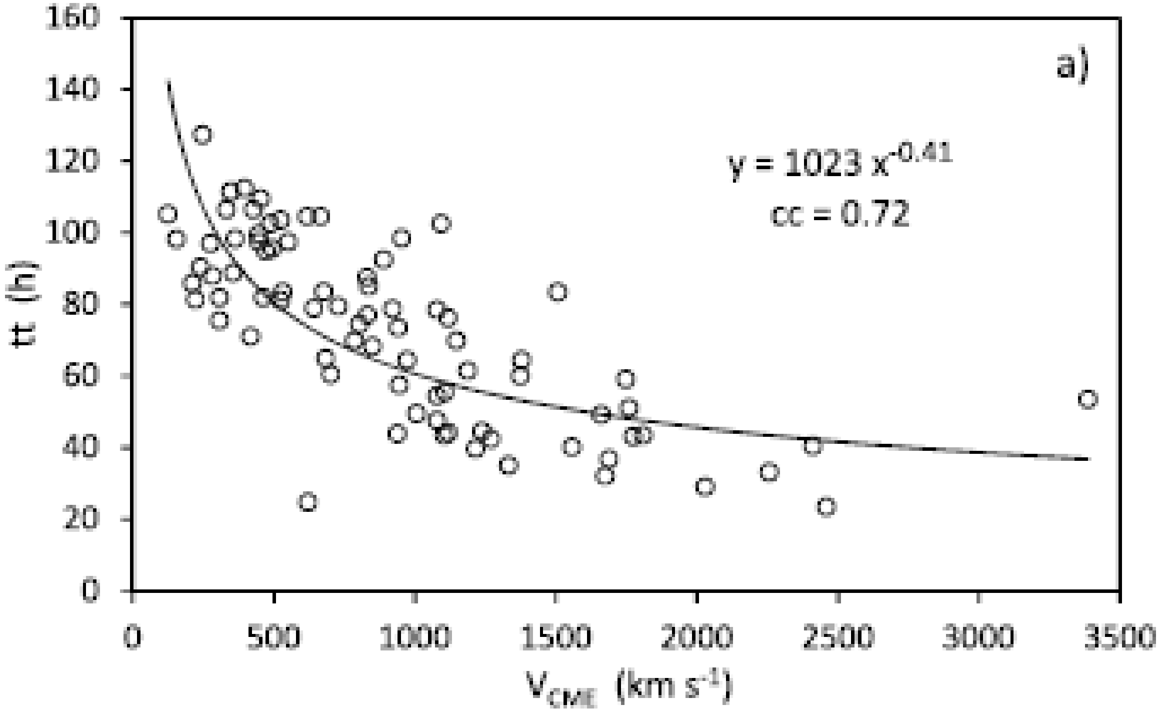
CME Arrival Time Predictions

- Several CME propagation models have been developed to predict the arrival time and speed of CMEs with various success rates.

-Brueckner 80h rule (Brueckner et al., 1998)
-Ballistic propagation (e.g., Murray et al., 2018)
-Statistics-based kinematical model (Gopalswamy et al, 2001, Reiner et al, 2007)
-Physics-based kinematical model: Drag-based model (Vrsnak et al., 2013)
-MHD Simulation: ENLIL (Odstrcil 2003), SUSANOO (Shiota & Kataoka 2016), EUHFORIA (Pomoell & Poedts, 2018)



(Manchester et al. 2017)

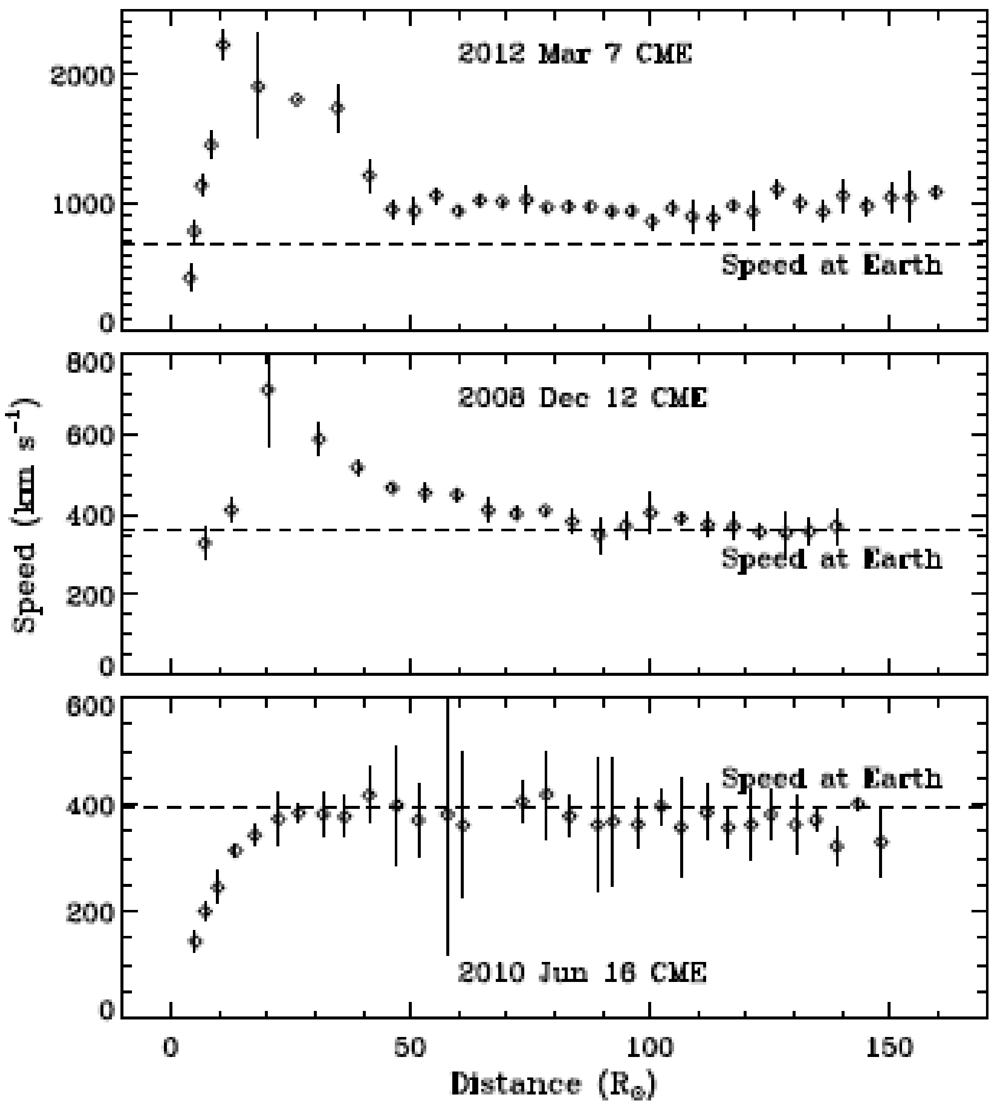
Drag-based Model (DBM)

- A CME moving at a certain speed (v) experiences a drag force from the ambient solar wind moving at a different speed (ω).
- A CME will be decelerated when v > ω, and accelerated when v < ω.

$$\mathrm{R(t)} = \frac{S}{\gamma} ln[S\gamma(v_0 - \omega)t + 1] + \omega \mathrm{t} + R_0$$

$$v_{as} = \frac{(v_0 - \omega)}{(S\gamma(v_0 - \omega)\mathrm{t} + 1)} + \omega$$

(Vrsnak et al., 2013)



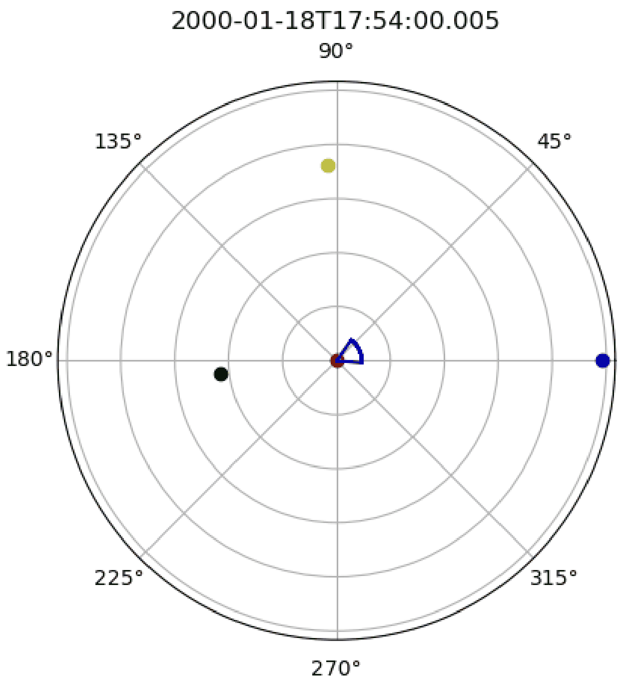
(Liu et al. 2016)

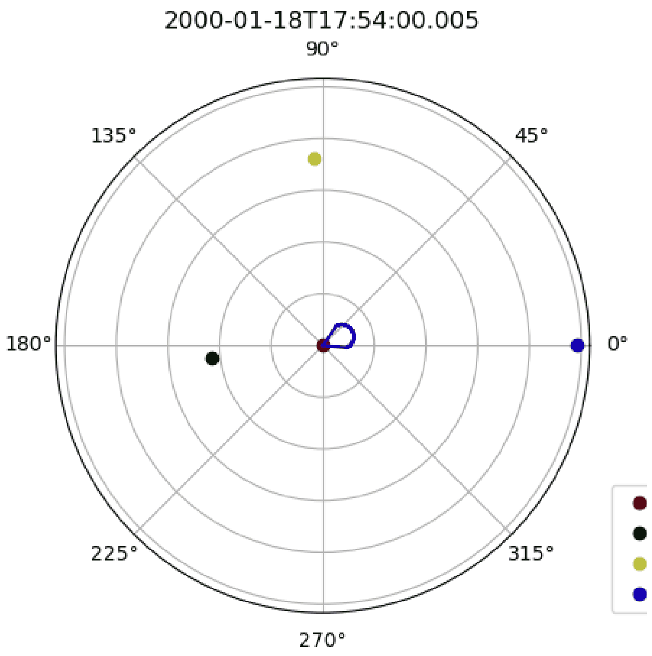
Model development:

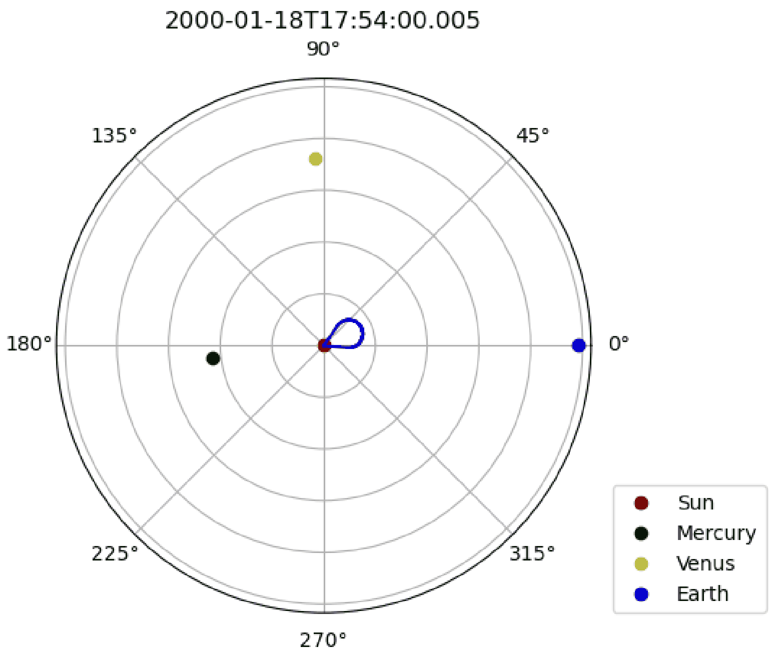
1D DBM (Vršnak et al., 2013, 2014), Enhanced DBM (Hess and Zhang, 2014, 2015), 2D DBM (Žic et al., 2015), the 2D Ellipse Evolution Model (ElEvo, Möstl et al., 2015), ElEvoHi (Rollett et al., 2016, Amerstorfer et al. 2018), DBEM (Dumbović et al. 2018), frontal deformation DBM (Hinterreiter et al. 2021).

2D DBM Self-similar Cone

The estimation of CME arrival time strongly depends on the CME propagation models in interplanetary space and the geometrical aspects of the CME model.



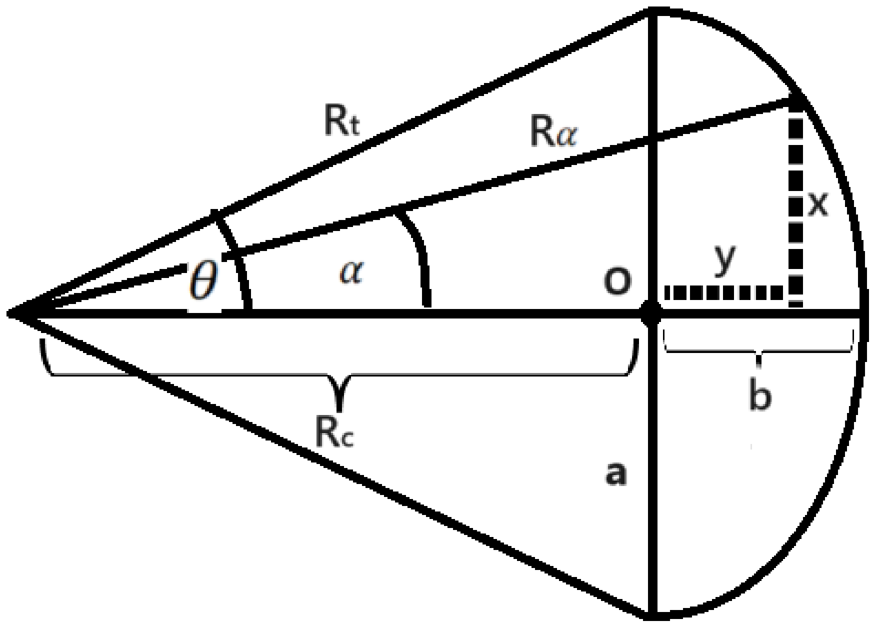




Objective

- Our study aims to investigate the connection between cone ellipticity and CME speed by identifying the optimal elliptical aspect ratio that best aligns with observed CME arrival times.
- We conducted ensemble simulations of CME propagations with various elliptical cone shapes to study the relation between the CME speed and the optimum cone shape.

Elliptical Model



$$R_t = \frac{S}{\gamma} ln[S\gamma(v_0 - \omega)t + 1] + \omega t + R_0$$

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \ ,$$

$$x = \tan\alpha\,(R_c + y)$$

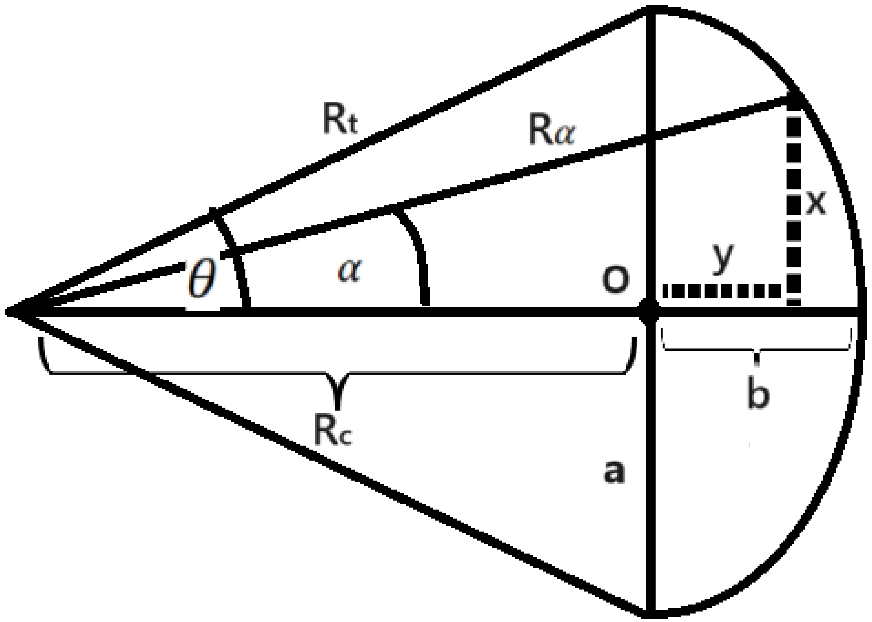
$$R_\alpha = \frac{R_c + y}{\cos\alpha}$$

- The ICME is modeled as a 2D cone model with the leading edge is considered as semi-elliptical shape.
- The semi-minor axis (b) acts as a free parameter, allowing for incremental adjustments to create an adaptable leading-edge that can range from a flattened shape to a semi-circular one.

Data

- 75 CME-ICME pairs 1997-2017 (Richardson and Cane): CME Arrival time
- CMEs that clearly have associated solar flares, neglecting CMEs from filament eruptions, multiple CME events, and stealth CMEs.
- CME space speeds (Napoletano et al., 2022)
- CME sources are determined by the location of the corresponding active region (AR) positions.
- CME initial appearance times, speeds, and central position angles from the SOHO LASCO catalog at CDAW (NASA).

Ensemble Simulations



- $\gamma = 0.2 \times 10^{-7}$ km^{-1}
- $\omega = 450$ km/s
- $R_0 = 20\ Rsun$
- v_s : Sky Speed (CDAW)
- v_0 : Space Speed (Napoletano et al. 2022)
- θ : The cone half-angle (Gopalswamy et al., 2010)

$\theta = 66°$ ($v_s > 900$ km/s),

$\theta = 45°$ (500 km/s $< v_s <$ 900 km/s),

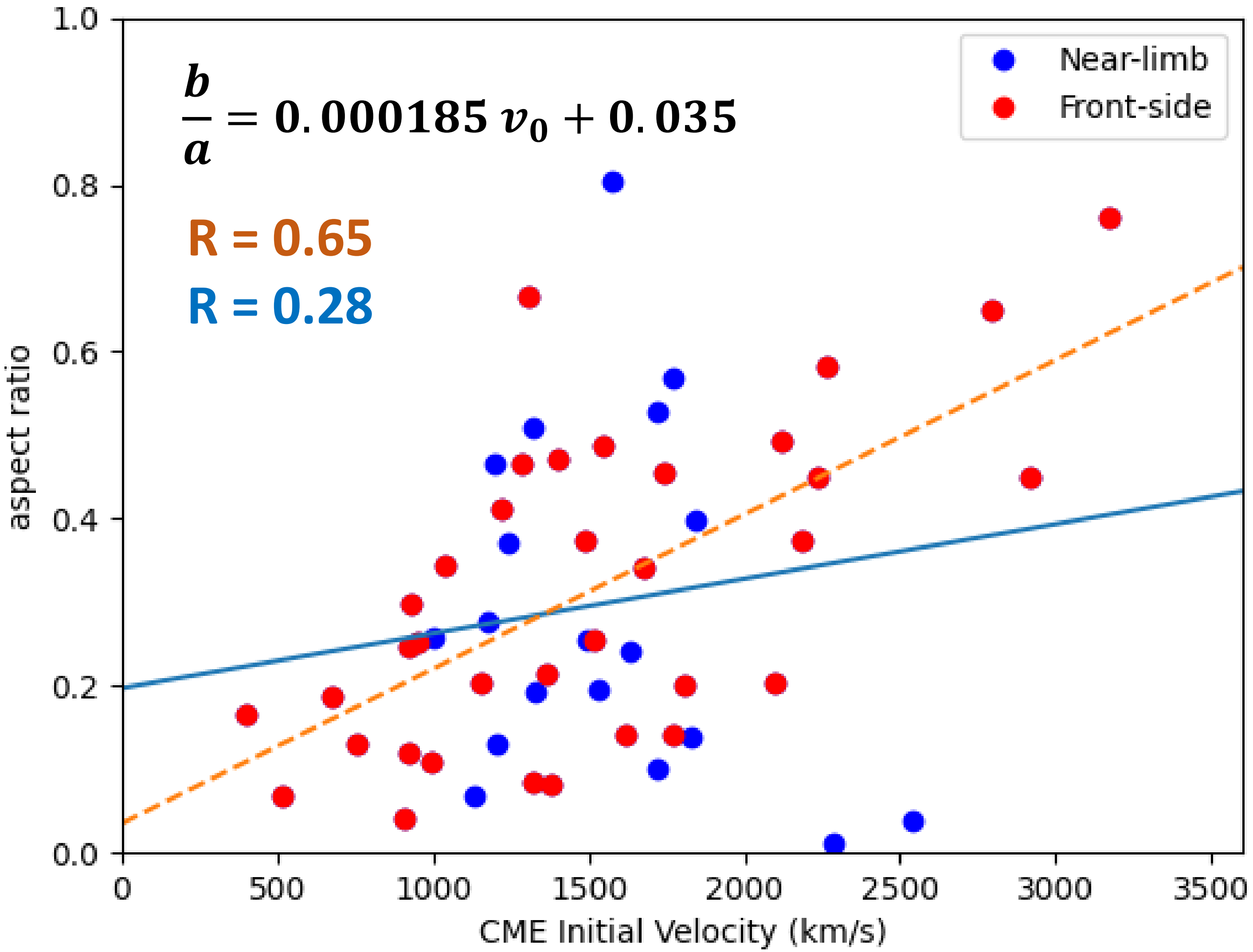
$\theta = 32°$ ($v_s < 500$ km/s)

- *b/a* : elliptical aspect ratio (0.001 – 1)

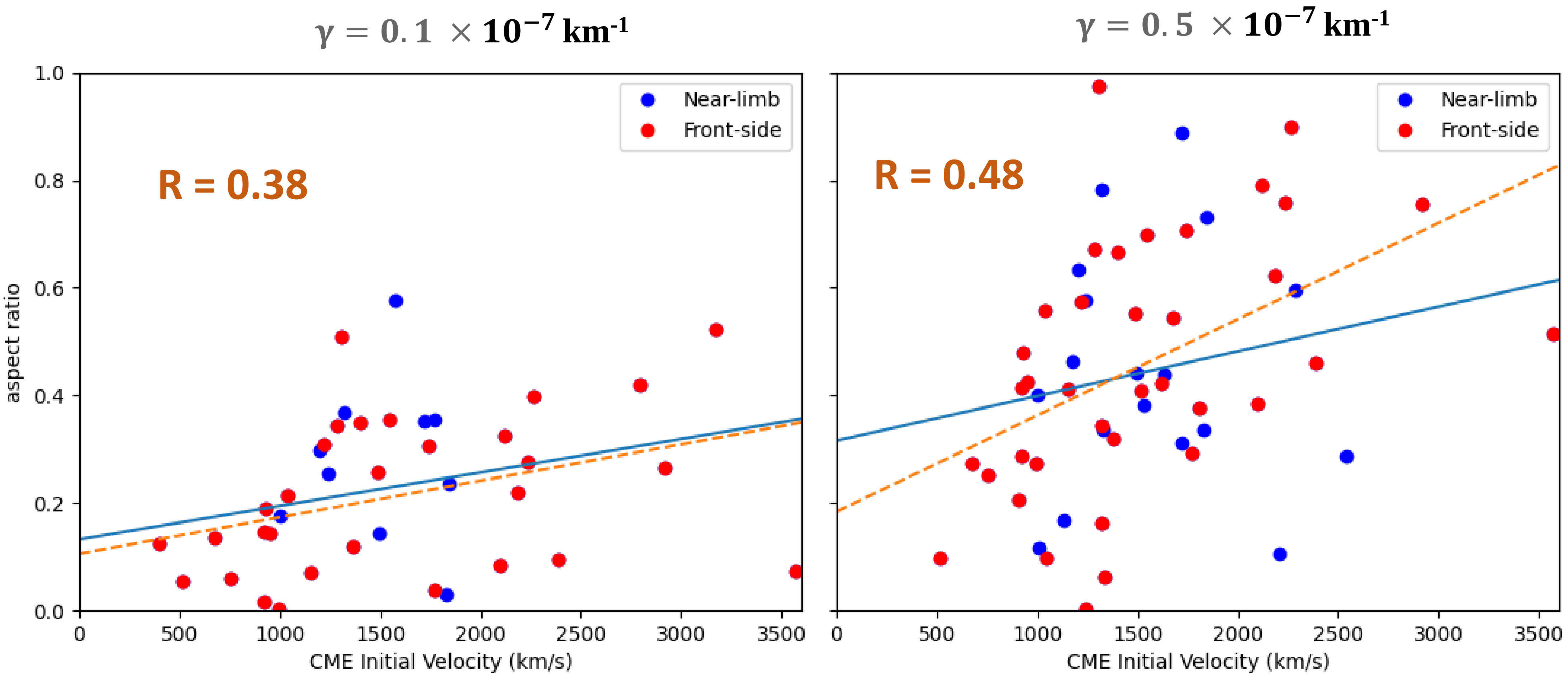
- Ensemble simulations are employed to determine the optimal aspect ratio (*b/a*) of the ellipse for each CME event within the dataset.
- This optimization process aimed to achieve the best fit between the simulated arrival time and the corresponding observed arrival time.

Results:

- Our simulations reveal a trend towards a more circular leading-edge (higher *b/a*) for CMEs with higher initial velocities.
- This relationship strengthens when considering only front-side CMEs (source region longitude < 30°).



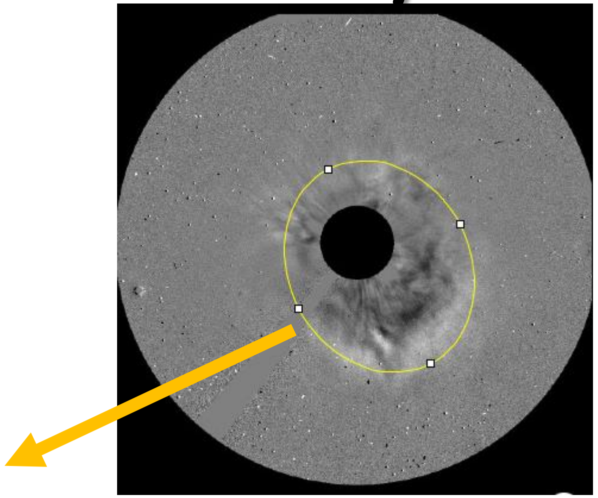
Results:



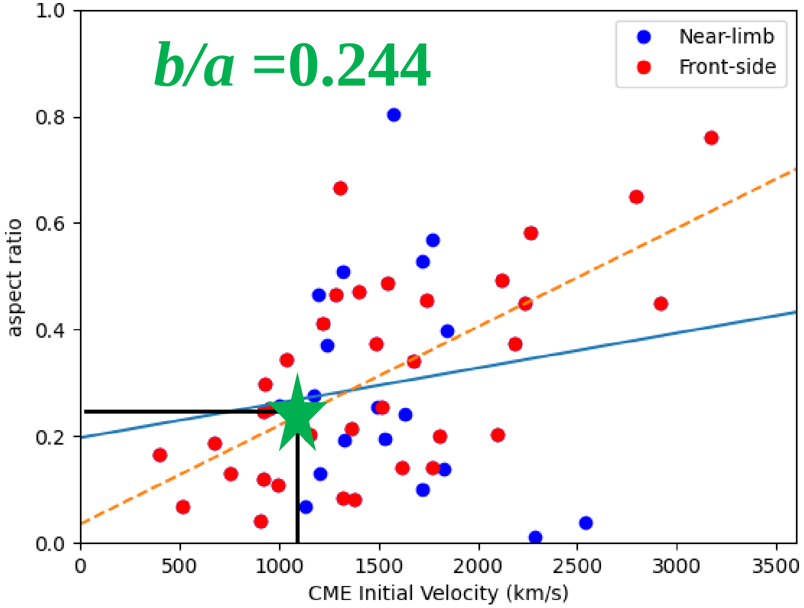
While the overall trend of aspect ratio dependence on initial speed remains relatively consistent, the specific relationship exhibits sensitivity to the chosen γ within the simulation. Our preliminary findings suggest that a combination of $\gamma = 0.2 \times 10^{-7}$ km^{-1} and $\omega = 450$ km/s offers a sufficient basis for estimating the appropriate aspect ratio based on initial CME velocity.

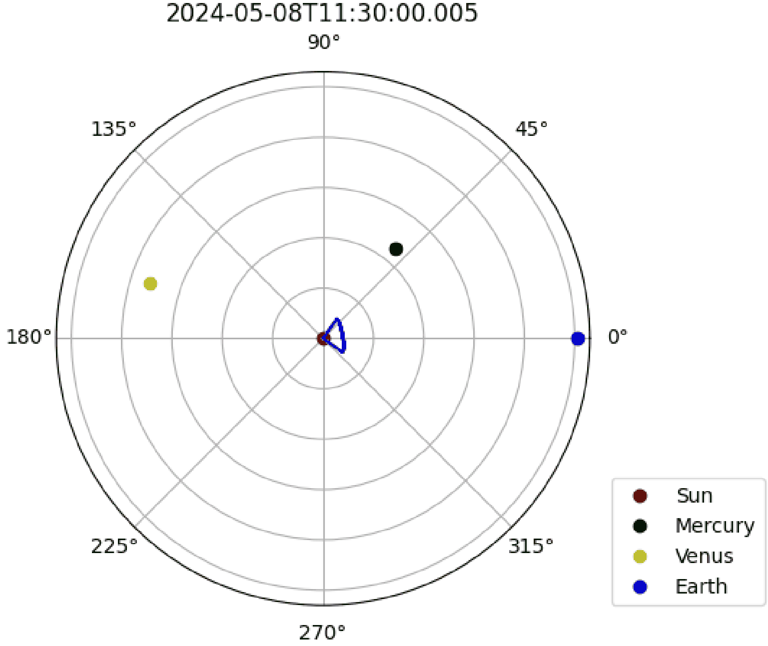
Preliminary Test: Superstorm May 2024

- $\gamma = 0.2 \times 10^{-7}$ km^{-1}
- $\omega = 450$ km/s
- $R_0 = 20$ Rsun
- $v_s = 729$ km/s (DONKI CCMC)
- $v_0 = 1130$ km/s (Cone model / Xie et al. 2004)
- $\theta = 45°$



CME: 8 May 2024 at 05.36 UT
Associated flare:
Long duration X1.0 flare
at 05.09 UT from AR 13664
(S22W10)





CME Scoreboard:

Transit time: 54.97 hrs
Predicted arrival time:
2024-05-10 18:27
Actual arrival time:
2024-05-10 16:36
Difference: 1.9 hrs

Conclusion

- Our findings demonstrate that faster CMEs exhibit a more circular leading-edge on the ICME cone.
- This suggests a more rapid expansion in all directions for stronger CMEs compared to their weaker counterparts. We believe that this is related to the strong Lorentz force that act on a flux rope during early expansion of a CME.
- Our results unveil the potential for developing a simplified 2D DBM model that solely requires adjustments to the elliptical aspect ratio based on the CME's initial speed for CME arrival time estimation.

Thank You for Your Attention