Ion Charge States in CMEs: Prospects for STEREO

- Martin Laming NRL
- Cara Rakowski NRL
- Susan Lepri U. Mich.
- Angelos Vourlidas NRL

Sample of CMEs from Rakowski et al. (2007), taken from Lynch (2006). All confirmed "flux rope" events except 2001 doy351, which is "classic breakout" (Ugarte Urra et al. 2007)

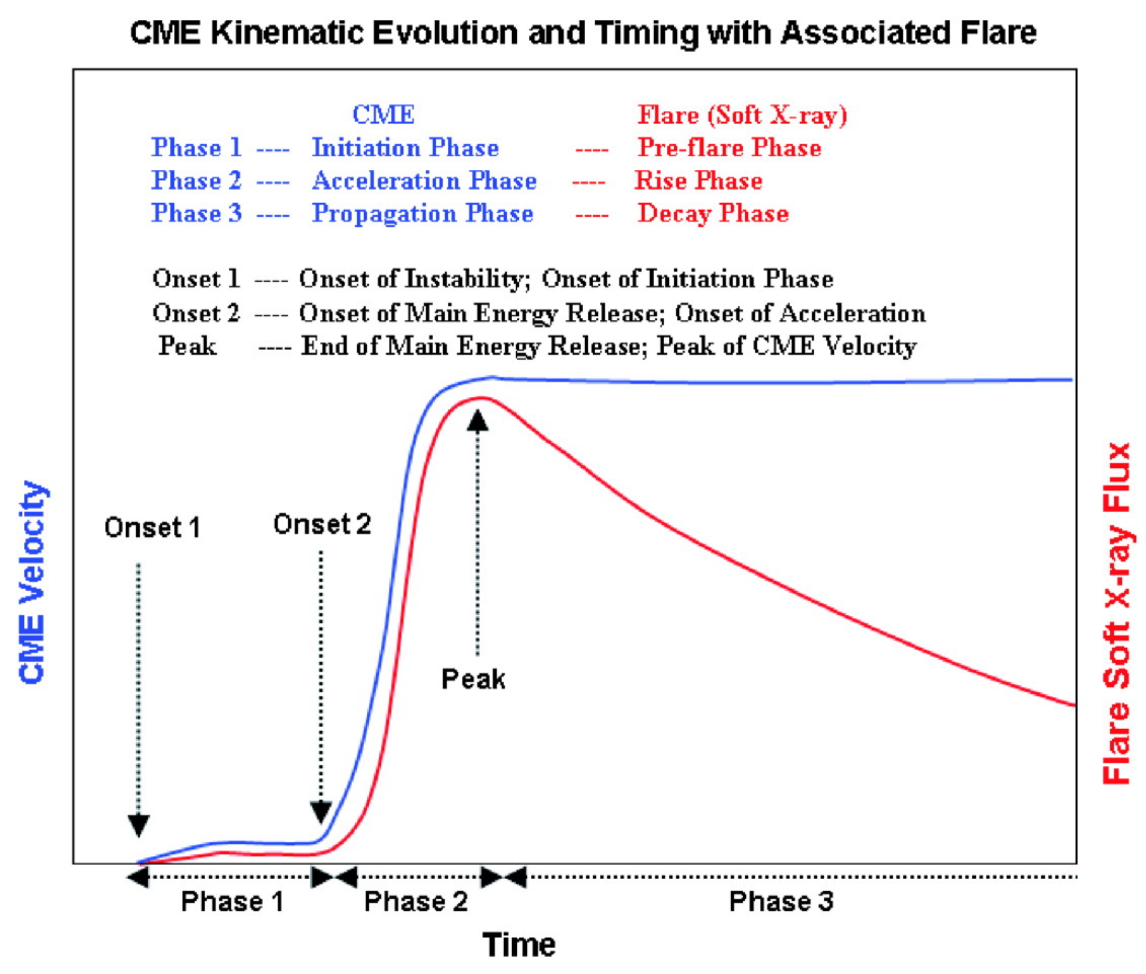
Table 1: ICME Observations

Year	Start	$v_{\mathrm{He}++}$ (km s^{-1}) [a]		$\rho_{\mathrm{H}+}$ (cm^{-3})		He/O[b]		Fe/O	
	(doy)	ave.	max	ave.	max.	ave.	max.	ave.	max.
2002	173	416±19	464	4.4±1.1	6.9	80±10	92	0.15±0.03	0.19
2000	178	504±42	569	5.2±2.3	13.0	99±38	171	0.21±0.04	0.29
2003	129	706±78	855	3.2±2.2	10.6	78±27	114	0.18±0.04	0.25
2000	262	718±47	804	4.4±3.1	13.3	222±64	335	0.28±0.17	0.67
1998	268	640±77	793	3.6±2.2	11.1	100±72	214	0.28±0.13	0.56
2003	302	993±305	1700	3.1±1.9	9.2	168±129	442	0.67±0.42	2.33
2000	210	442±34	474	15.1±7.5	35.9	227±245	1020	0.34±0.31	0.90
2001	351	477±20	500	3.6±0.8	5.5	123±16	147	0.06	0.07

[a] Ranges given are the standard deviation in the values over the ICME event and do not include uncertainties in the measurement.

[b] Ratio of the number densities of the given elements

Zhang & Dere (2006); typical CME velocity profile



Most CMEs are sub-Alfvenic prior to freeze-in of charge states → no shock and no SEP acceleration to worry about.

Equations for ionization balance and temperature evolution.

$$\frac{dn_{iq}}{dt} = n_e \left(C_{ion,q-1} n_{i\ q-1} - C_{ion,q} n_{iq}\right) + n_e \left(C_{rr,q+1} + C_{dr,q+1}\right) n_{i\ q+1} - n_e \left(C_{rr,q} + C_{dr,q}\right) n_{iq} \quad (1)$$

$$\frac{dT_{iq}}{dt} = -0.13 n_e \frac{\left(T_{iq} - T_e\right)}{M_{iq} T_e^{3/2}} \frac{q^3 n_{iq} / \left(q+1\right)}{\left(\sum_{iq} n_{iq}\right)} \left(\frac{\ln \Lambda}{37}\right) \quad (2)$$

$$\frac{dT_e}{dt} = \frac{0.13 n_e}{T_e^{3/2}} \sum_{iq} \frac{\left(T_{iq} - T_e\right)}{M_{iq}} \frac{q^2 n_{iq} / \left(q+1\right)}{\left(\sum_{iq} n_{iq}\right)} \left(\frac{\ln \Lambda}{37}\right) - \frac{T_e}{n_e} \left(\frac{dn_e}{dt}\right)_{ion} - \frac{2}{3 n_e k_B} \frac{dQ}{dt}. \quad (3)$$

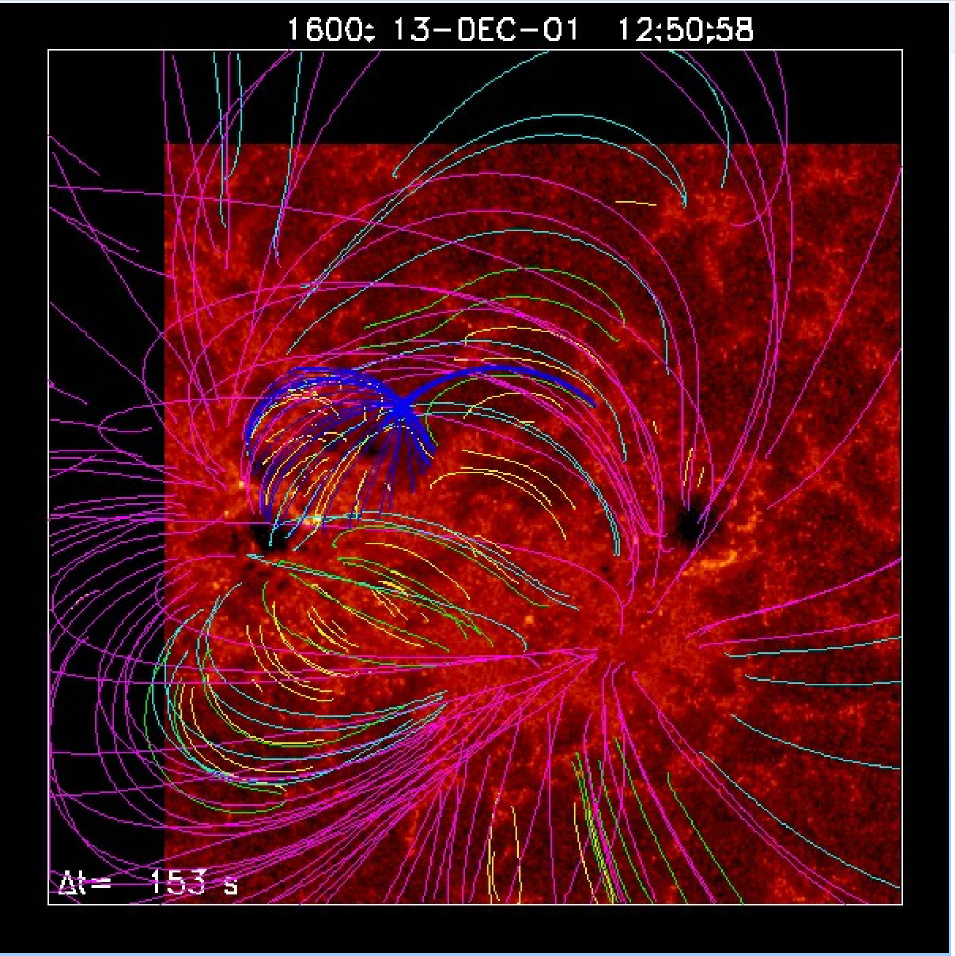
Latest evaluation of ionization and recombination coefficients: Bryans et al. (2006) --- not the last word!

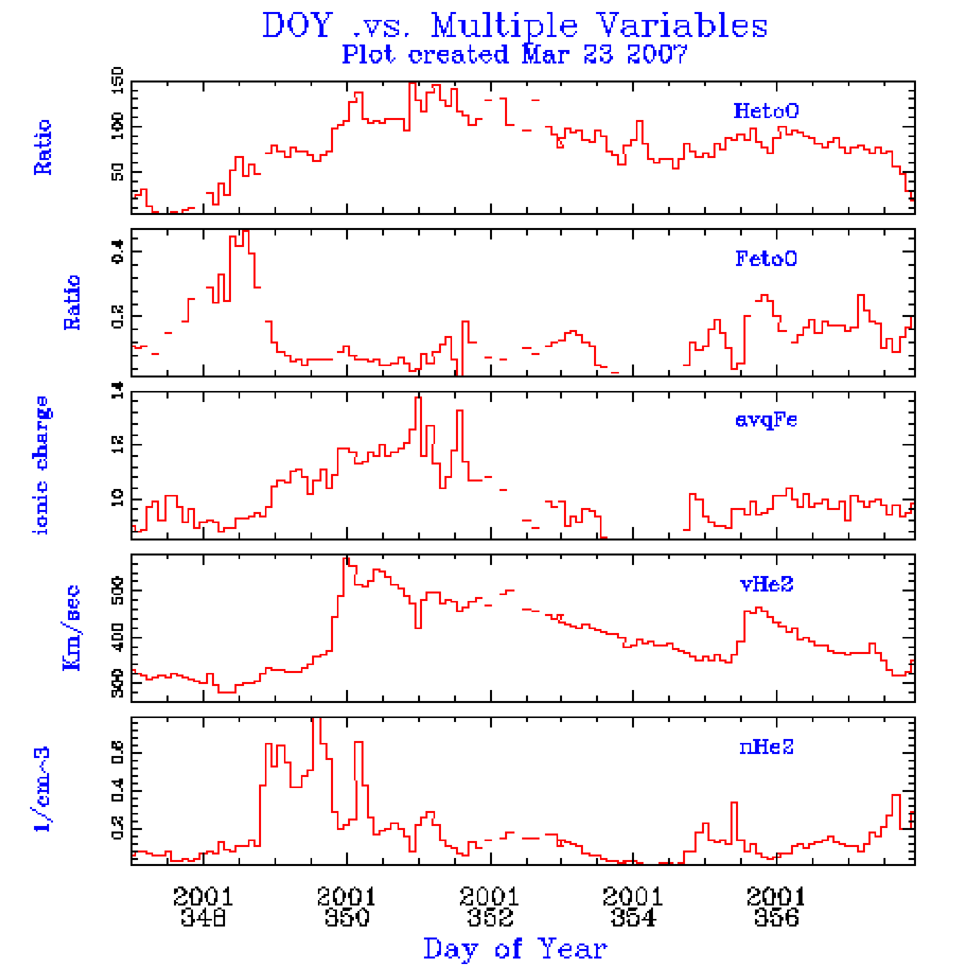
Density ~ $1/r^{(2+VA/(VA+vr))}$, 10^7 - 10^8 cm^{-3} @ 1.5 $R_\odot$

Alfven speed VA ~ $1/r^{1/3}$, typically 1000 km/s @ 1.5 $R_\odot$

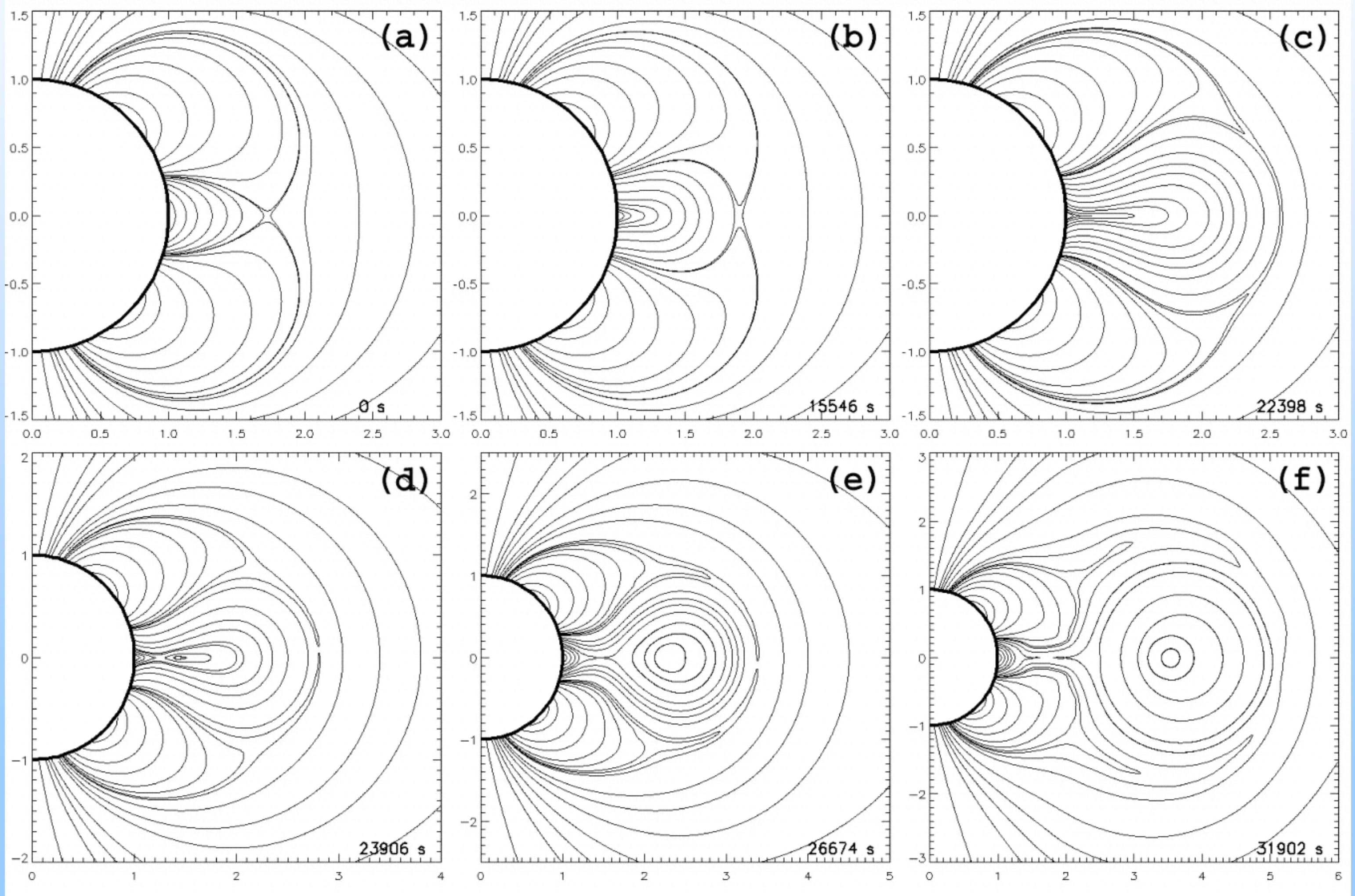
ACE Observations 2001 Dec 13 CME from http://www.srl.caltech.edu/ACE/ASC/level2/index.html

Magnetic field extrapolation and magnetogram from http://tcrb.nrl.navy.mil/~iuu/cmehtml/ (courtesy Ignacio Ugarte-Urra)

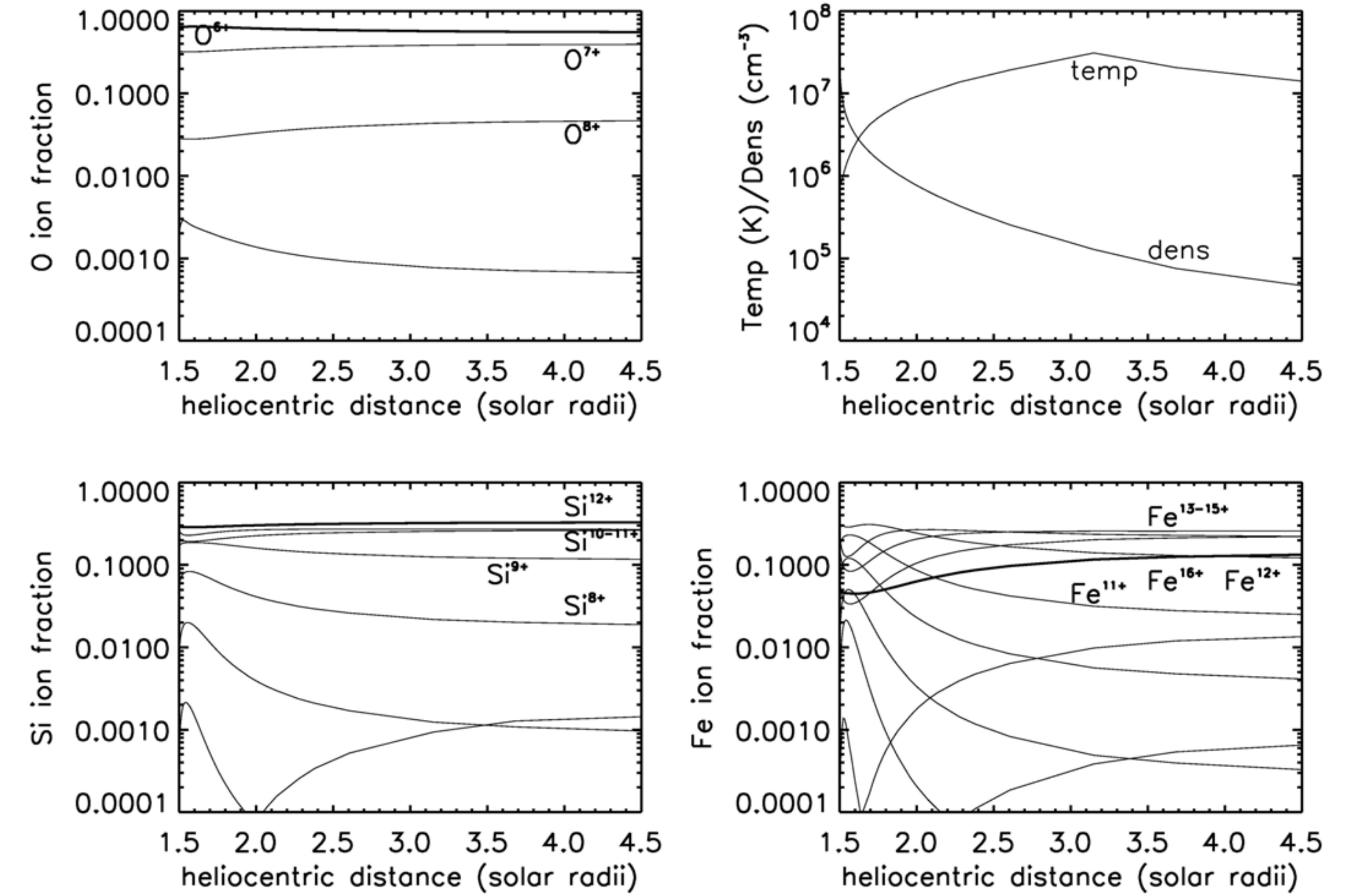




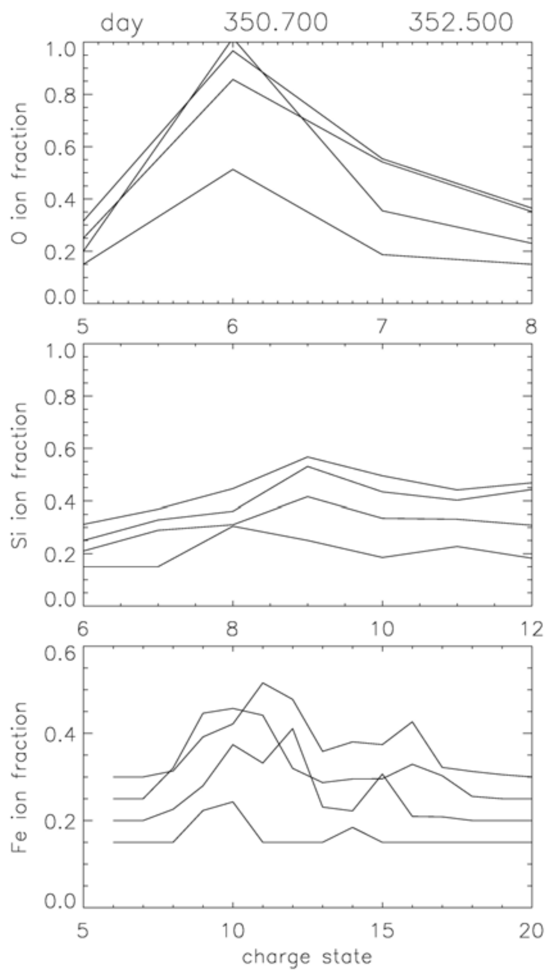
CME eruption from breakout (also from Lynch et al. 2004), reconnection ahead of event necessary to remove overlying magnetic field, reconnection behind not strictly necessary to achieve explosion, but needed to form postflare loops.

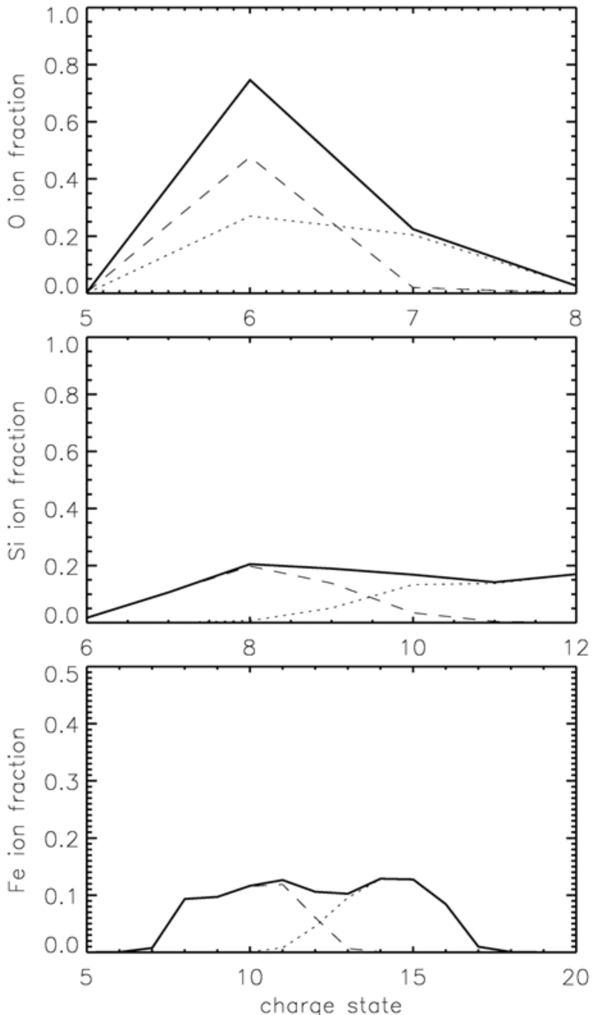


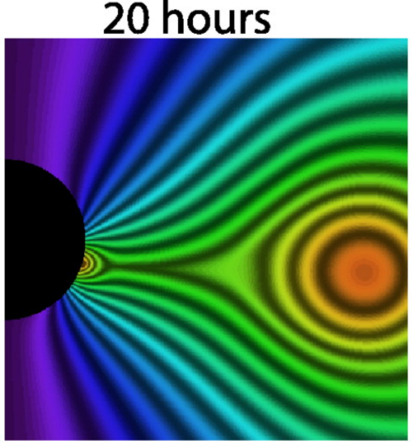
Model charge state/temperature/density Evolution of O, Si, Fe for 2001 Dec 13 CME. Plasma is heated between 1.5 and 3.15 solar radii.



Final Charge States, O, Si, Fe for 2001 Dec 13 ICME. Observations on left, model on right (50% core, 50% cavity).

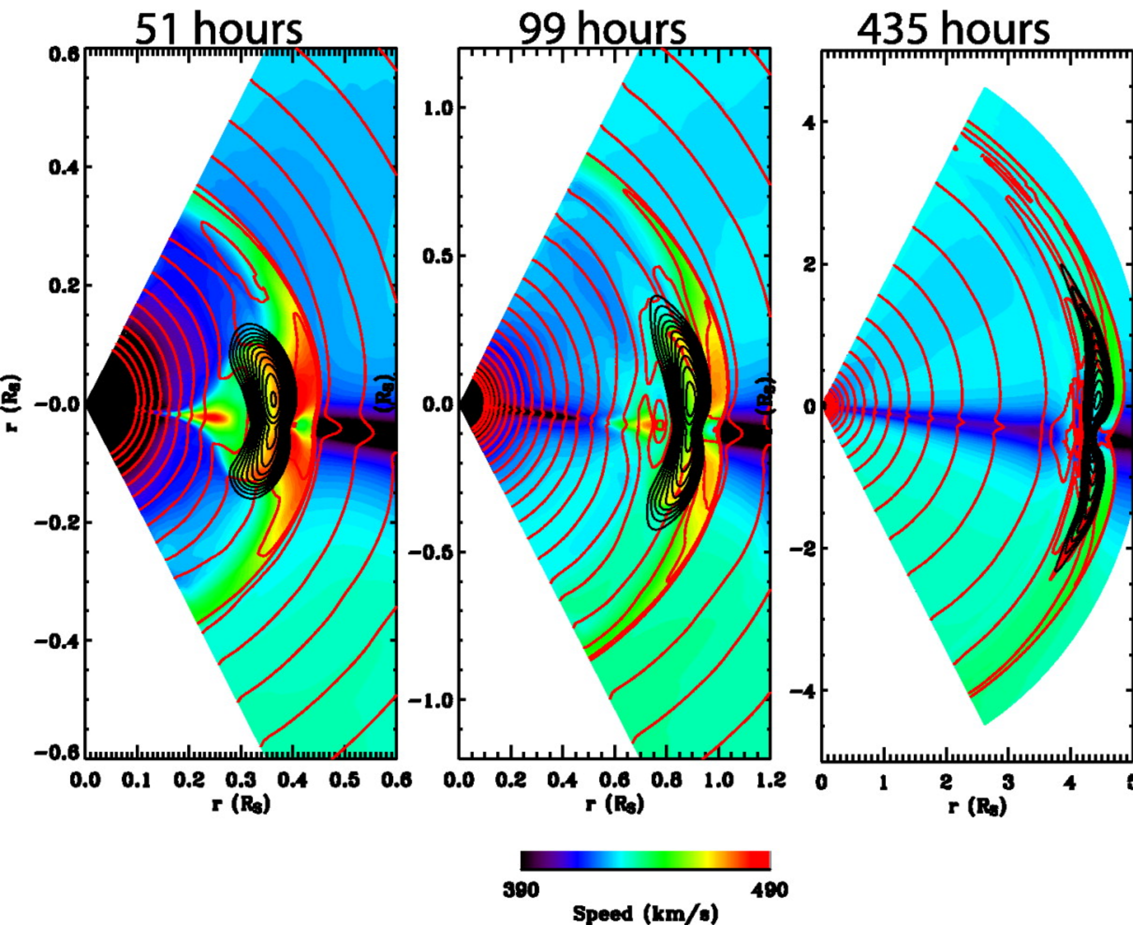






Flux rope evolution to 1 A.U.

Riley & Crooker (2004)



Substantial lateral expansion caused by pressure gradients and spherical expansion giving large cross section for ACE to “hit”.

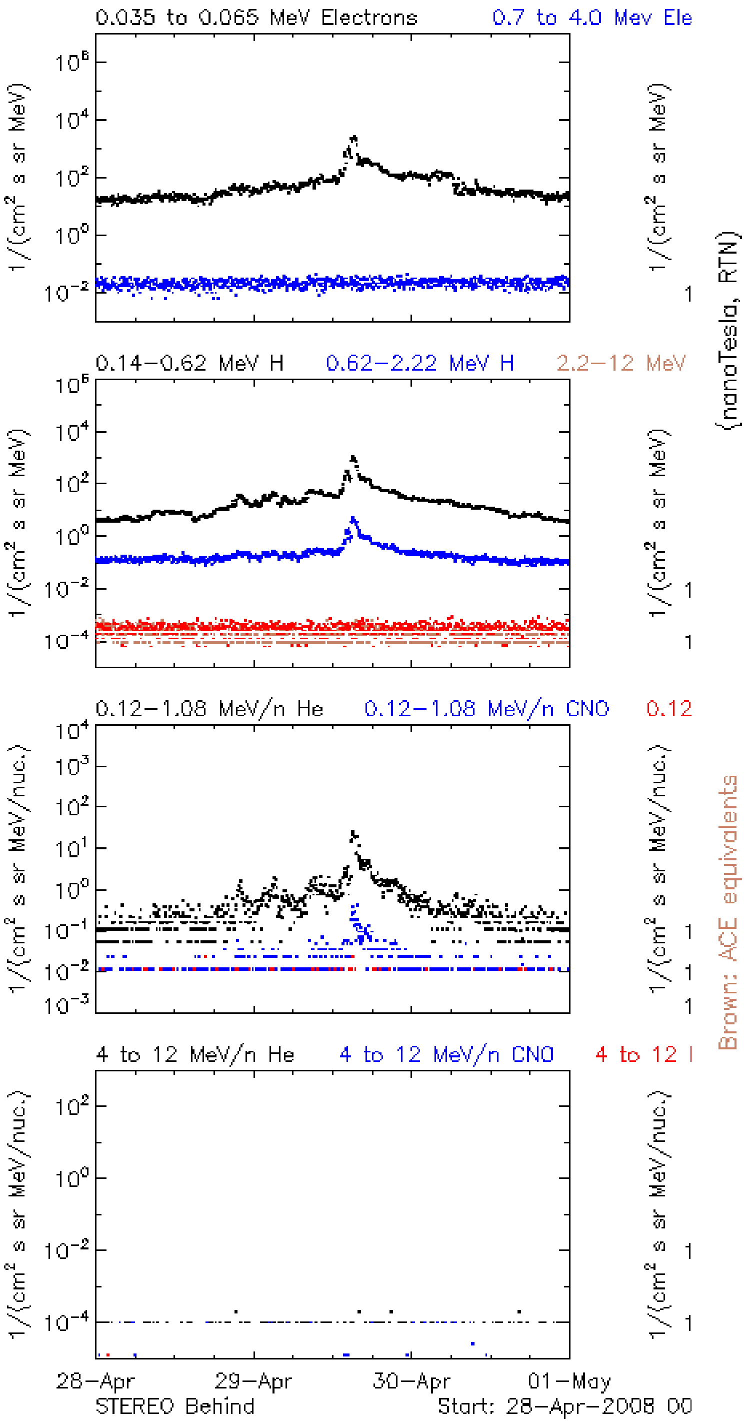
Velocity shear may lead to reconnection within flux rope, mixing core and cavity material (Schmidt & Cargill 2001).

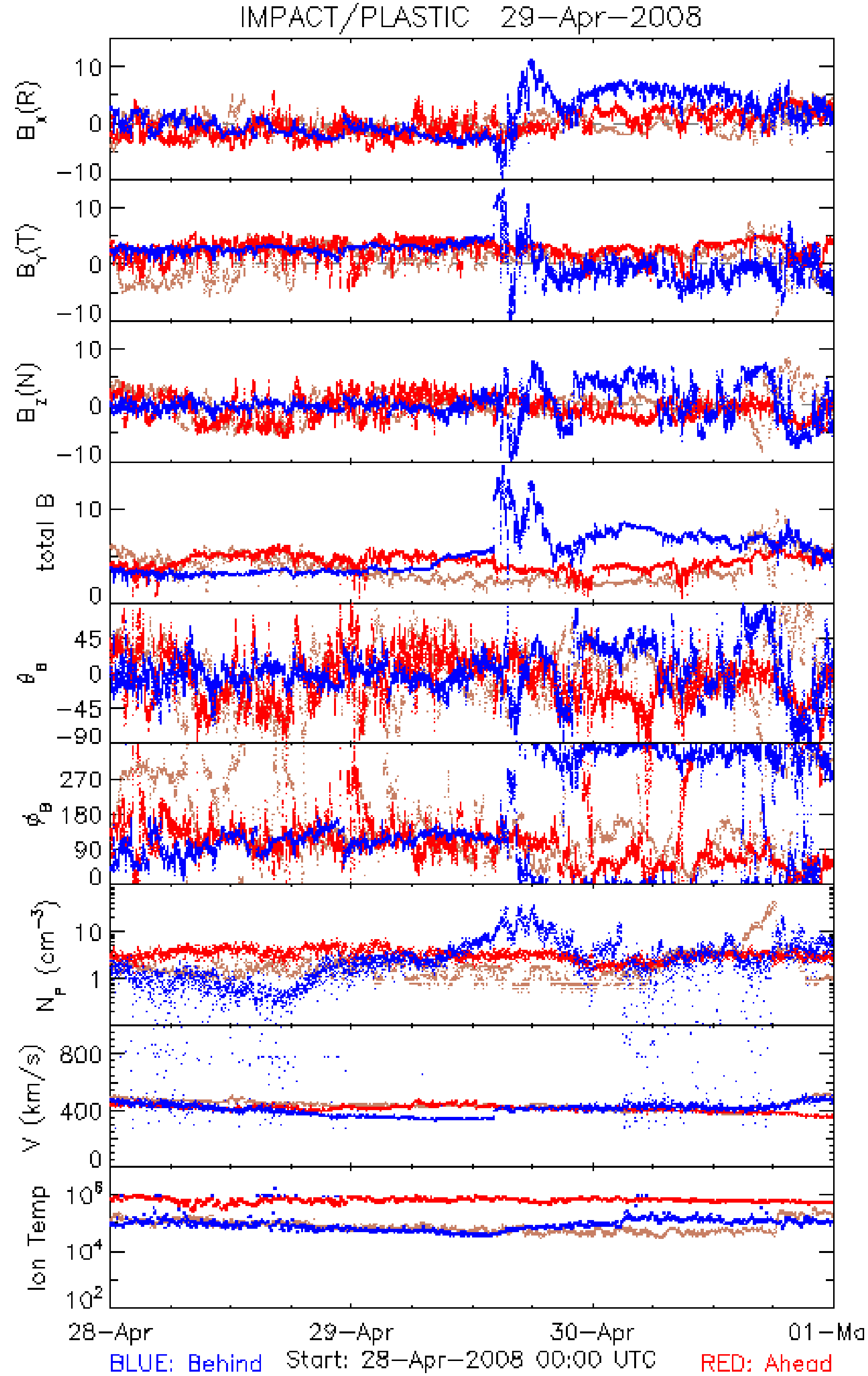
For STEREO Charge States…

- CMEs with imaging in STEREO A and particles in STEREO B (easier to distinguish CME from CIR e.g. Brian Wood, 4/26/08 maybe the most interesting).
- Reasonably fast, so that CME charge states differ from ambient solar wind; suggests also 2007/5/19, 2008/2/4, 2008/5/17…

For Other Issues…

- Can element abundances in CMEs be related to pre-CME loop? (FIP effect, He/H; Rakowski & Laming, work in progress)
- Spheromak CME expansion model (Lyutikov)


0.035 to 0.065 MeV Electrons
0.7 to 4.0 Mev Ele
0.14–0.62 MeV H
0.62–2.22 MeV H
2.2–12 MeV
0.12–1.08 MeV/n He
0.12–1.08 MeV/n CNO
0.12
4 to 12 MeV/n He
4 to 12 MeV/n CNO
4 to 12 I
1/(cm2 s sr MeV)
1/(cm2 s sr MeV/nuc.)
(nanoTesla, RTN)
Brown: ACE equivalents
28–Apr
29–Apr
30–Apr
01–May
STEREO Behind
Start: 28–Apr–2008 00


IMPACT/PLASTIC 29–Apr–2008
Bx(R)
By(T)
Bz(N)
total B
θB
φB
Np (cm−3)
V (km/s)
Ion Temp
28–Apr
29–Apr
30–Apr
01–May
BLUE: Behind
Start: 28–Apr–2008 00:00 UTC
RED: Ahead

Conclusions

- Thermal energy input = few times K.E. input; similar conclusion to analyses of UVCS data in Akmal et al. (2001) Ciaravella et al. (2001)
- Timescale of thermal energy input comparable to SEP electron observations in e.g. 2003 Oct 28 event (e.g. Klassen et al. 2005) → similar source for both?
- Full impact to be realized when analyses of charge states are correlated with investigations of source regions, coupled with realistic hydrodynamics for the CME expansion. Obvious topic for STEREO.
- Many other interesting aspects to investigate in the fastest CMEs, connection to astrophysical shocks and particle acceleration.