Dynamics of CMEs and Evolution of CME Magnetic Fields in Interplanetary Space

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EARTH-SUN SYSTEM EXPLORATION VARIABILITY IN SPACE PLASMA PHENOMENA
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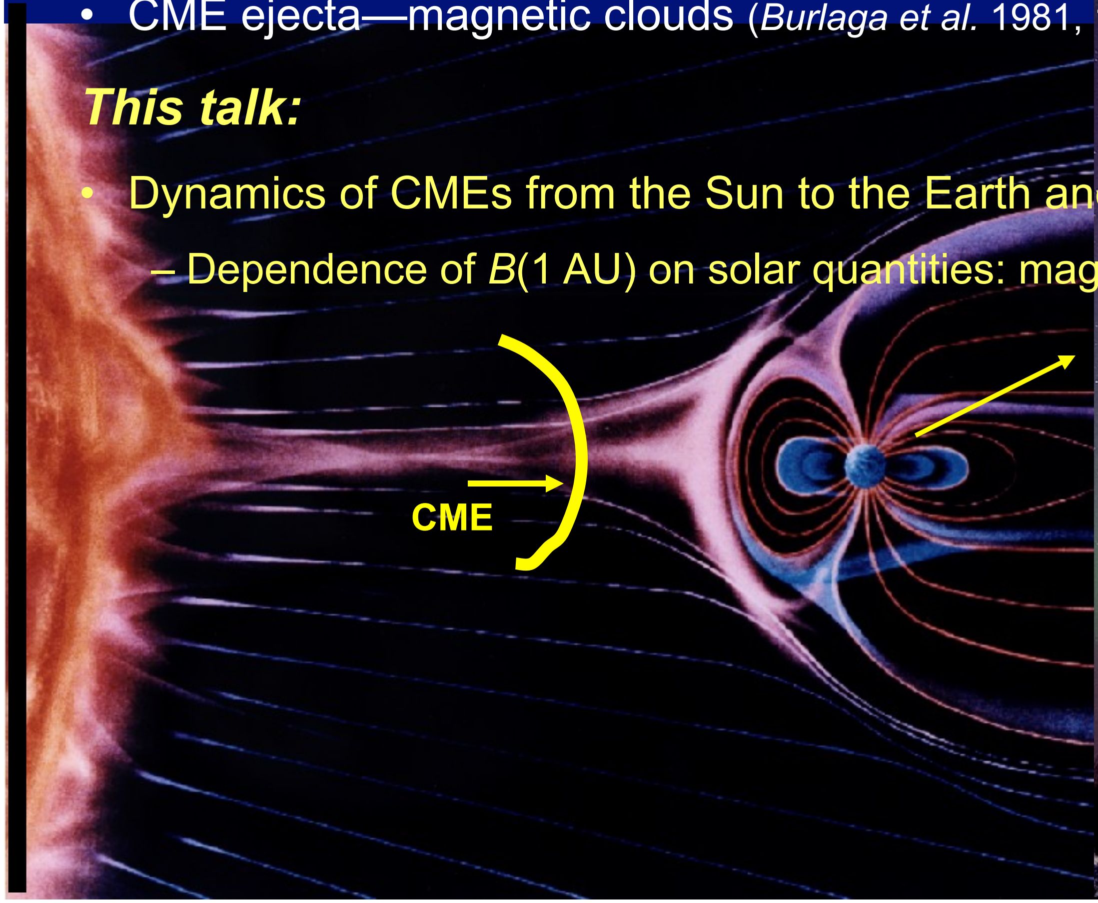
SOLAR ERUPTIONS AND THE EARTH

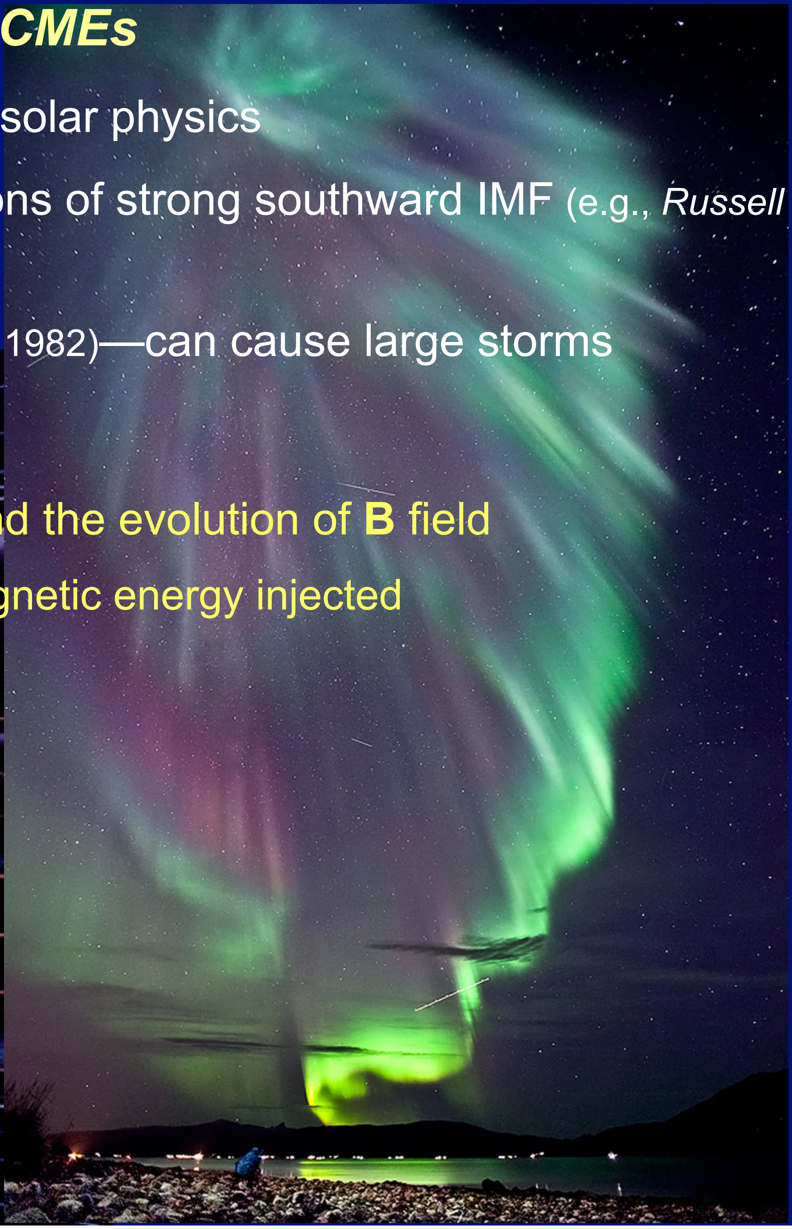
Physics and Terrestrial Consequences of CMEs

- Physics of CMEs is a major question in modern solar physics
- Geomagnetic storms are caused by long-durations of strong southward IMF (e.g., *Russell et al.* 1974)
- CME ejecta—magnetic clouds (*Burlaga et al.* 1981, 1982)—can cause large storms

This talk:

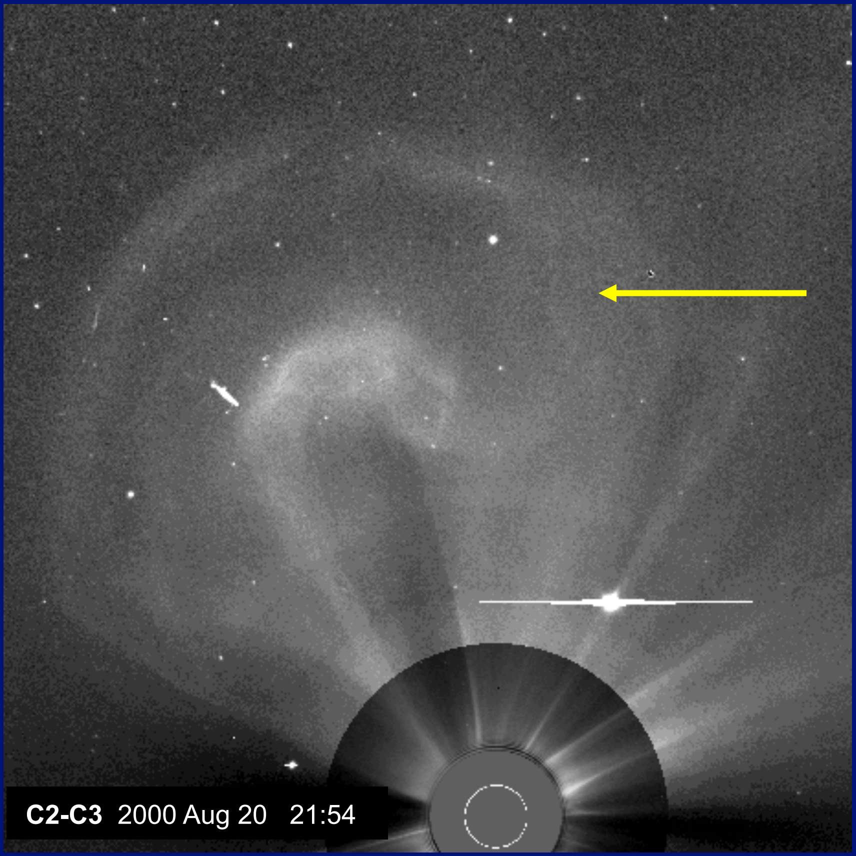
- Dynamics of CMEs from the Sun to the Earth and the evolution of **B** field
  - Dependence of *B*(1 AU) on solar quantities: magnetic energy injected

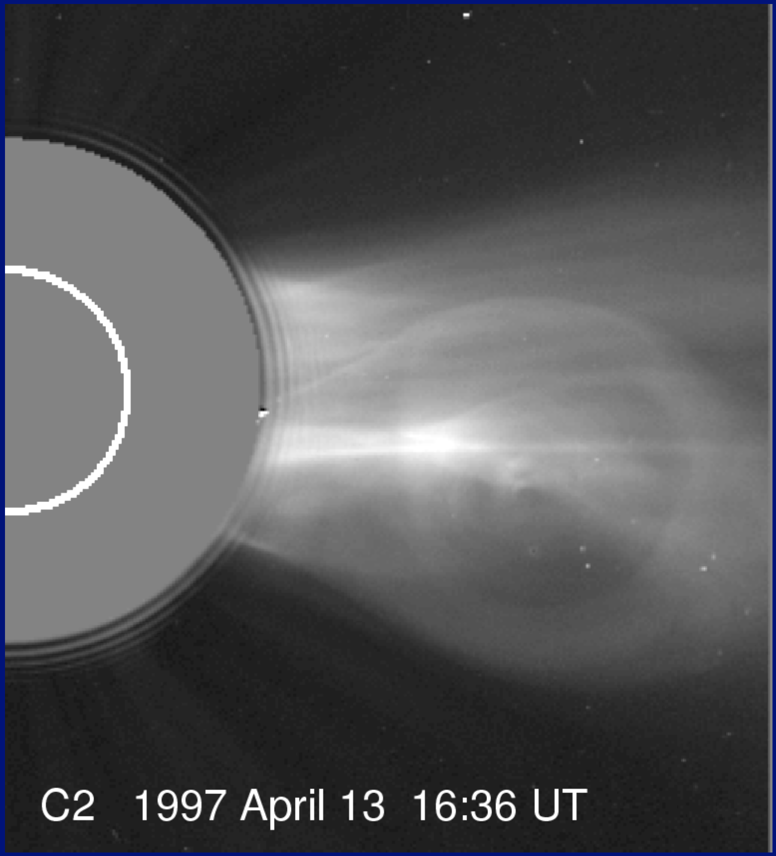




OBSERVED FLUX-ROPE CMES – EXAMPLES

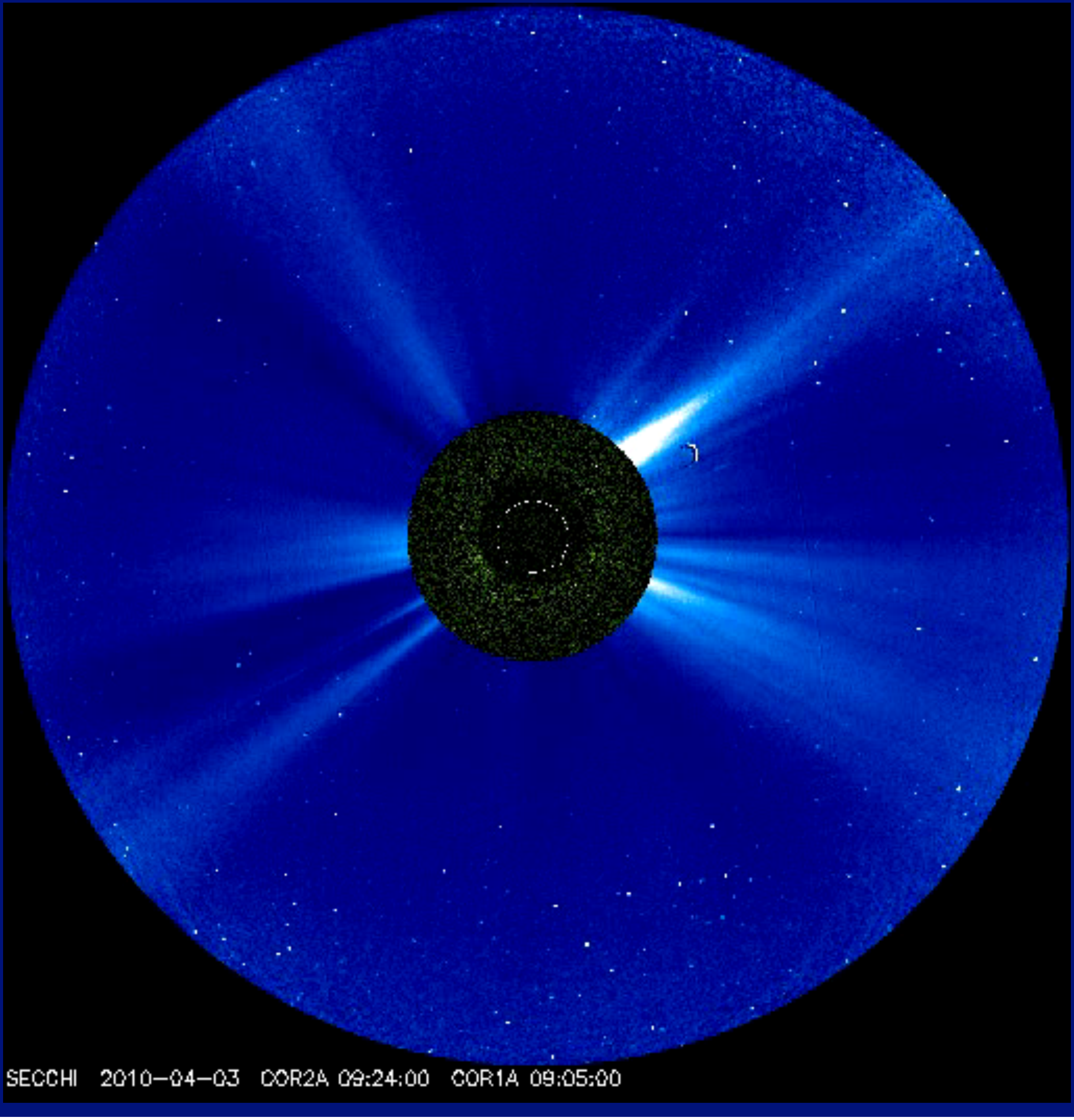
LASCO / *SOHO*





- A flux rope viewed from the side A flux rope viewed end-on
- Halo CMEs [*Howard et al.* 1982] are flux ropes viewed head on [*Krall et al.* 2006]

3 APRIL 2010 CME—STEREO COR1 & COR2



PHYSICS OF CMEs: Forces

- “Toroidal” magnetic flux rope *with fixed footpoints* separated by S_f
- Major Radial Forces: integrate $\mathbf{f} = \rho\, d\mathbf{v}/dt = c^{-1}\mathbf{J}\mathrm{x}\mathbf{B} - \nabla p + \rho\nabla\phi_g$

$$M\frac{d^2Z}{dt^2} = \frac{\Phi_p^2(t)}{c^4L^2R}\left[\overset{J_t\times B_p}{\ln\left(\frac{8R}{a}\right)} + \overset{\nabla p}{\frac{1}{2}\beta_p} - \overset{J_p\times B_t}{\frac{1}{2}\frac{B_t^2}{B_p^2}} + \overset{J\ \times B_c}{2\left(\frac{R}{a}\right)\frac{B_c}{B_p}} - 1 + \frac{\xi_i}{2}\right] + F_g + F_d$$

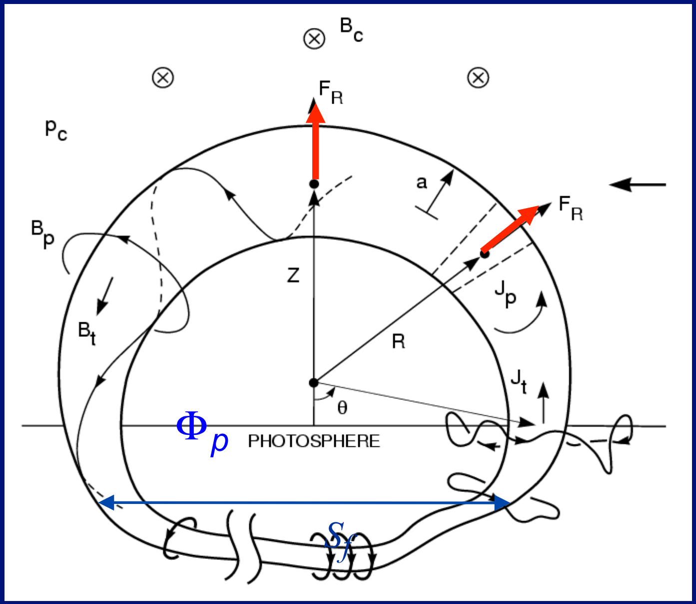
[*Shafranov* 1966; *Chen* 1989; *Garren and Chen* 1994]

$$M\frac{d^2a}{dt^2} = \frac{a}{4}\left(\overset{J_p\times B_t}{B_t^2} \underset{J_t\times B_p}{- B_p^2} + \overset{\nabla p}{\beta_p B_p^2}\right)$$

$$\Phi_p = cLI_t, \qquad L = 4\pi\,\Theta R\left[\ln\left(\frac{8R}{a_f}\right) - 2\right]$$

- Initiation of eruption:

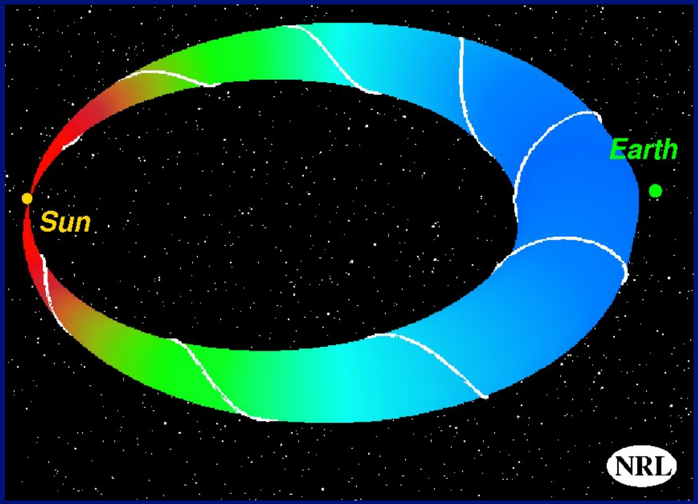
$$\boxed{\frac{d\Phi_p(t)}{dt} = \text{poloidal flux "injection"}}$$



CALCULATED MAGNETIC FIELD

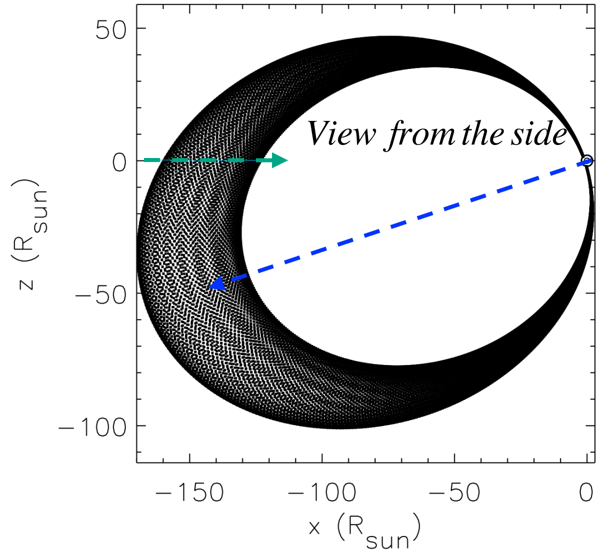
$$B_p(r\,|\,t) = \begin{cases} 3B_{pa}\left(1 - \dfrac{r^2}{a^2(t)} + \dfrac{r^4}{3a^4(t)}\right), & r \leq a(t), \\ 3B_{pa}\,\dfrac{r}{a(t)}, & r > a(t), \end{cases}$$

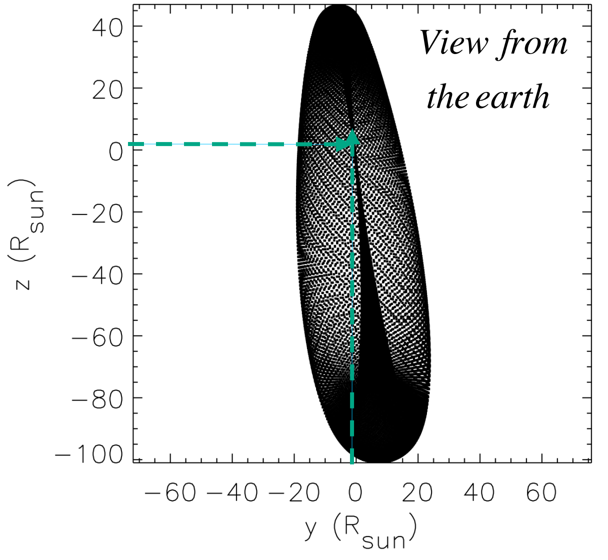
$$B_t = \begin{cases} 3B_t\left(1 - 2\dfrac{r^2}{a(t)^2} + \dfrac{r^4}{a(t)^4}\right), & r \leq a(t) \\ 0, & r > a(t) \end{cases}$$

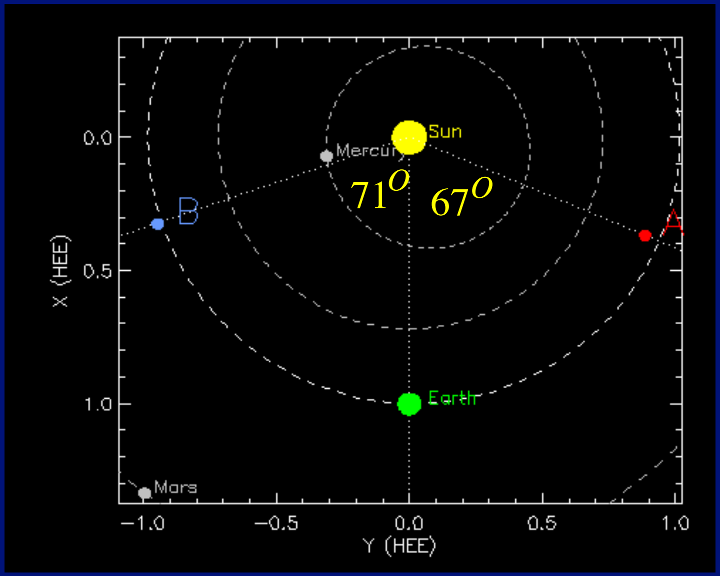


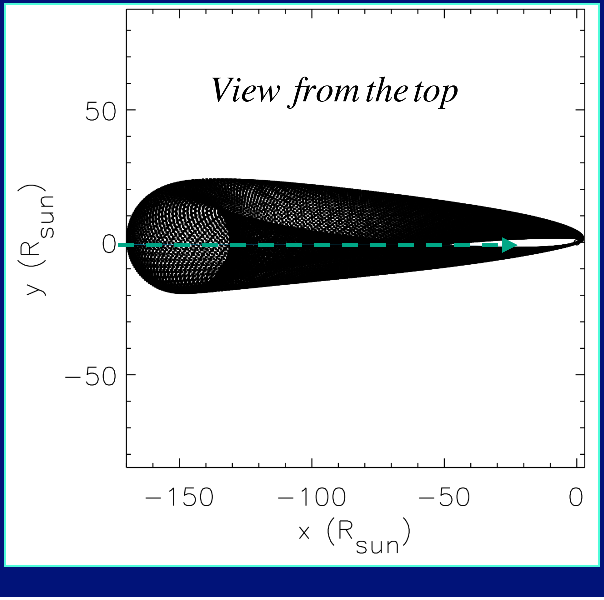
a(t) is given by the equation of motion.

GEOMETRY OF CME AT 1 AU

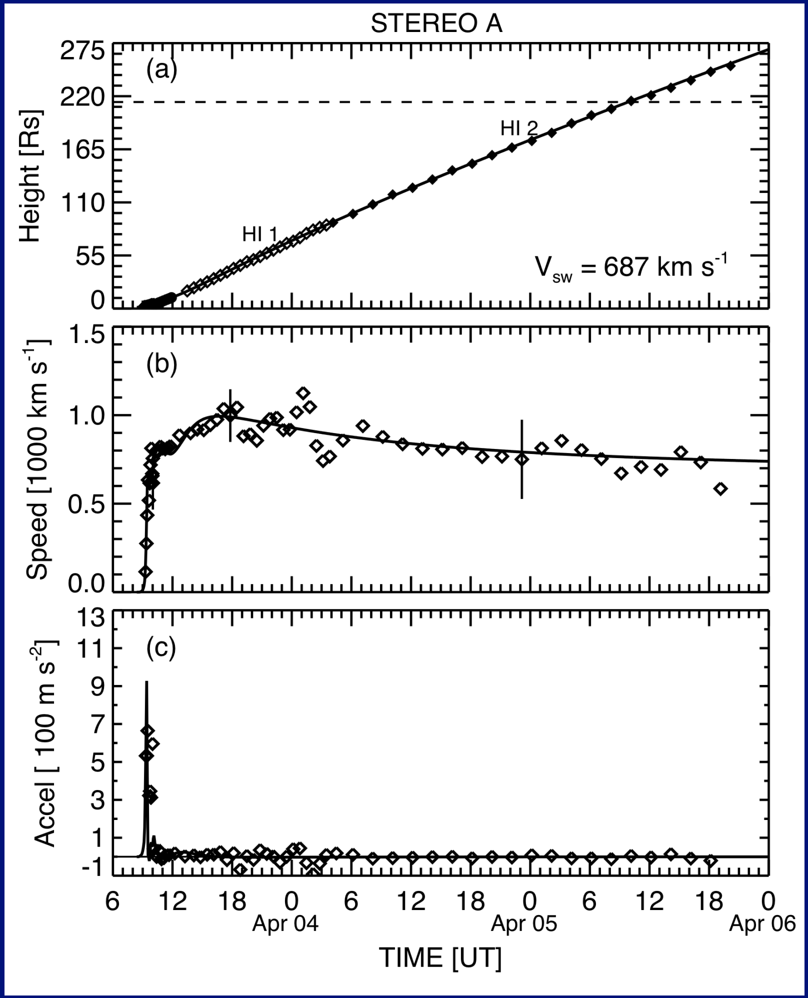


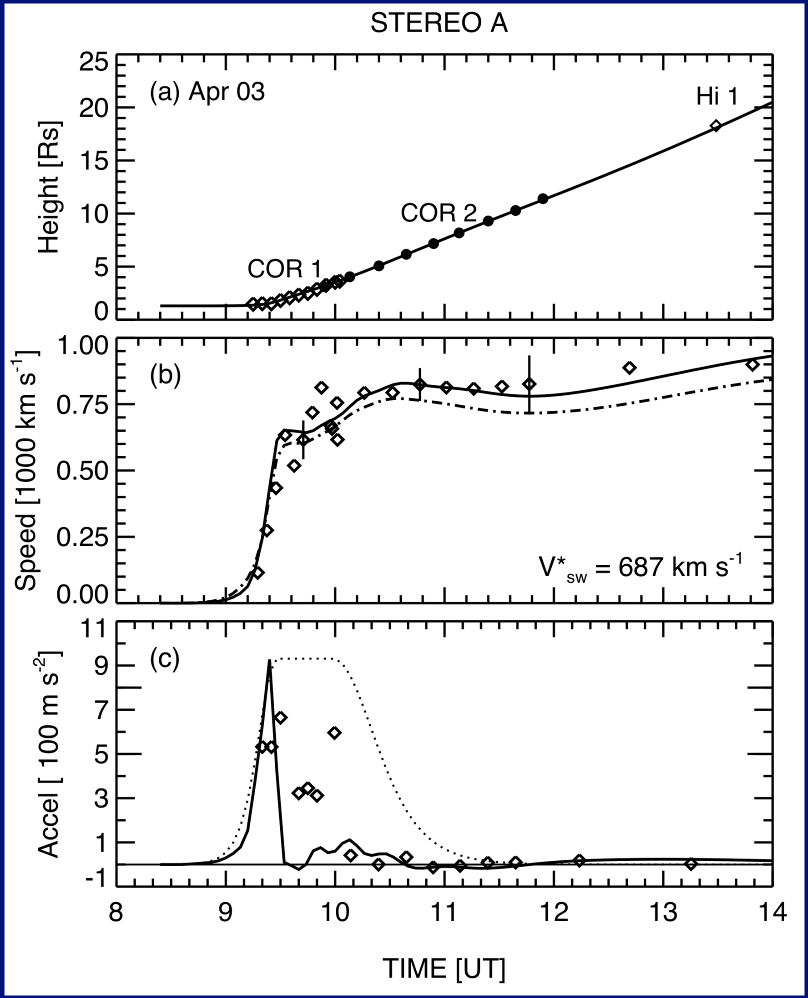






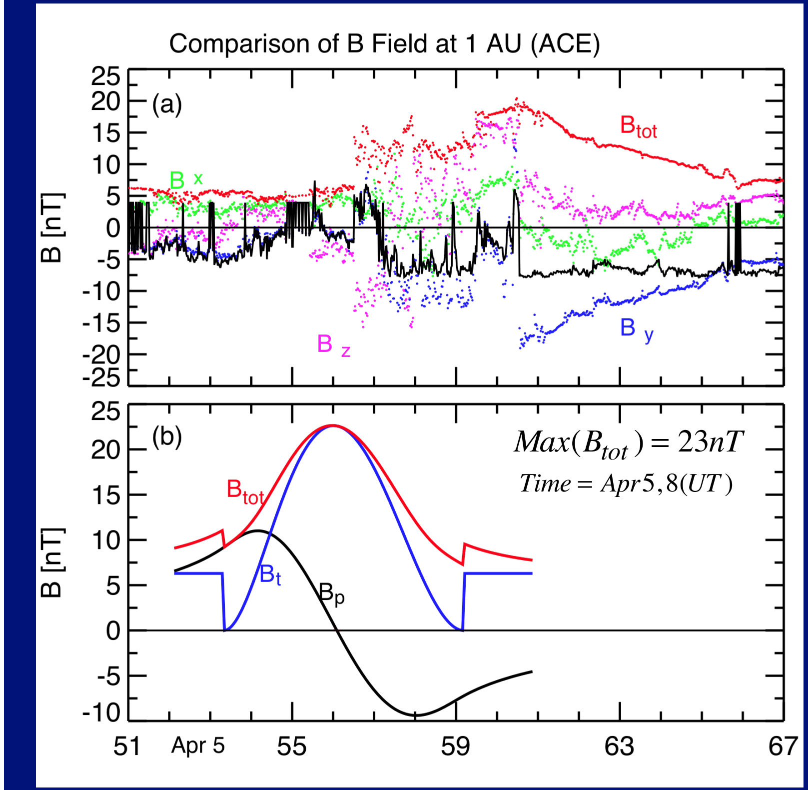
THEORY FIT TO CME TRAJECTORY

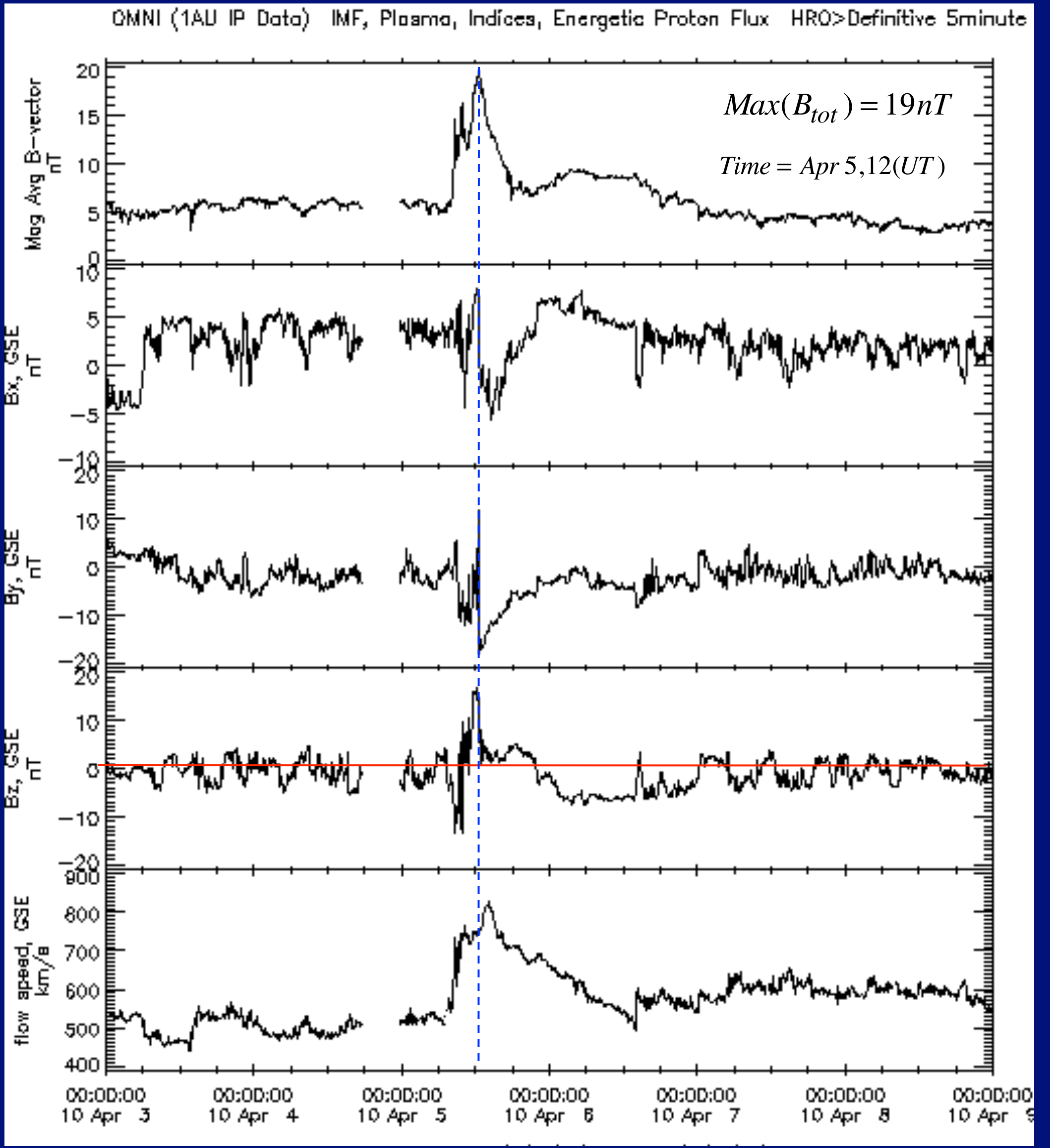




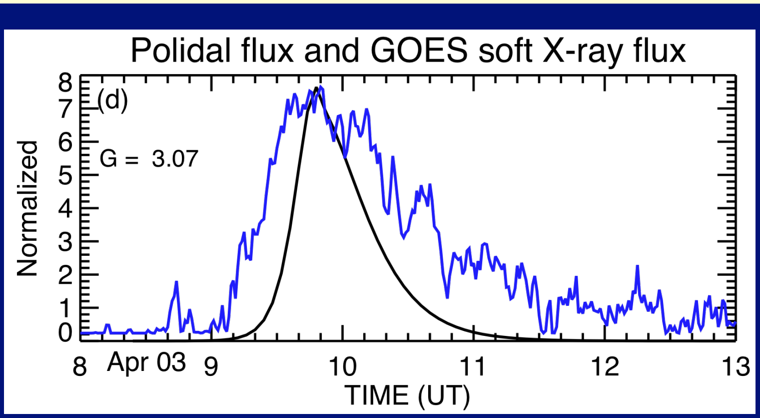
Sf = 1.6e+05 Z0 = 6.0e+04 G = 0.90 tshft = 8.40

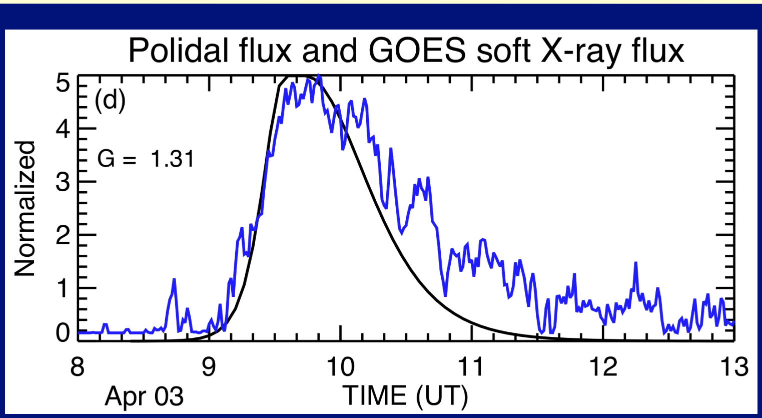
EVOLUTION OF B FIELD AT 1AU

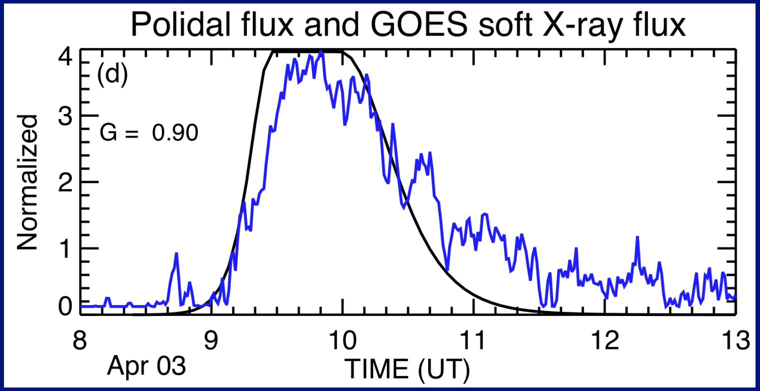




Poloidal Flux and GOES soft X-ray flux







G	Φ_{p0}	$(d\Phi_p / dt)$	$(\Delta U_p)_{tot}$	$B(1AU)$	$T(1AU)$
	$[Mx]$	$[Mx / \sec]$	$[erg]$	$[nT]$	$[UT]$
3.07	$4.55\ 10^{20}$	$7.29\ 10^{18}$	$8\ 10^{31}$	23	56
1.15	$4.55\ 10^{20}$	$4.99\ 10^{18}$	$8\ 10^{31}$	23	56
0.89	$4.55\ 10^{20}$	$3.96\ 10^{18}$	$8\ 10^{31}$	23	56

SUMMARY

- Imposed CME height-time data on the EFR model to obtain best-fit solutions
  - The flux injection function $d\Phi_p(t)/dt$ is a physical prediction
  - *B* and plasma parameters (*e.g., n, T*) at 1 AU are also predictions—in good agreement with IMPACT/PLASTIC data
- *B*(1 AU) is insensitive to the form of $d\Phi_p(t)/dt$ provided the total injected poloidal magnetic energy is unchanged.

END