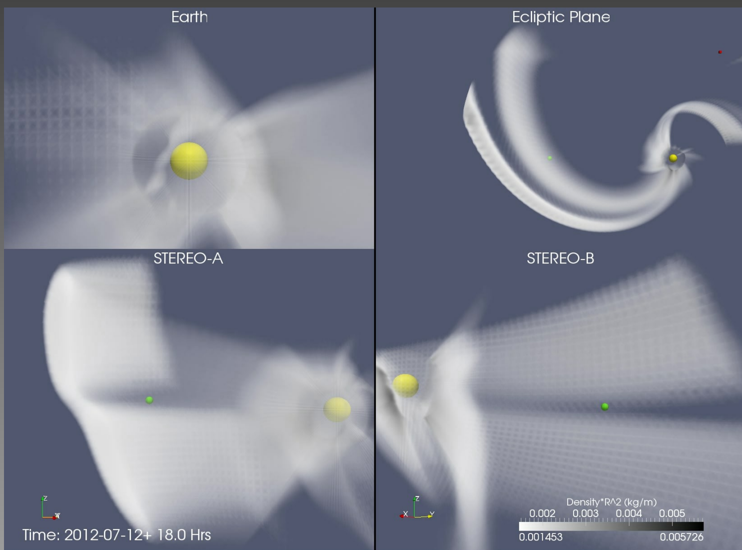
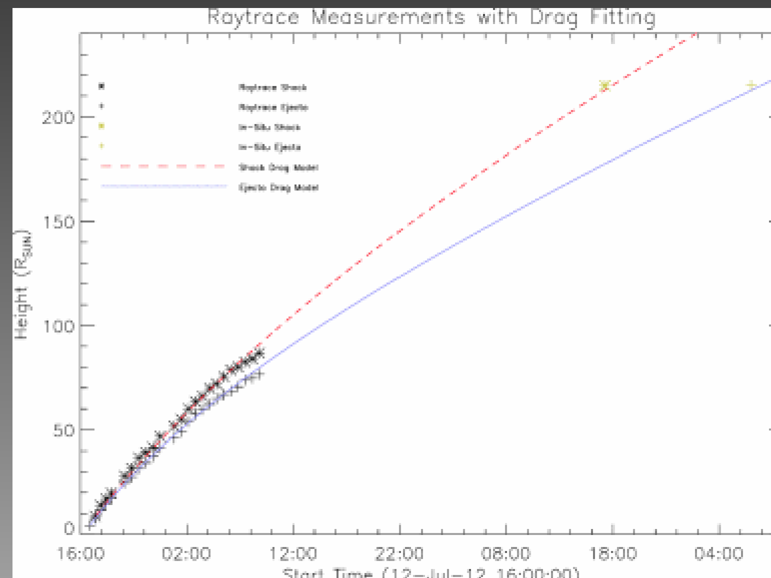
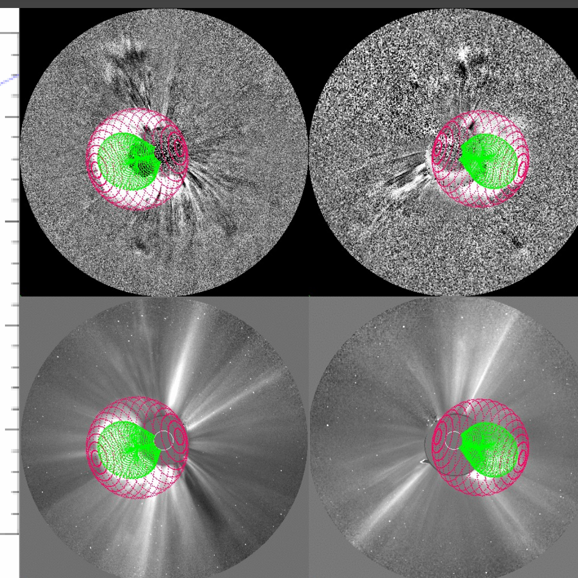
# Combining Models, Theory and Observations to Reconstruct CME and Shock Morphology



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October 18, 2014

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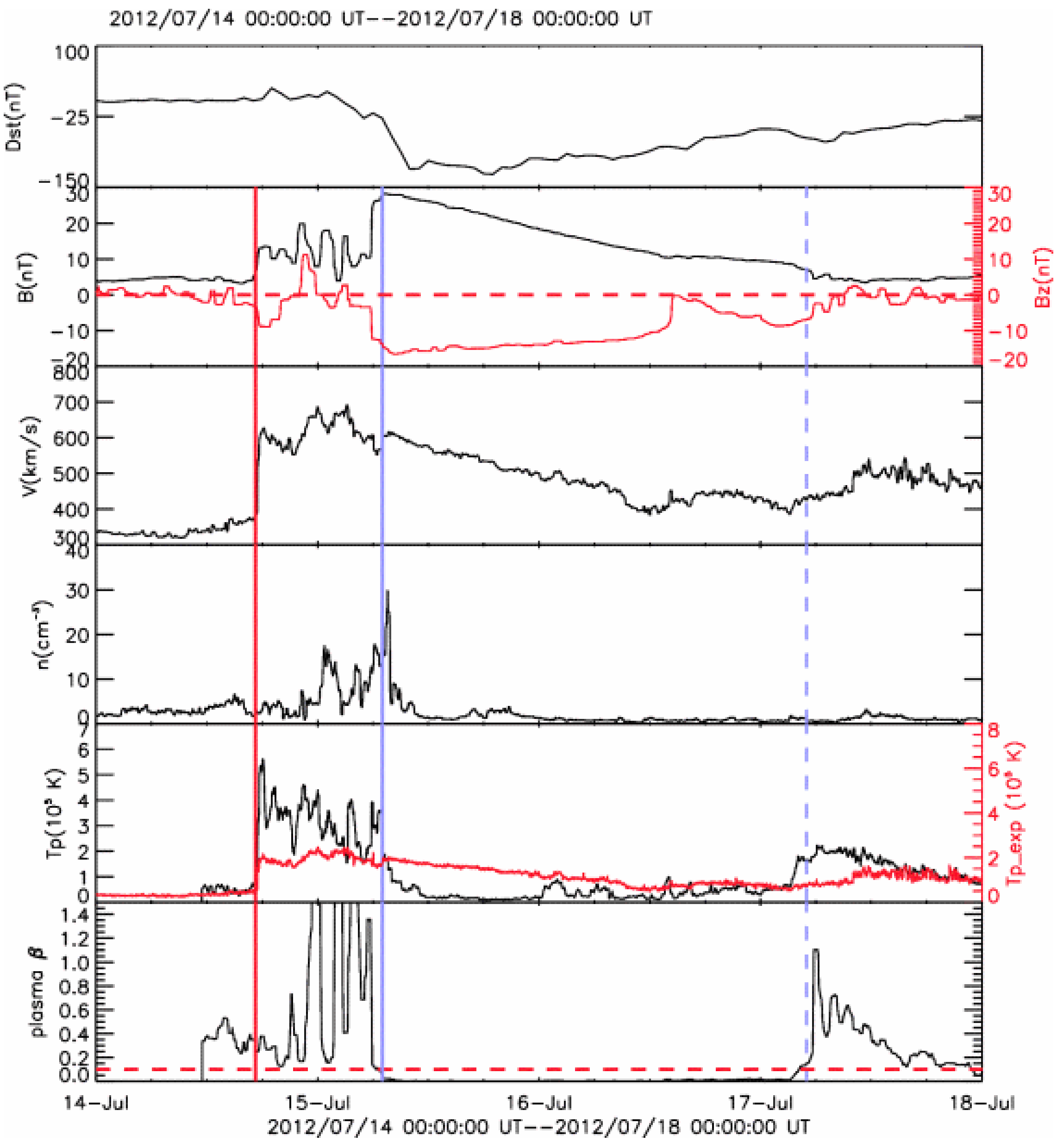
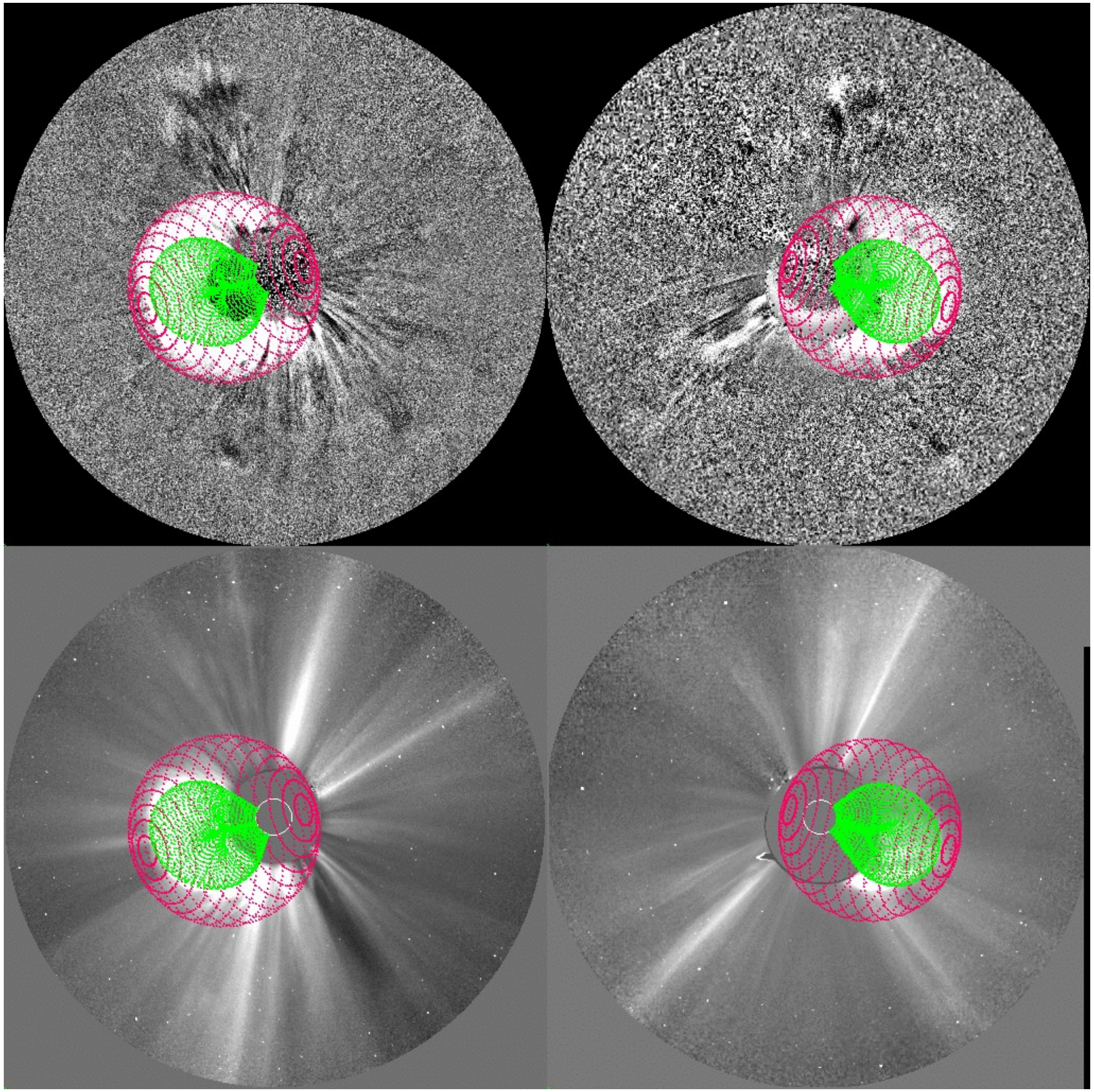
# Introduction

- The goal of this work, like ISEST itself, is to to drive analytical and numerical models with observational data for a series of geo-effective CMEs
- We want to address both the scientific question of physical processes governing CME evolution and the more practical aspect of space weather forecasting
- One key for both purposes is be the treating of the CME driver (flux rope) and shock as distinct features in the heliosphere
- For more detail on our methods, see Hess & Zhang Apj. 2014

# Observations: In-situ



# Observations and Measurement: Remote-Sensing



# Theoretical Model: Drag Model

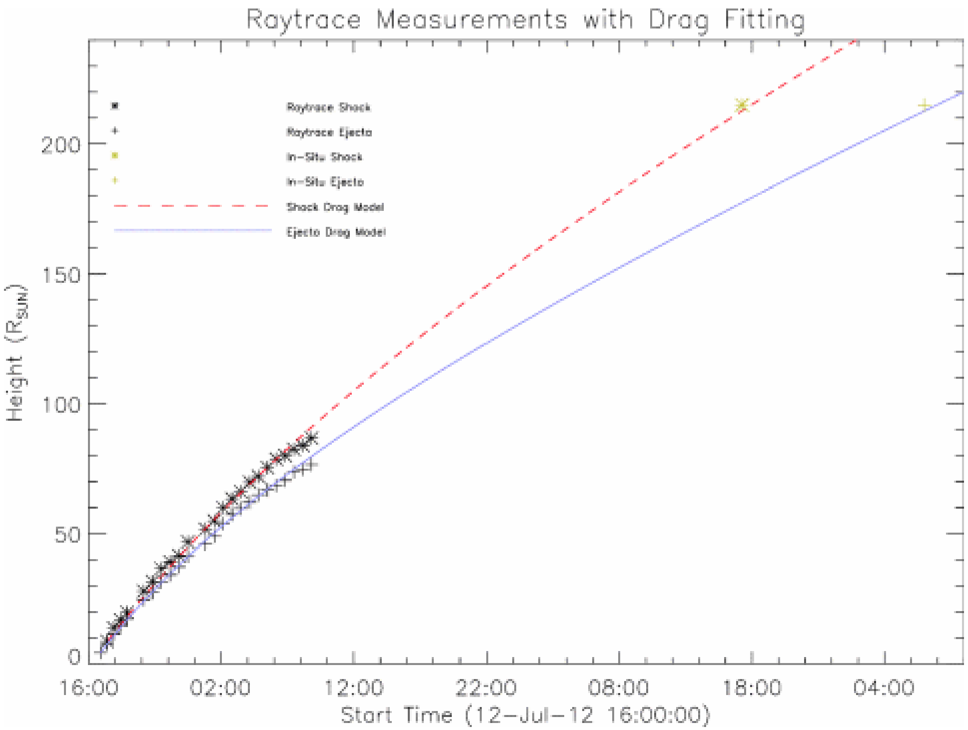
- To get an accurate kinematic profile, we fit the height-time measurements
- We use the Drag-Based Model (Vrsnak et al. 2013), which assumes that aerodynamic drag force dominates CME propagation

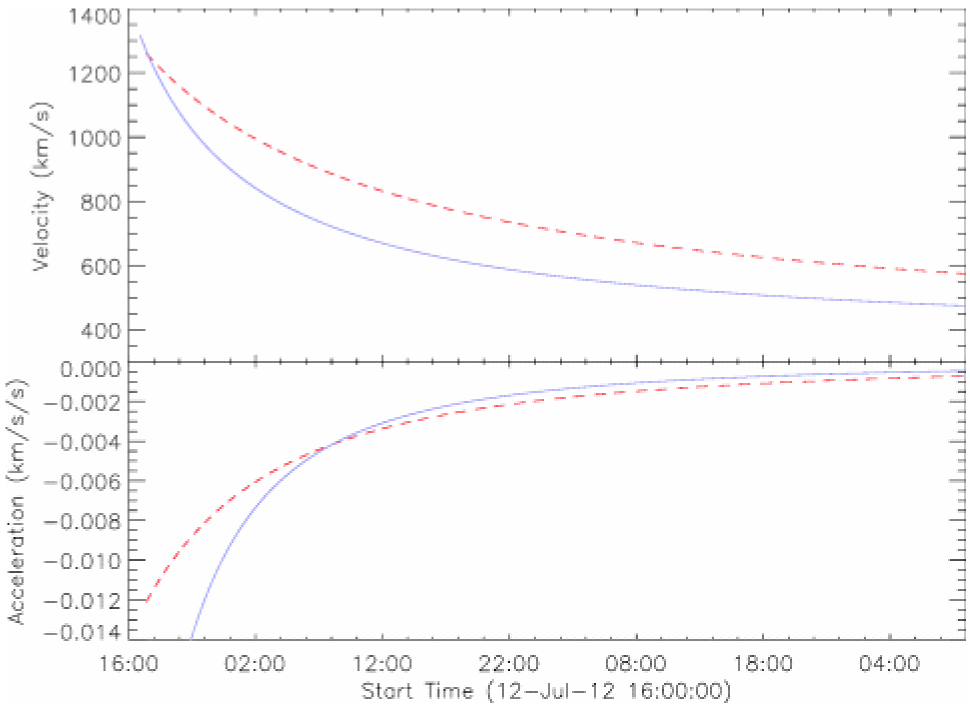
$$a(t) = -\gamma (v(t) - v_{sw}) |v(t) - v_{sw}|$$

$$v(t) = \frac{v_0 - v_{sw}}{1 + \gamma (v_0 - v_{sw}) t} + v_{sw}$$

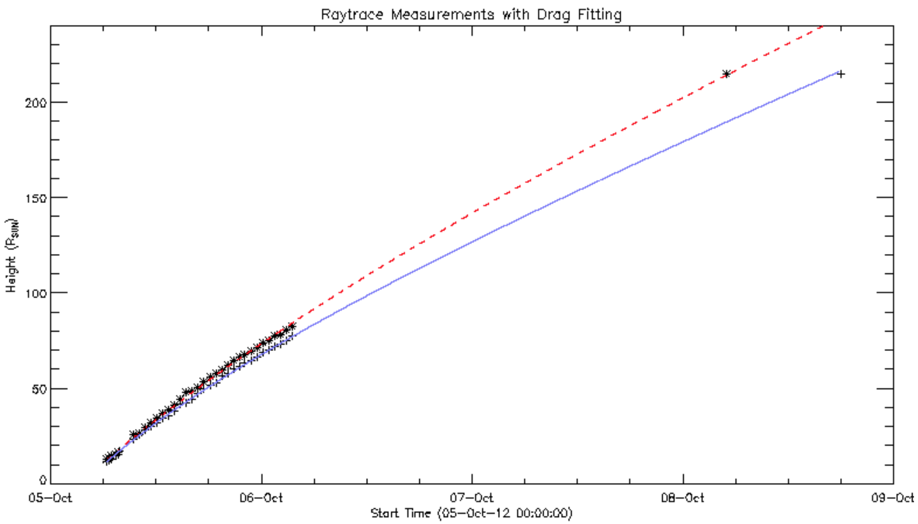
$$r(t) = \frac{1}{\gamma} \ln[1 + \gamma (v_0 - v_{sw}) t] + v_{sw} t + r_0$$

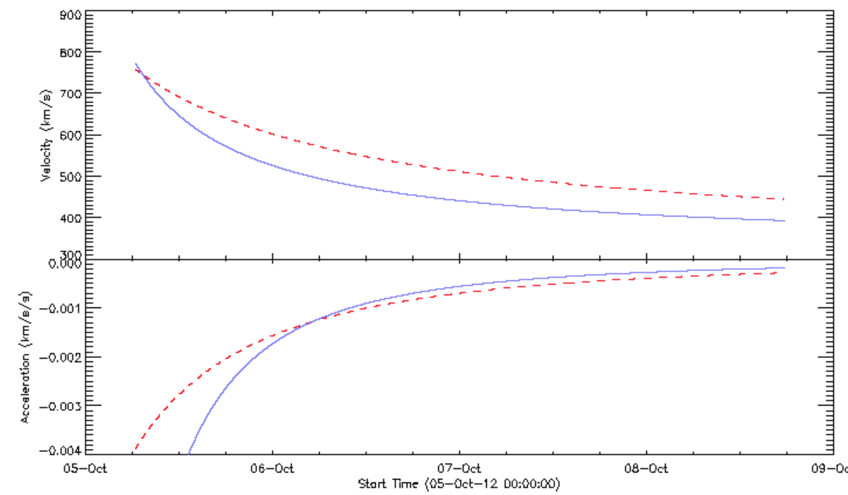
# Drag Model Fitting Result

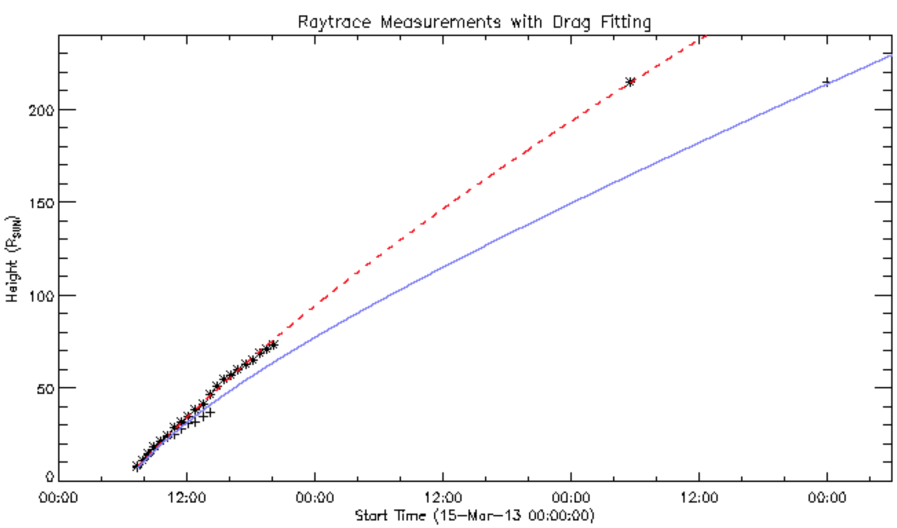


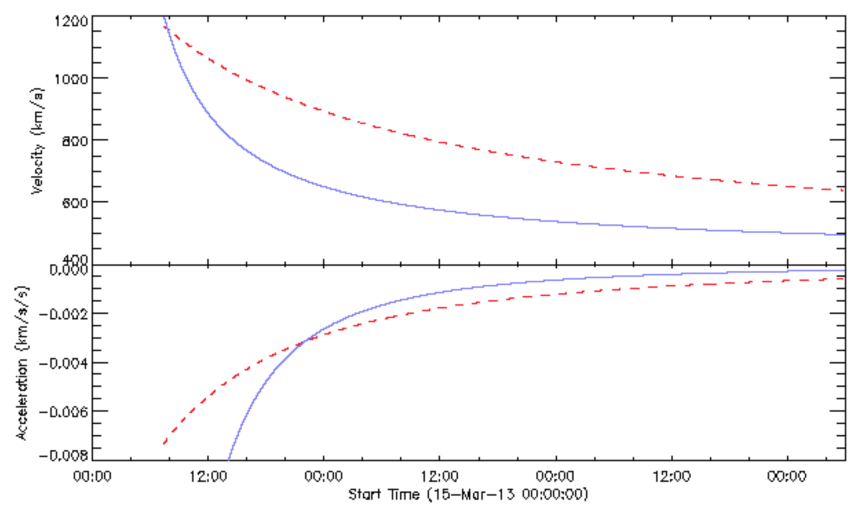




| | $\gamma$ (/km) | $V_0$ (km/s) | $V_f$ (km/s) | $R_0(Rs)$ | In-Situ Velocity (km/s) | Drag Model (km/s) | $\Delta T$ (hours) |
|---|---|---|---|---|---|---|---|
| Flux Rope | 3.09e-8 | 1316.5 | 353.7 | 4.29 | 487.7 | 477.9 | .69 |
| Shock | 1.47e-8 | 1259.4 | 353.7 | 8.69 | 608.3 | 625.5 | .89 |
| Flux Rope Prediction | 6.15e-8 | 1423.8 | 500 | 4.29 | 487.7 | 571.5 | -3.8 |
| Shock Prediction | 4.77e-8 | 1548.6 | 500 | 8.69 | 608.3 | 598.9 | 4.2 |


Raytrace Measurements with Drag Fitting
Height (R$_{SUN}$)
0
50
100
150
200
05−Oct
06−Oct
07−Oct
08−Oct
09−Oct
Start Time (05−Oct−12 00:00:00)

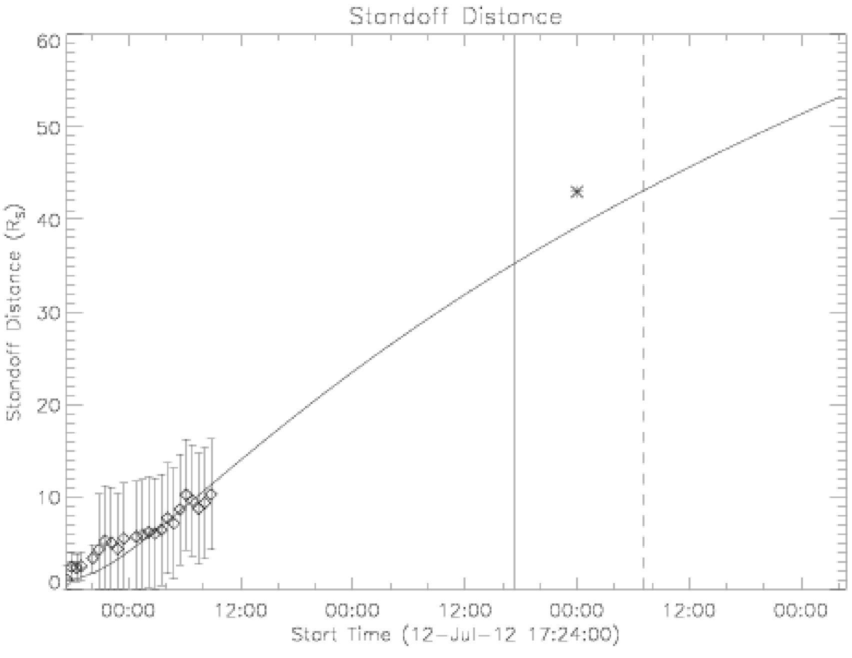

Velocity (km/s)
300
400
500
600
700
800
900
Acceleration (km/s/s)
0.000
−0.001
−0.002
−0.003
−0.004
05−Oct
06−Oct
07−Oct
08−Oct
09−Oct
Start Time (05−Oct−12 00:00:00)


Raytrace Measurements with Drag Fitting
Height (R$_{SUN}$)
0
50
100
150
200
00:00
12:00
00:00
12:00
00:00
12:00
00:00
Start Time (15−Mar−13 00:00:00)

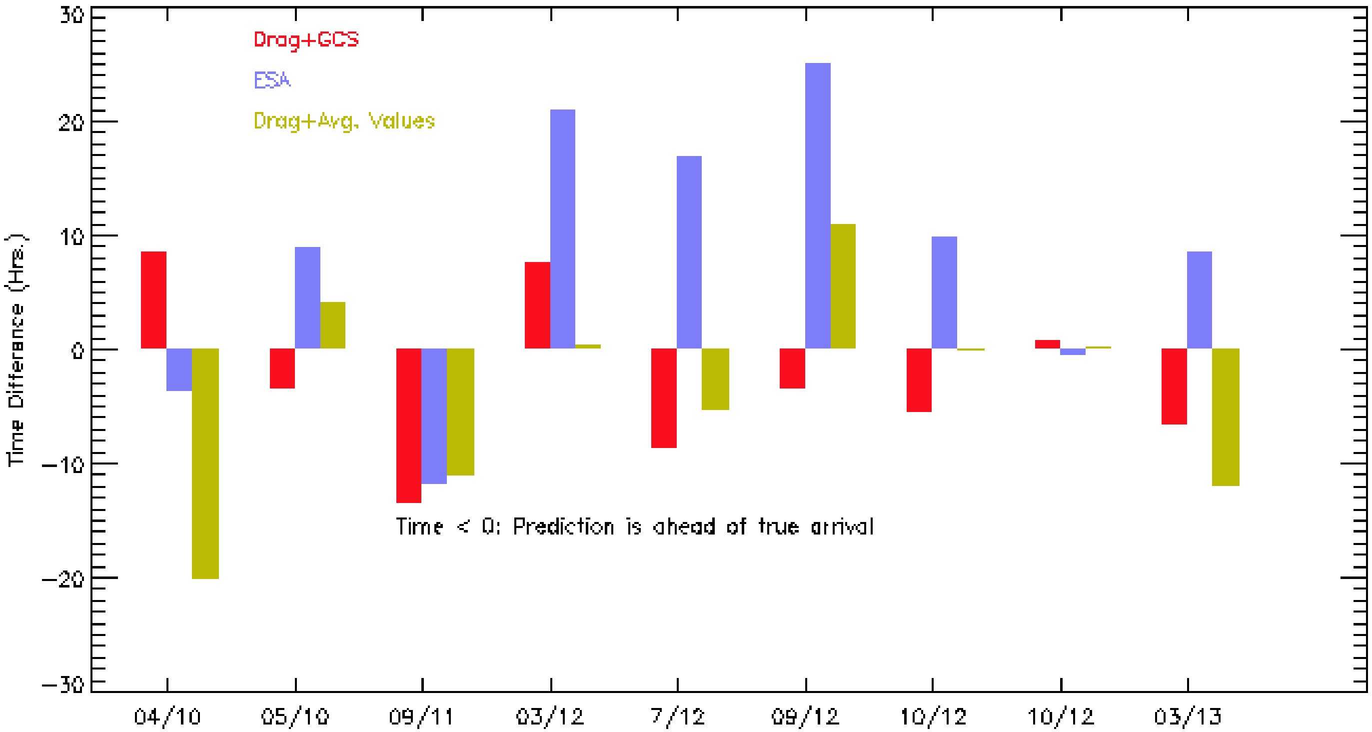

Velocity (km/s)
400
600
800
1000
1200
Acceleration (km/s/s)
0.000
−0.002
−0.004
−0.006
−0.008
00:00
12:00
00:00
12:00
00:00
12:00
00:00
Start Time (15−Mar−13 00:00:00)

# Implications of Drag Fittings

- While traveling at similar speeds near the Sun, the flux rope appears to undergo a rapid deceleration early in its propagation from the Sun to the Earth. The shock undergoes a much more gradual decrease as it propagates
- This also means, the standoff distance begins increasing linearly, but eventually the rate of this increase may slow down as the speeds converge to $V_{sw}$



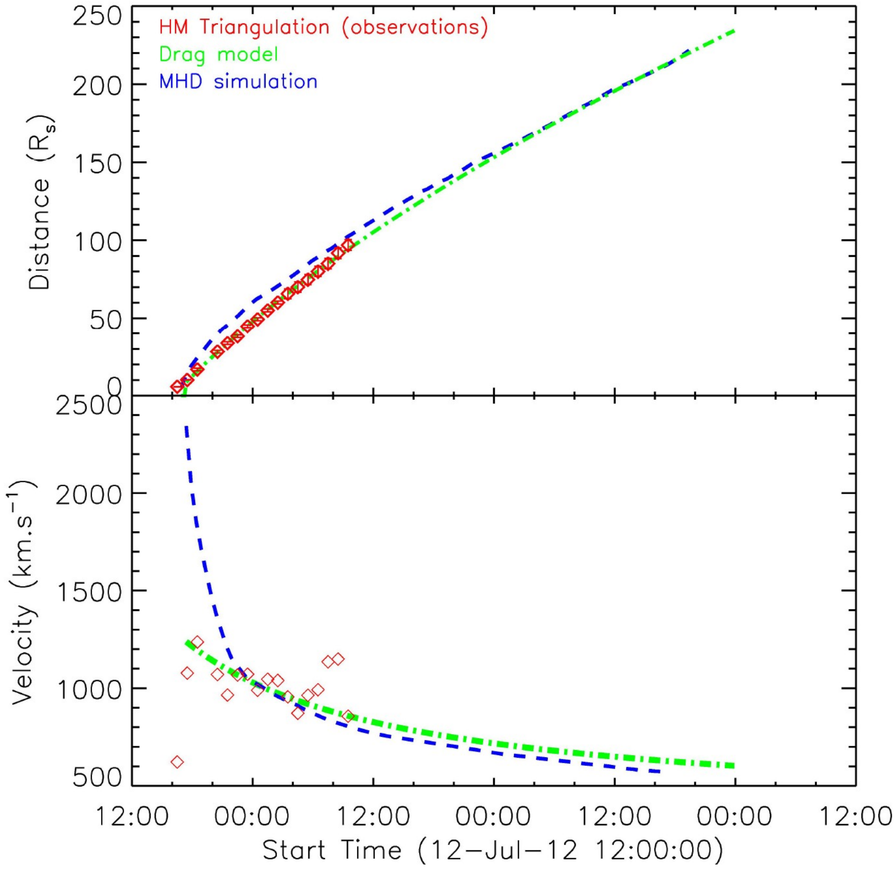
# Drag Fittings as Predictive Model




| | Drag+GCS | ESA | Drag Avg. Val. |
|---|---|---|---|
| Average | -4.60 | 8.21 | -3.71 |
| Standard Dev. | 6.10 | 11.96 | 9.46 |
| Abs Average | 6.46 | 11.79 | 7.13 |
| Abs Std | 3.74 | 7.90 | 6.90 |

# Comparison to Numerical Models: COIN-TVD

- Using our data as inputs, the CME was simulated with the COIN-TVD model (Shen et al 2014)



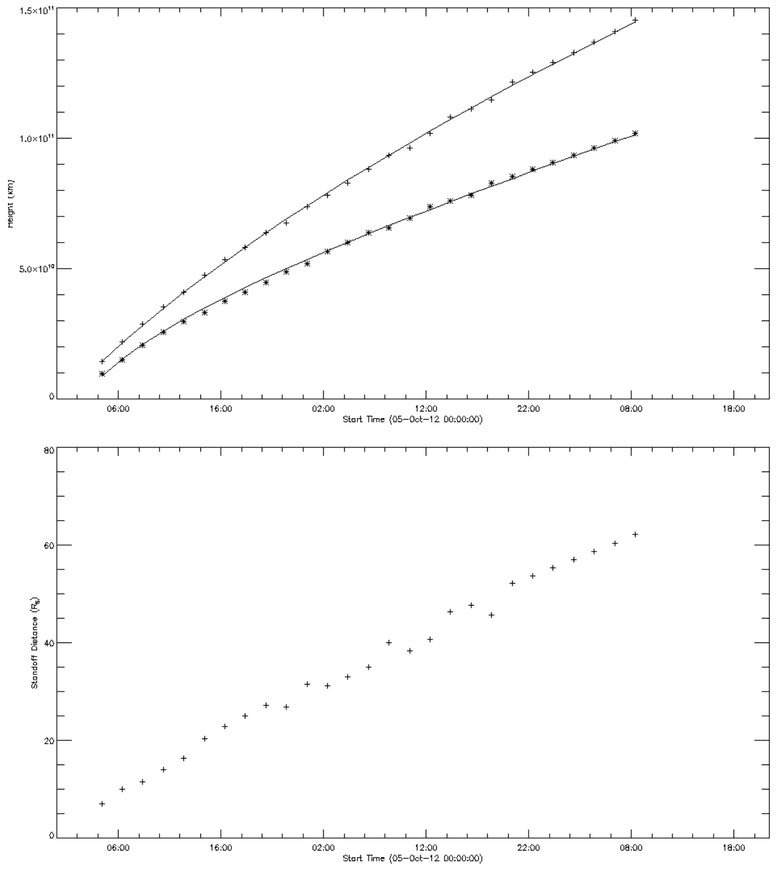
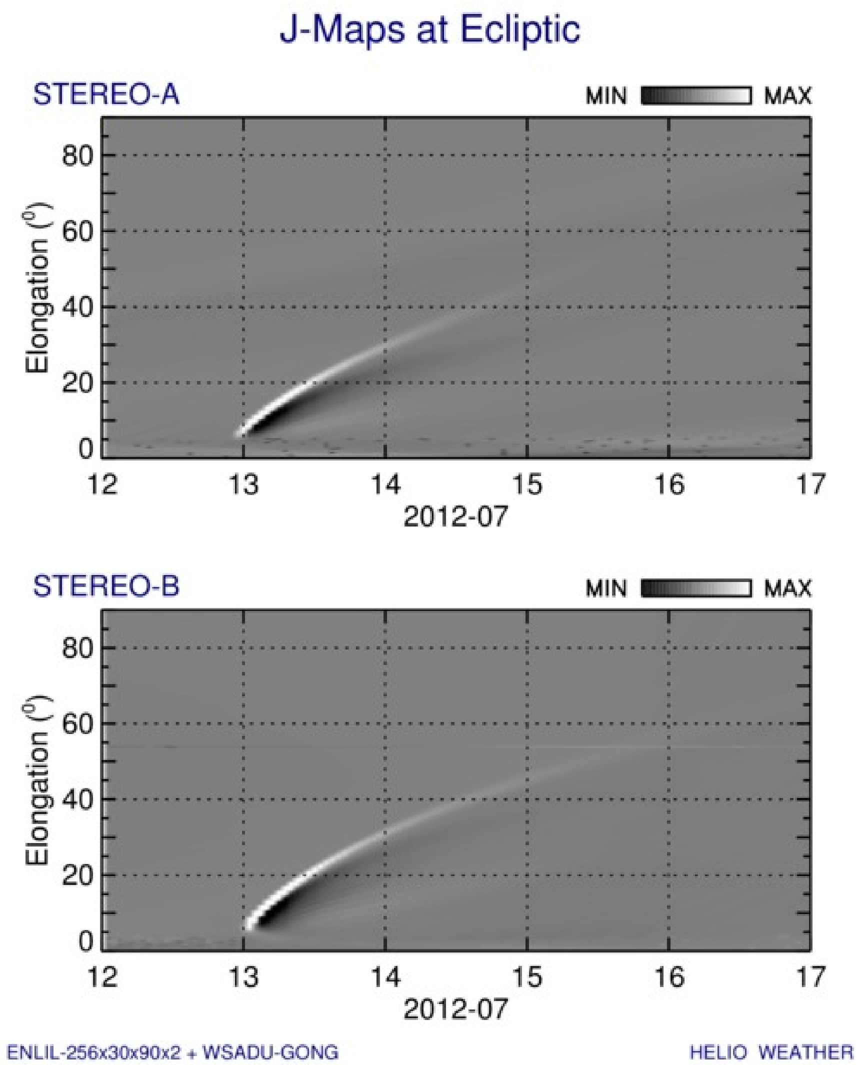
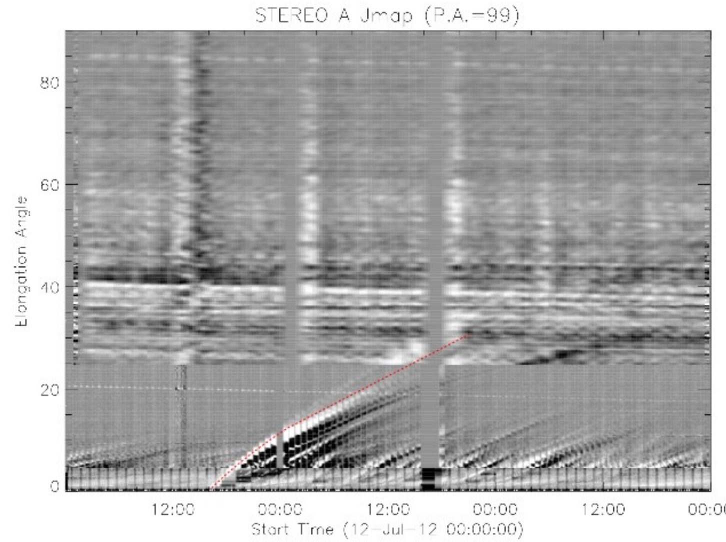
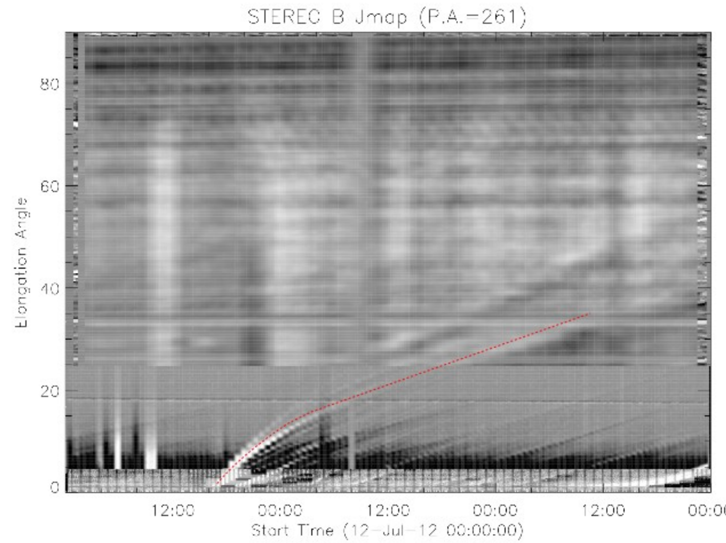




*Figure and Simulation Data Courtesy F. Shen*

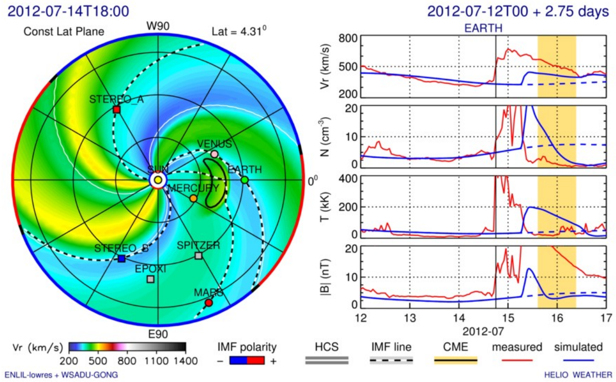


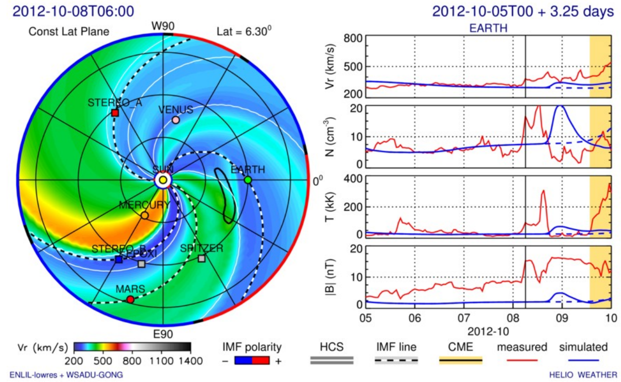



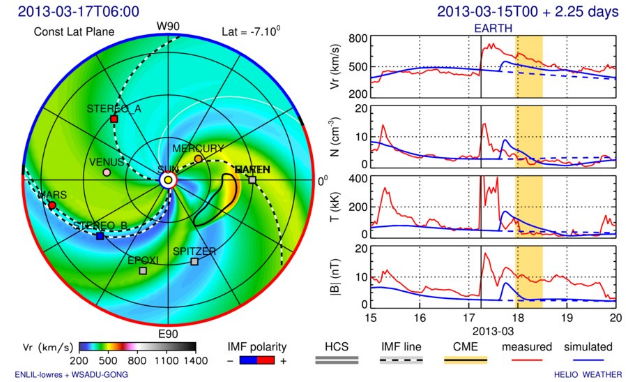



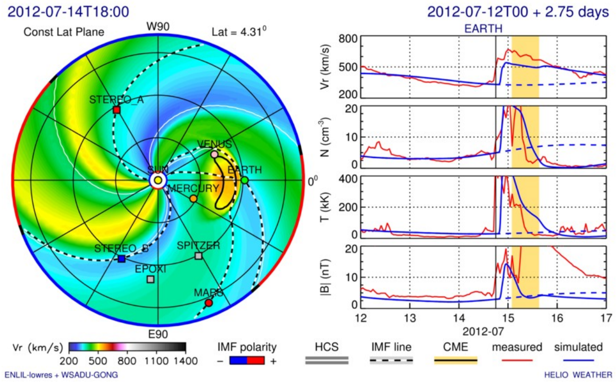

*Figures and Data Courtesy D. Odstrcil*

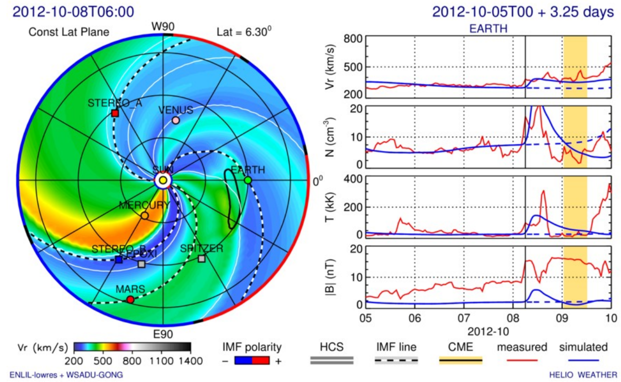
# Comparison to Numerical Models: ENLIL

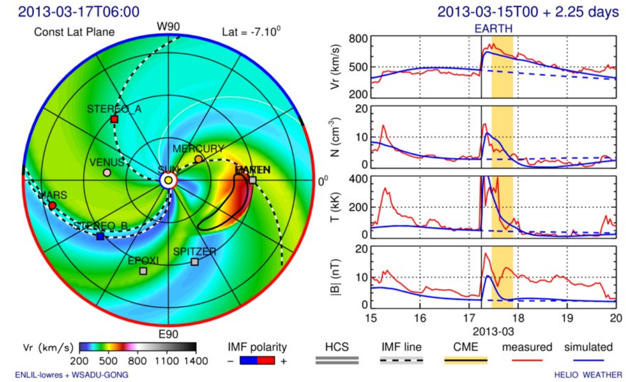



*Figures and Data Courtesy D. Odstrcil*

# Physical Findings and Future work

- For all well observed events studied, the shock decelerates more gradually than the flux rope
- The drag model does well in capturing measurements of each separate front, but how exactly is the drag being controlled? Does shock propagation have an additional term?
- Does the standoff distance follow consistent and predictable behavior for fast CMEs? Can we use the standoff distnace to help determine phsyical properties during CME propagation
- We will also compare the drag model profiles to the Eruptive Flux Rope Model (Chen et al 1996) to determine the importance of magnetic forces

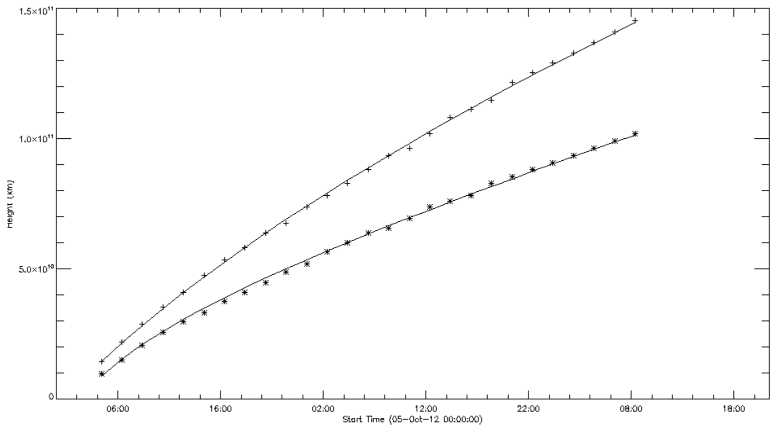
# Applications For Forecasting and Drawbacks

- Without having any knowledge of the ambient solar wind environment, the drag model can still do reasonably well at forecasting, and with just a little bit of input data can be run quickly and repeatedly.
  - Good measurements shortly after eruption are needed
  - Complex events cannot be captured
- Accurate $V_{sw}$ models can further constrain predictions
- We must study a statistically significant number of events and also compare to simulation to accurately predict drag
- An empirical model like this need not compete with numerical forecasting models, but can be used side by side to improve them

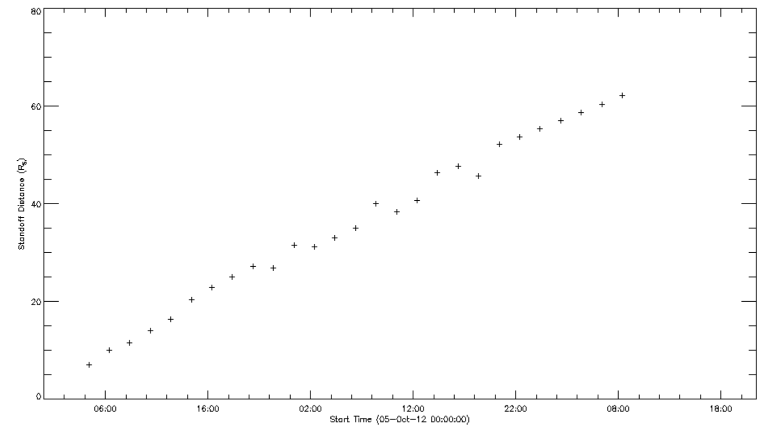
Thank you all for your attention

We encourage you all to visit and contribute to the ISEST Event Wiki (http://solar.gmu.edu/heliophysics)

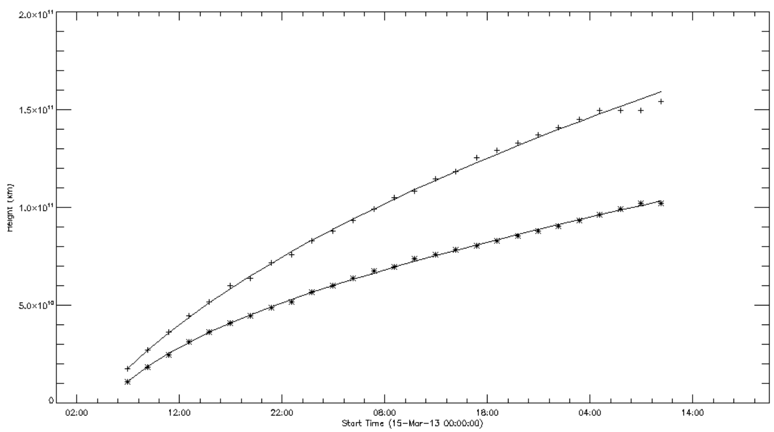
With Questions or Comments contact me at phess4@gmu.edu



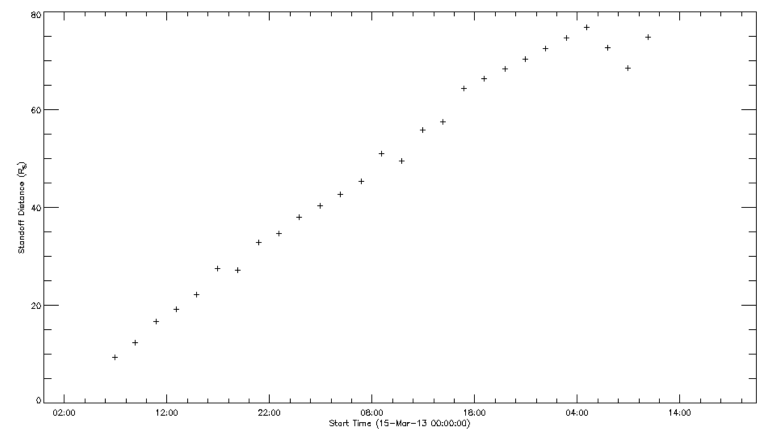
1.5×10¹¹
1.0×10¹¹
5.0×10¹⁰
0
Height (km)
06:00
16:00
02:00
12:00
22:00
08:00
18:00
Start Time (05-Oct-12 00:00:00)

80
60
40
20
0
Standoff Distance (R_E)
06:00
16:00
02:00
12:00
22:00
08:00
18:00
Start Time (05-Oct-12 00:00:00)

2.0×10¹¹
1.5×10¹¹
1.0×10¹¹
5.0×10¹⁰
0
Height (km)
02:00
12:00
22:00
08:00
18:00
04:00
14:00
Start Time (15-Mar-13 00:00:00)

80
60
40
20
0
Standoff Distance (R_E)
02:00
12:00
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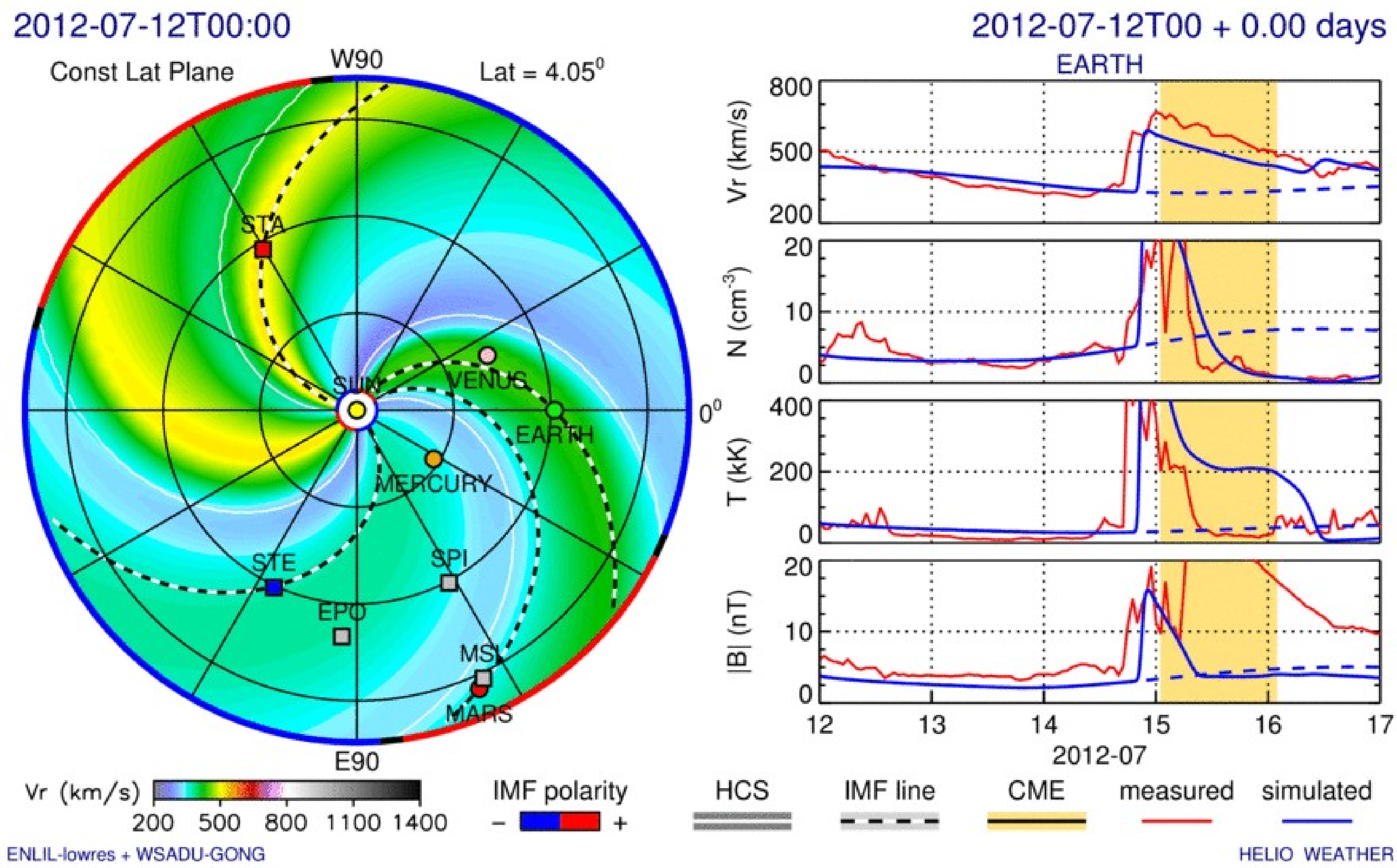
08:00
18:00
04:00
14:00
Start Time (15-Mar-13 00:00:00)



2012-07-12T00:00
Const Lat Plane
W90
Lat = 4.05°
STA
SUN
VENUS
EARTH
MERCURY
STE
SPI
EPO
MSI
MARS
E90
0°
Vr (km/s)
200 500 800 1100 1400
IMF polarity
− +
HCS
IMF line
CME
measured
simulated
ENLIL-lowres + WSADU-GONG
2012-07-12T00 + 0.00 days
EARTH
Vr (km/s)
N (cm⁻³)
T (kK)
|B| (nT)
12 13 14 15 16 17
2012-07
HELIO WEATHER

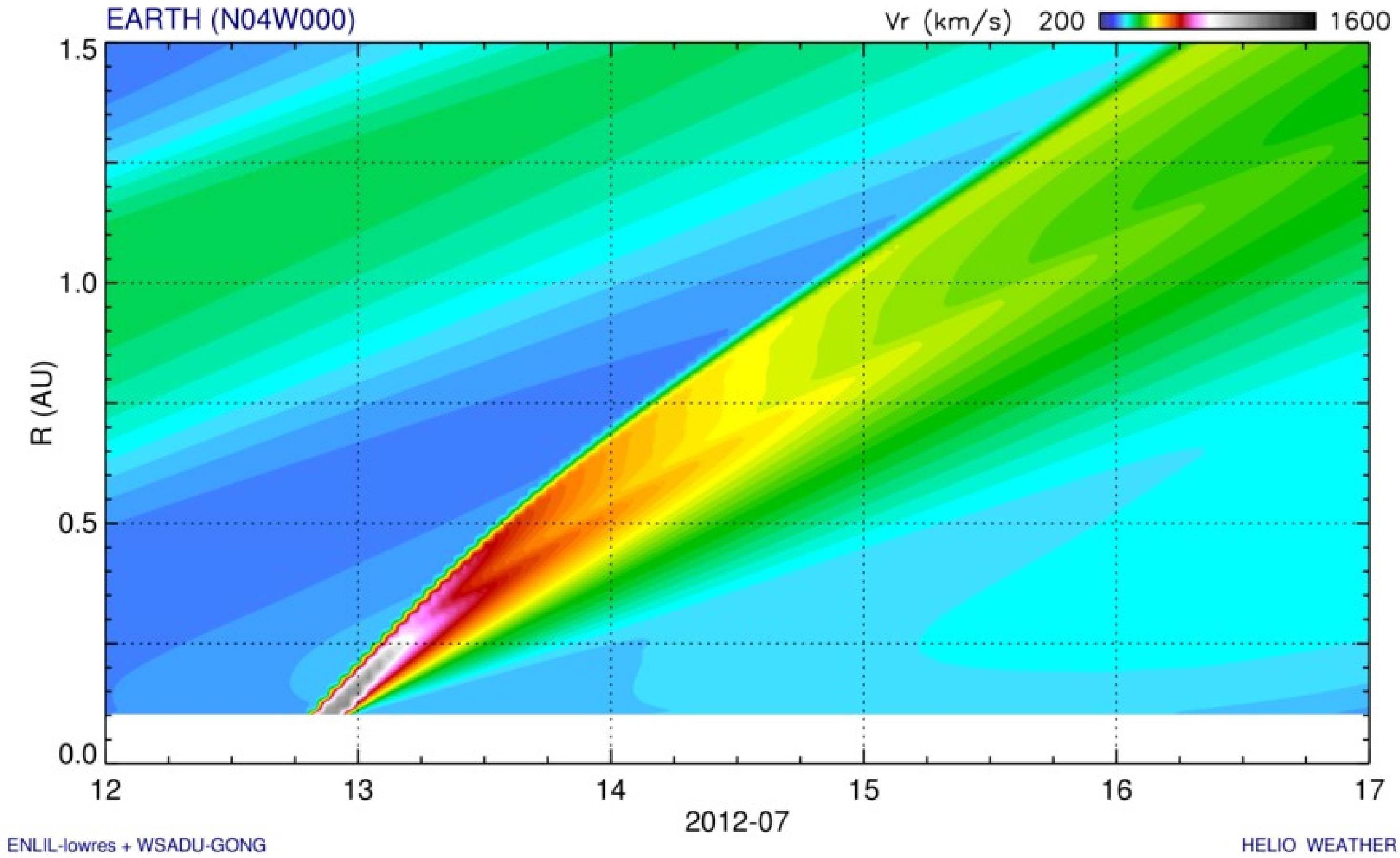
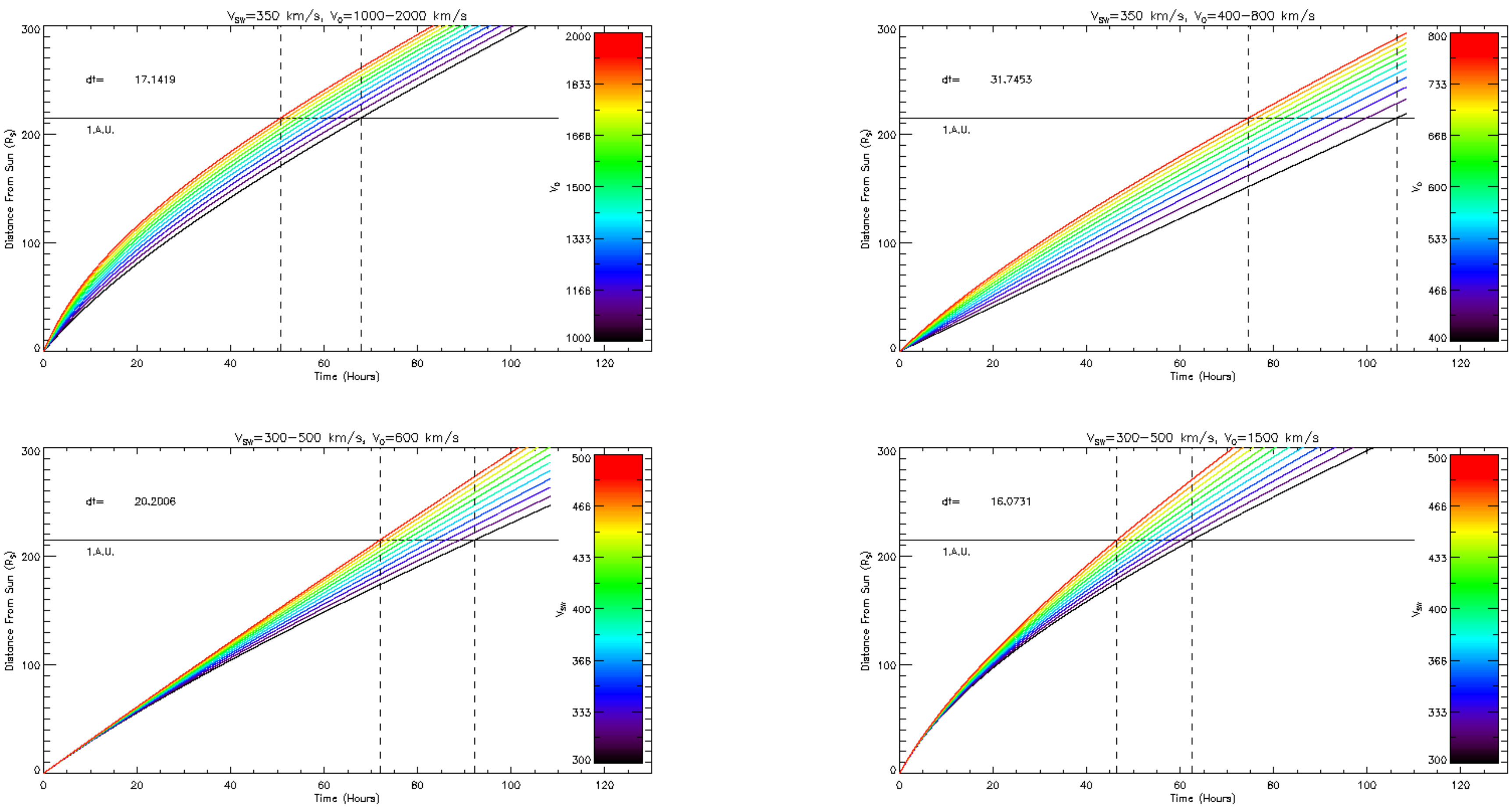
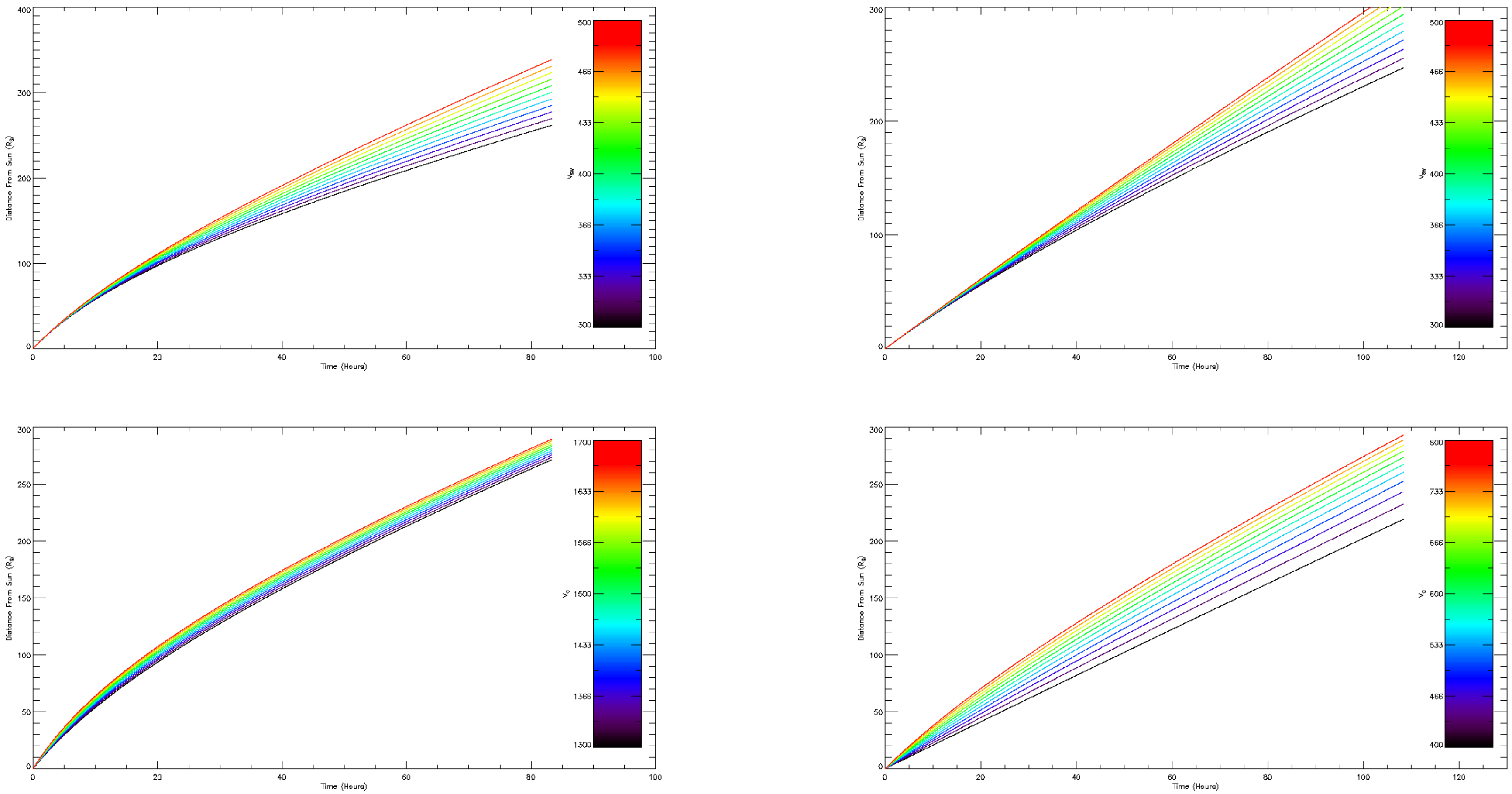



*Figure and Data Courtesy D. Odstrcil*

| | GAMMA | V_0 | V_F | R_0 | T | dT | V | TESA | Tdesa |
|---|---|---|---|---|---|---|---|---|---|
| 2010-04-03 | 2.8091382e-08 | 988.74812 | 512.40002 | 6 | 46.6 | -8.46 | 644.6 | 50.3364042 | -3.7364042 |
| | 4.0330168e-08 | 892.99465 | 512.40002 | 5.5 | 50.1 | -10.3 | 601.2 | 55.79172308 | -5.69172308 |
| 2010-05-27 | 5.9977073e-08 | 639.66562 | 362.29999 | 14.835299 | 83.1 | -3.44 | 408.4 | 74.2220389 | 8.877961104 |
| | 1.9762295e-07 | 700 | 362.29999 | 4.5956402 | 88.1 | -11.6 | 375.8 | 69.23314229 | 18.86685771 |
| 2011-09-14 | 8.2629160e-08 | 519.45986 | 396.89999 | 22.521601 | 73.6 | -13.5 | 427.63 | 85.48564475 | -11.8856447 |
| | 6.8357169e-07 | 650.49362 | 396.89999 | 5.3045201 | 81.6 | -16.2 | 401 | 73.2959368 | 8.304063205 |
| 2012-03-07 | 1.2062524e-08 | 3223.3 | 289.29999 | 11.2613 | 34.3 | 7.68 | 892.9 | 13.38808235 | 20.91191765 |
| | 1.5238070e-08 | 2666.8 | 289.29999 | 9.8299999 | 43.3 | 9.13 | 704.2 | 15.44750969 | 27.85249031 |
| 2012-07-12 | 2.7765080e-08 | 1468.5346 | 353.70001 | 8.6863604 | 48.4 | -8.63 | 506.5 | 31.61683347 | 16.78316653 |
| | 3.6328909e-08 | 1388.337 | 353.70001 | 4.2897301 | 62 | -3.49 | 458.5 | 33.95234174 | 28.04765826 |
| 2012-09-28 | 3.8493893e-08 | 1084.5798 | 310.39999 | 16.295401 | 70.6 | -3.43 | 398 | 45.5508431 | 25.0491569 |
| | 4.1096929e-08 | 1218.4183 | 310.39999 | 6.3045206 | 83.6 | 6.59 | 390.4 | 39.84023682 | 43.75976318 |
| 2012-10-05 | 3.3830160e-08 | 816.51022 | 328.79999 | 12.643499 | 70.6 | -5.61 | 417 | 60.69613255 | 9.903867453 |
| | 3.1233322e-08 | 728.38013 | 328.79999 | 11.5682 | 83.6 | 4.95 | 417.9 | 67.02589731 | 16.57410269 |
| 2012-10-27 | 9.9999997e-10 | 427.78379 | 289.79999 | 24.059099 | 94.9 | 0.698 | 422.1 | 95.41927077 | -0.51927077 |
| | 9.9999997e-10 | 394.13749 | 289.79999 | 6.2272301 | 103.9 | 0.253 | 390.3 | 99.39104181 | 4.508958188 |
| 2013-03-15 | 2.6733692e-08 | 1277.9352 | 429.29999 | 7.8414998 | 46.1 | -6.7 | 589 | 37.61959755 | 8.480402453 |
| | 1.2765252e-07 | 1400 | 429.29999 | 7.3757496 | 64.6 | -10.9 | 457.3 | 33.59647154 | 31.00352846 |



V_SW=350 km/s, V_0=1000-2000 km/s
dt= 17.1419
1.A.U.
Distance From Sun (R_S)
Time (Hours)
V_0
2000
1833
1666
1500
1333
1166
1000
V_SW=350 km/s, V_0=400-800 km/s
dt= 31.7453
1.A.U.
Distance From Sun (R_S)
Time (Hours)
V_0
800
733
666
600
533
466
400
V_SW=300-500 km/s, V_0=600 km/s
dt= 20.2006
1.A.U.
Distance From Sun (R_S)
Time (Hours)
V_SW
500
466
433
400
366
333
300
V_SW=300-500 km/s, V_0=1500 km/s
dt= 16.0731
1.A.U.
Distance From Sun (R_S)
Time (Hours)
V_SW
500
466
433
400
366
333
300



Distance From Sun (R$_S$)
Time (Hours)
V$_{SW}$
Distance From Sun (R$_S$)
Time (Hours)
V$_{SW}$
Distance From Sun (R$_S$)
Time (Hours)
V$_0$
Distance From Sun (R$_S$)
Time (Hours)
V$_0$