Ion Charge States in Halo CMEs: 2003/10/29 and 2005/01/20

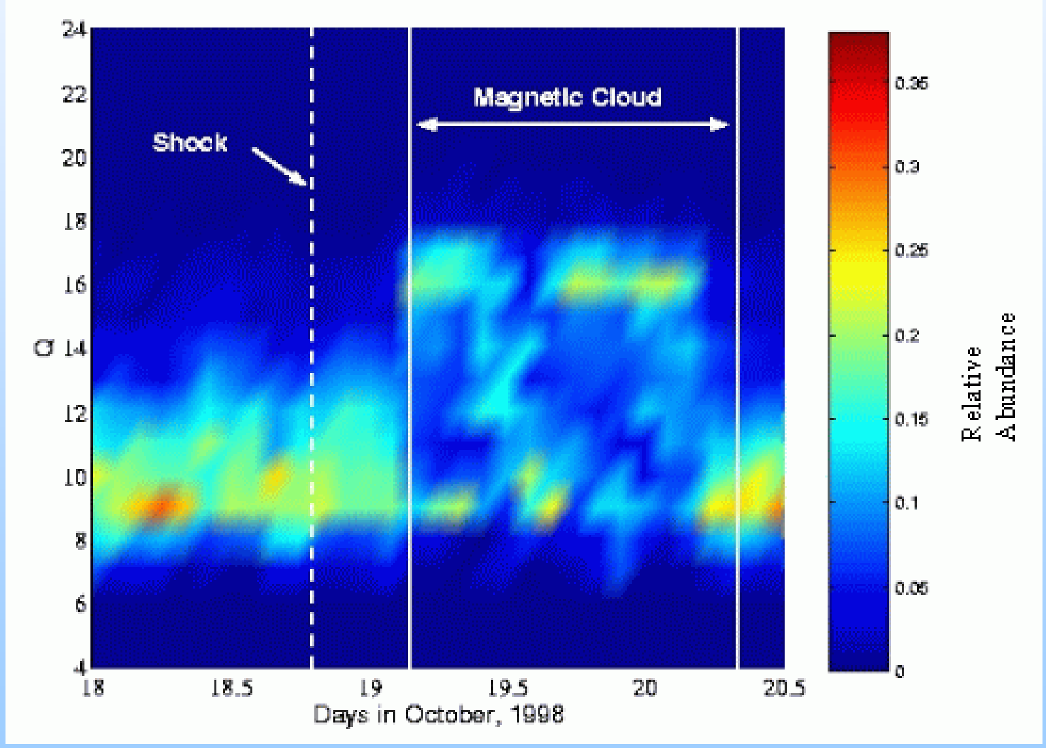
Cara Rakowski NRL/NRC
Martin Laming NRL
Susan Lepri U. of Michigan

ApJ in press astro-ph/0706.3395

Quantitative Measure of Physical Conditions through Atomic Physics

- **Spectroscopy** (UVCS) e.g. Lee et al. ’07 Akmal et al. ’01 Ciaravella et al. ’01
- **Ion Charge States** e.g. Lepri et al. ’01 Zurbuchen ’04 Hencke et al. ’01 Gloecker et al. ’98
- O, Si, Fe complementary

Fe charge states in an ICME



http://www.srl.caltech.edu/ACE/ACENews/ACENews52.html

Temperature and Charge State Evolution

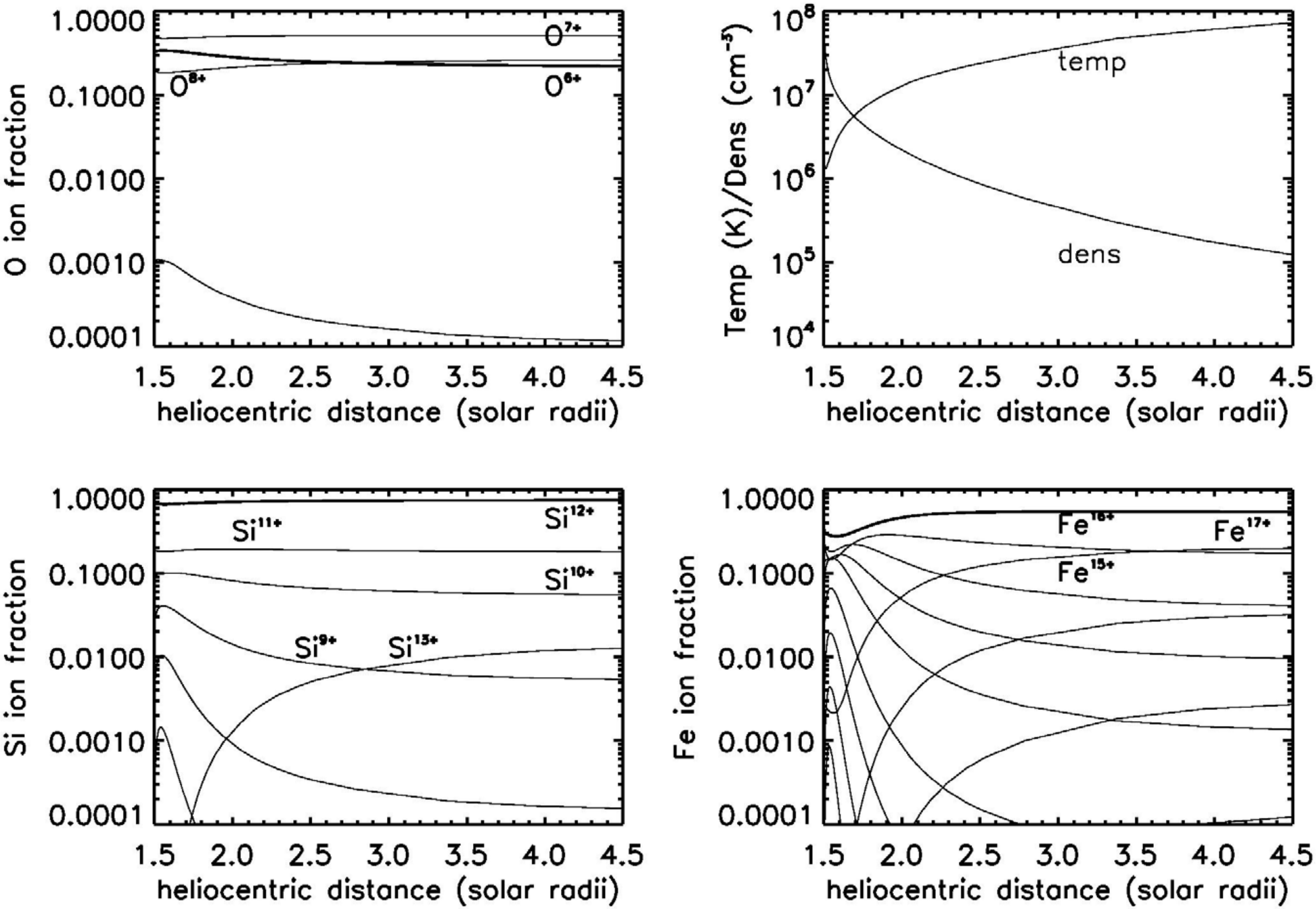
$$\frac{dn_{iq}}{dt} = n_e \left(C_{ion,q-1} n_{i\ q-1} - C_{ion,q} n_{iq}\right) + n_e \left(C_{rr,q+1} + C_{dr,q+1}\right) n_{i\ q+1} - n_e \left(C_{rr,q} + C_{dr,q}\right) n_{iq} \quad (1)$$

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

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

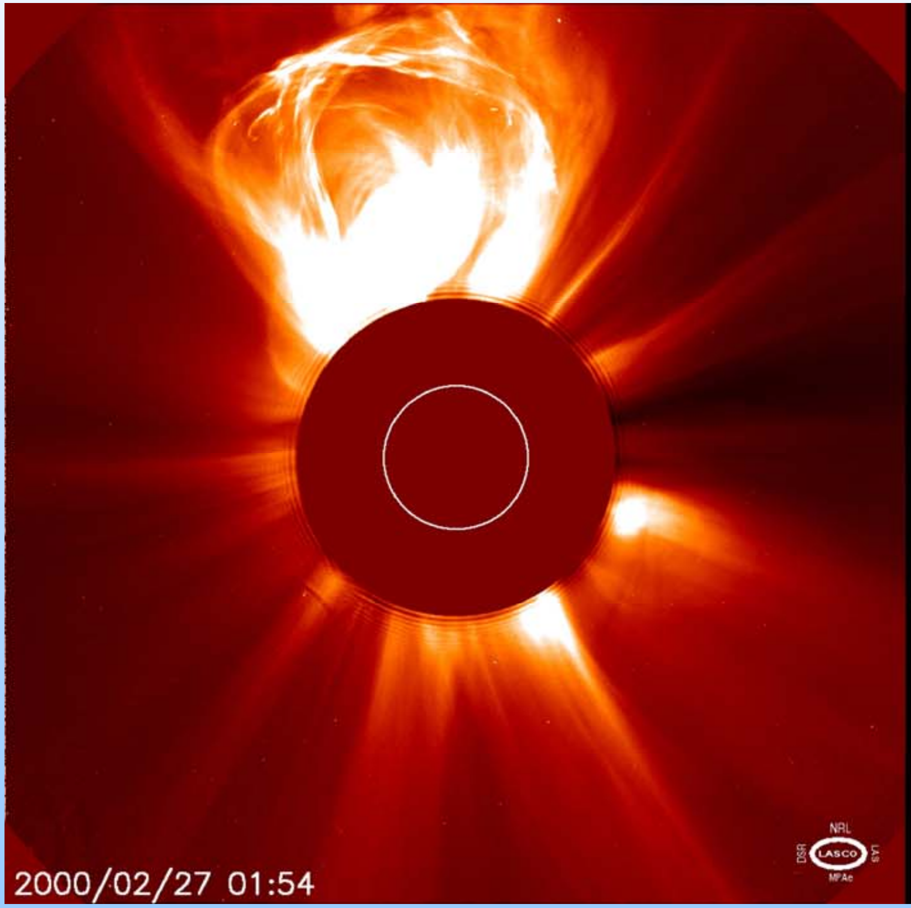
Latest evaluation of ionization and recombination coefficients:
Bryans et al. 2006, ApJS, **167**, 343

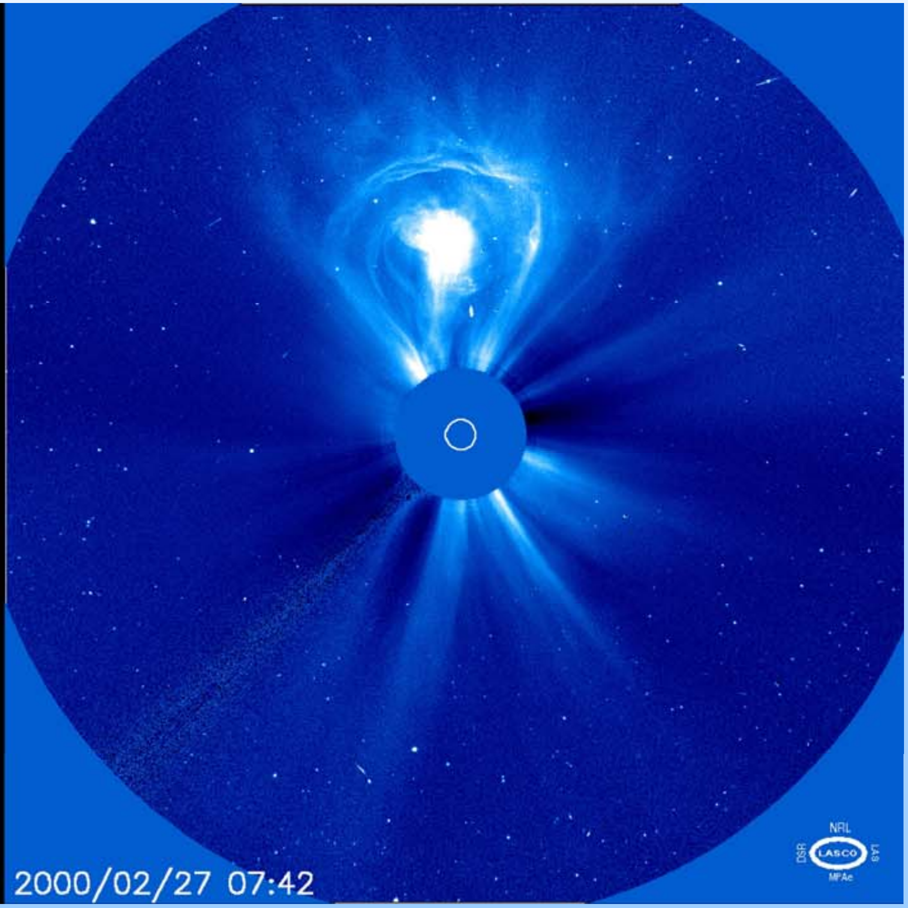
Density ~ $1/r^{(2+vA/vr)}$, 10^7 - 10^8 cm^{-3} @ 1.5 $R_\odot$
Alfven speed vA ~ $1/r^{1/3}$, typically 1000 km/s @ 1.5 $R_\odot$



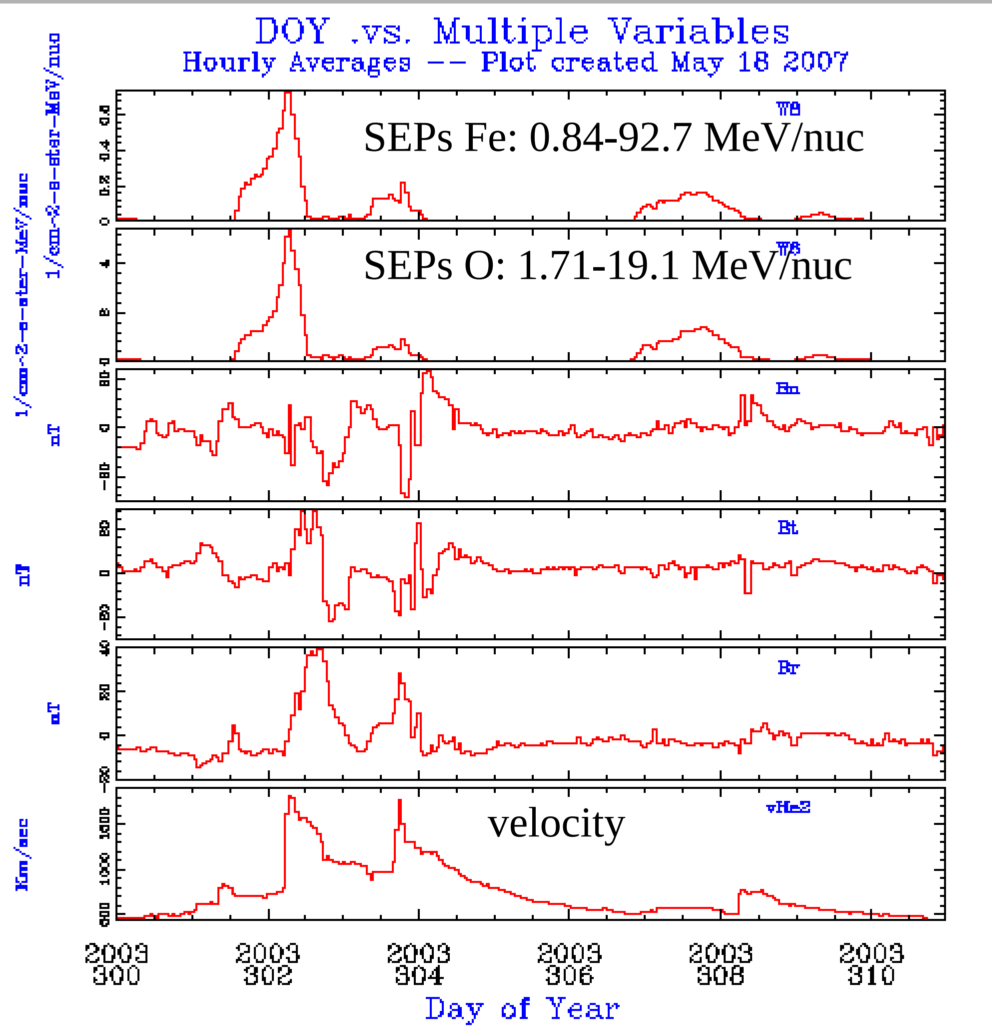
O ion fraction
1.0000
0.1000
0.0100
0.0010
0.0001
O7+
O8+
O6+
heliocentric distance (solar radii)
1.5 2.0 2.5 3.0 3.5 4.0 4.5
Temp (K)/Dens (cm-3)
10^8
10^7
10^6
10^5
10^4
temp
dens
heliocentric distance (solar radii)
Si ion fraction
Si11+
Si12+
Si10+
Si9+
Si13+
heliocentric distance (solar radii)
Fe ion fraction
Fe16+
Fe17+
Fe15+
heliocentric distance (solar radii)

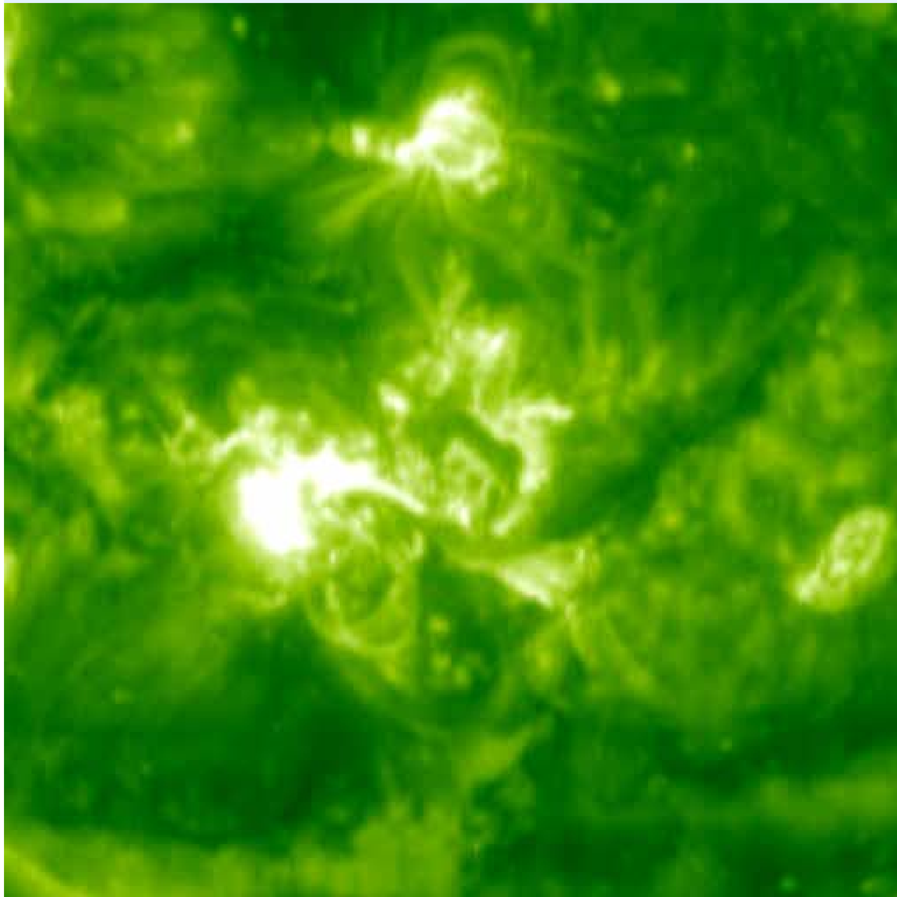
Magnetic Cloud/Flux Rope CMEs





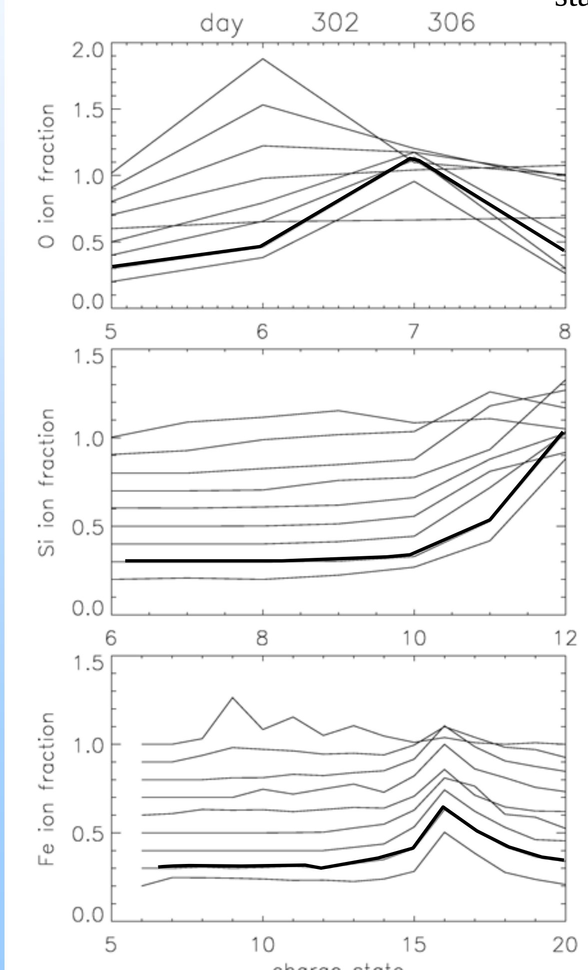
Magnetic field at the forward shock of the 2003/10/29 CME

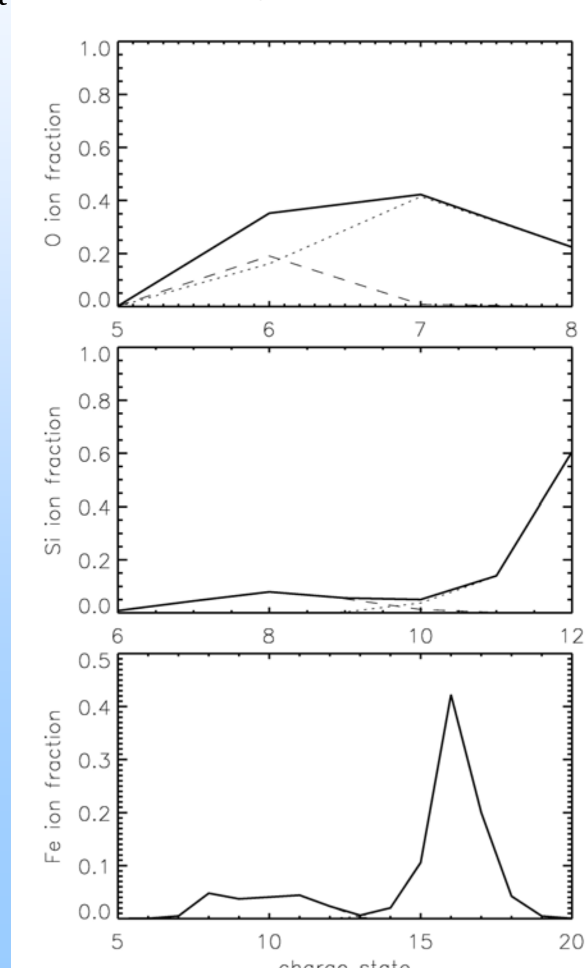




Halloween Final Charge States

ACE SWICS core: T_{start}=2.3E6K, QE/KE=4, frac=0.8

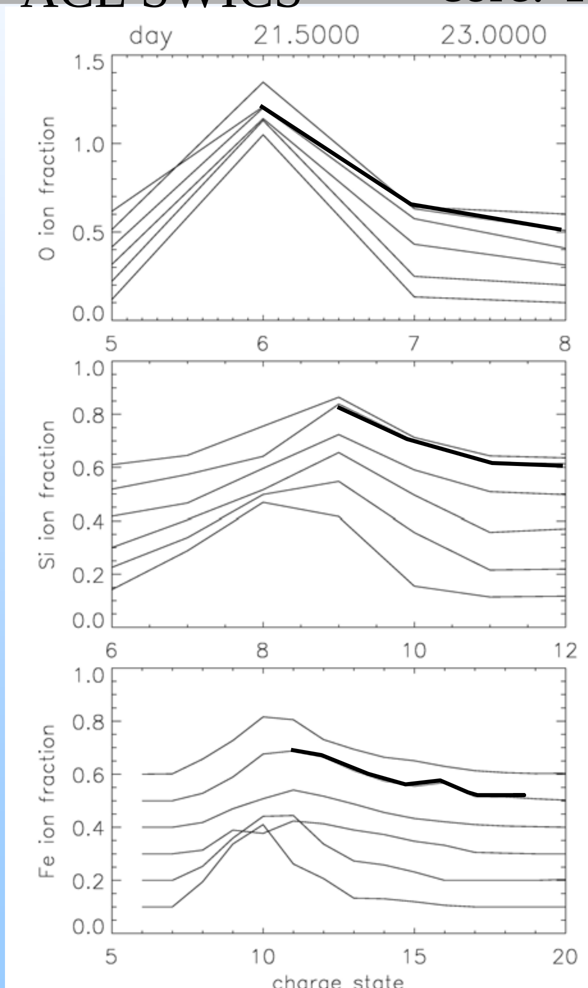


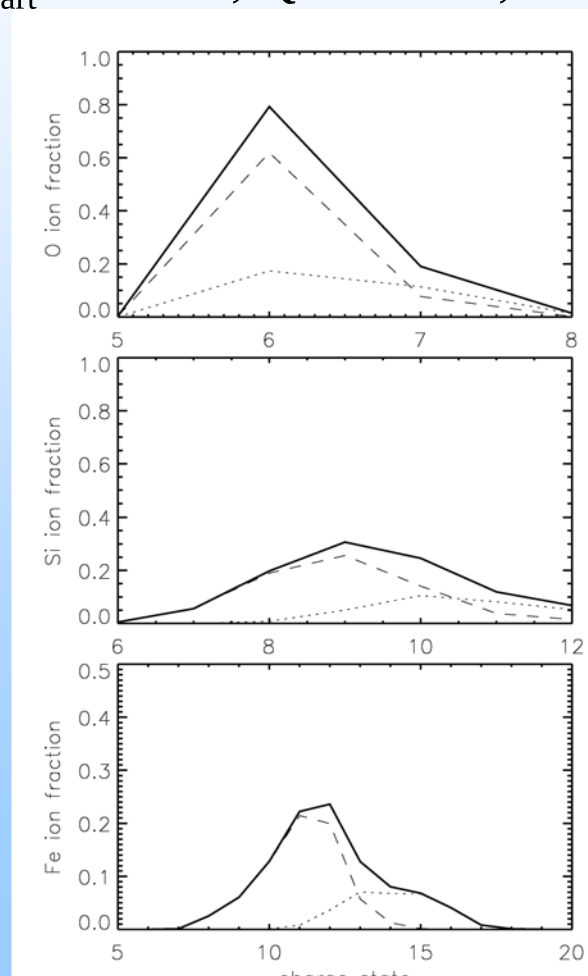


- high Si, Fe charge states
- almost pure "core" material
- comparable fraction of energy into heating as acceleration

21 January 2005 ICME

ACE SWICS core: T_{start}=1.5E6K, QE/KE=10, frac=0.3

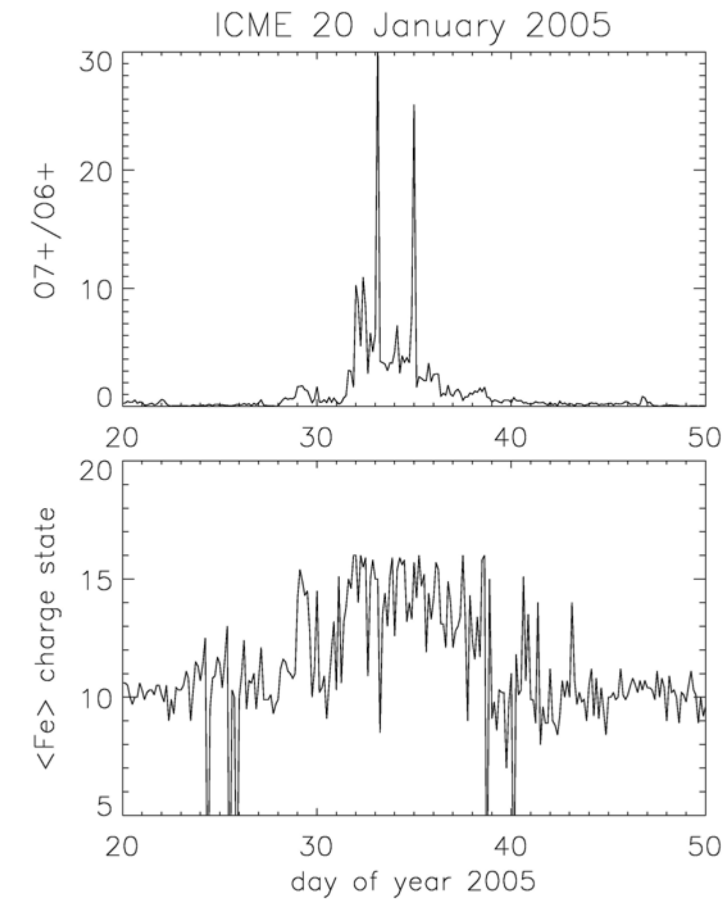




- broad charge state distribution starting at day 21 hour 18
- coincident with “ejecta boundary” of Foullon et al. 2007
- Fe 14+,15+,16+ present in small quantities
- consistent with outskirts of core ejecta

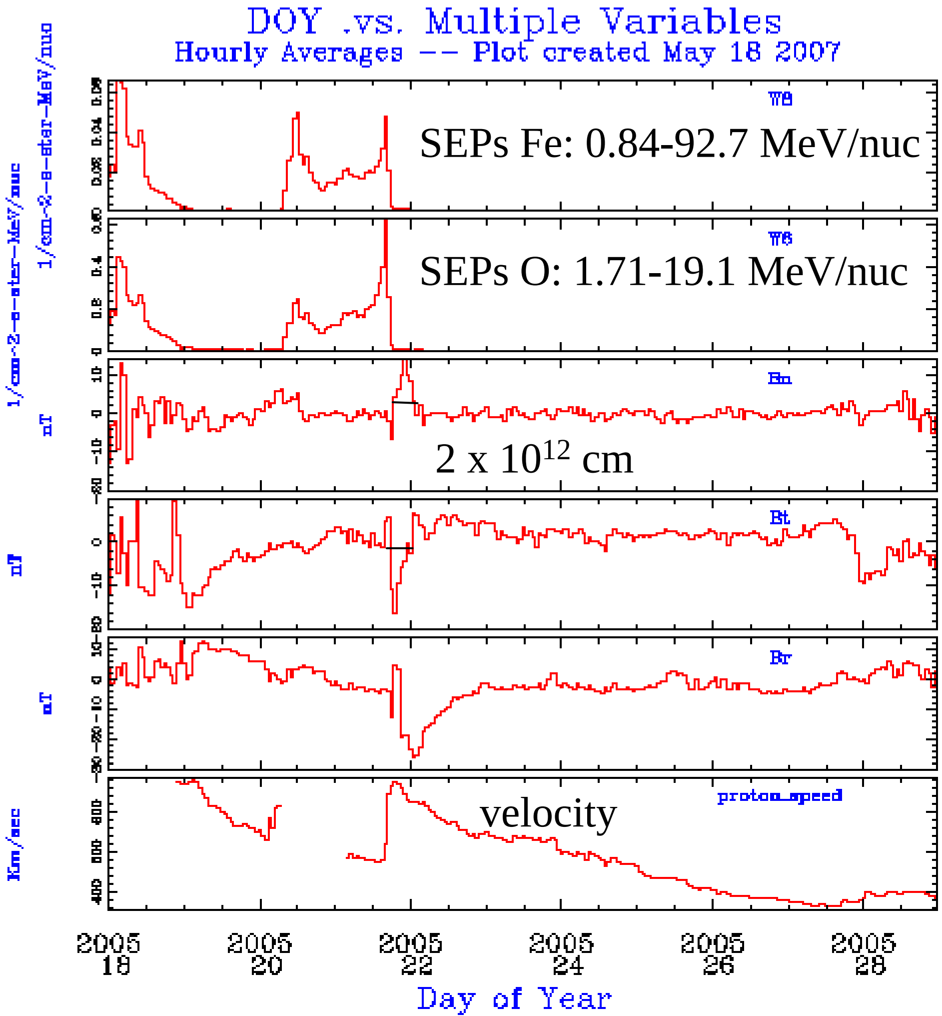
2005/01/20 charge states at Ulysses

- Foullon et al 2007: clearer signature of flux-rope ICME at Ulysses
  - rotating B_n from Jan 31- Feb 5
- Charge States:
  - $O^{7+}/O^{6+} > 2$
  - $<<Fe^+>> = 14$, $max(<Fe^+>)=16$



Magnetic Field amplification at the shock another SNR/CME connection

Magnetic field at the forward shock of the 2005/1/20 CME



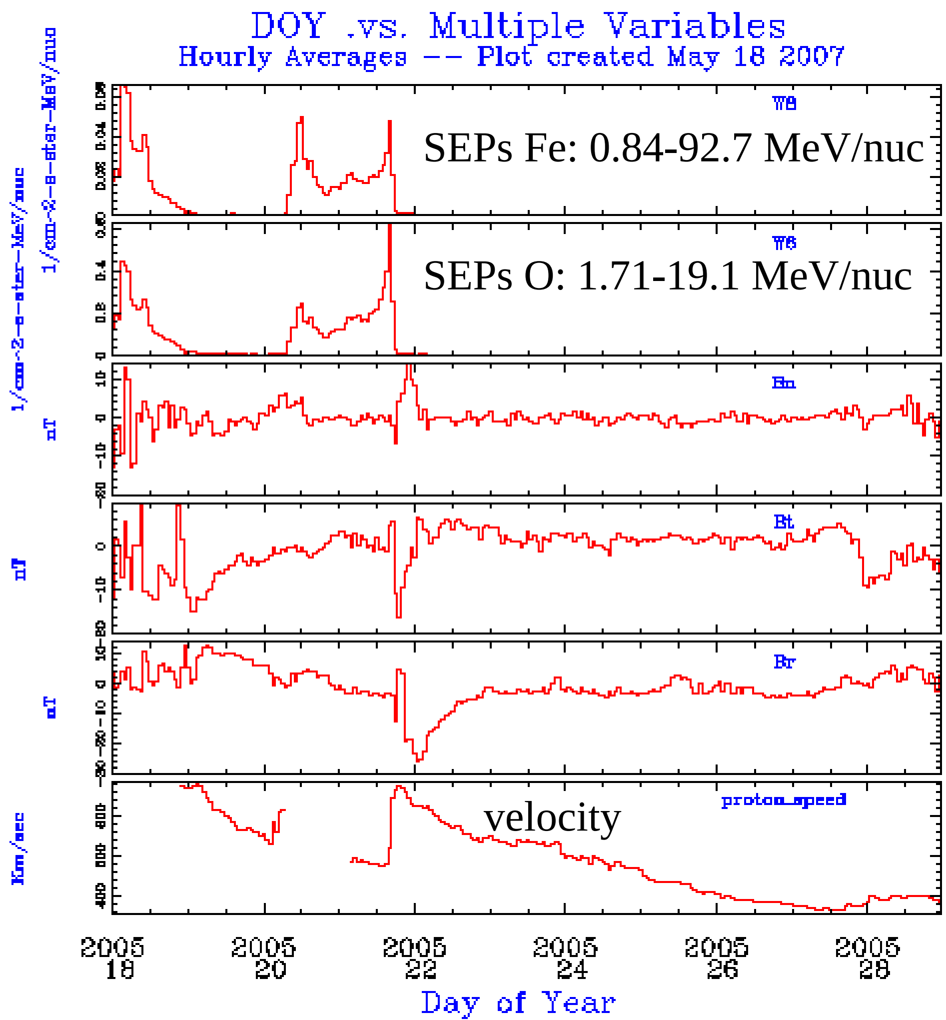
- B field amplification implied in supernova remnant shocks but here detected in situ
- Rapid amplification of B fields at the shock, much greater than shock compression alone
- High energy particles ahead of the shock, not coincident with amplified field.
- Firehose instability of the thermal ions generate Alfven waves? Upstream turbulence generating B field? (Giacalone & Jokipii 2007)
- Distance consistent with estimates of turbulent cascade by Pohl et al 2005 modified from SNR conditions to solar wind.

Final comments

- Thermal energy input = few times K.E. input; similar conclusion to analyses of UVCS data in Akmal et al. 2001, ApJ, **553**, 922, Ciaravella et al. 2001, ApJ, **557**, 351
- 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.

the end

Magnetic field at the forward shock of the 2005/1/20 CME



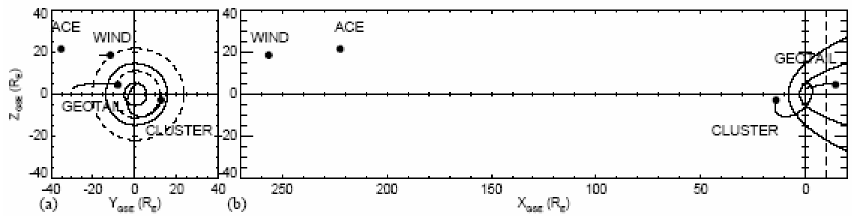


Figure 1. Spacecraft positions and orbit traces, in the GSE Cartesian coordinate system, during the passage of the ICME on January 21-22, 2005 in (left) the plane across the Sun-Earth line (as seen from the Sun) and (right) the noon-midnight meridional plane. The spacecraft positions on January 21, 2005 at 12 UT are shown as full circles. Orbit traces are shown from those starting positions until January 22, 2005 at 24 UT. A solar wind pressure of 50 nPa and an IMF B_z of 0 nT were used to compute the GSE aberrated magnetopause model from Roelof and Sibeck (1993) and bow shock model from Fairfield (1971). In panel (a) they are represented by plain contours at $X_{GSE} = 0$ R_E and dashed contours at $X_{GSE} = -10$ R_E. The level $X_{GSE} = -10$ R_E is also indicated as a dashed line in panel (b).

Selected ICMEs

Table 1: ICME Observations

Year	Start	v_{He++} (km s^{-1}) [a]		ρ_{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

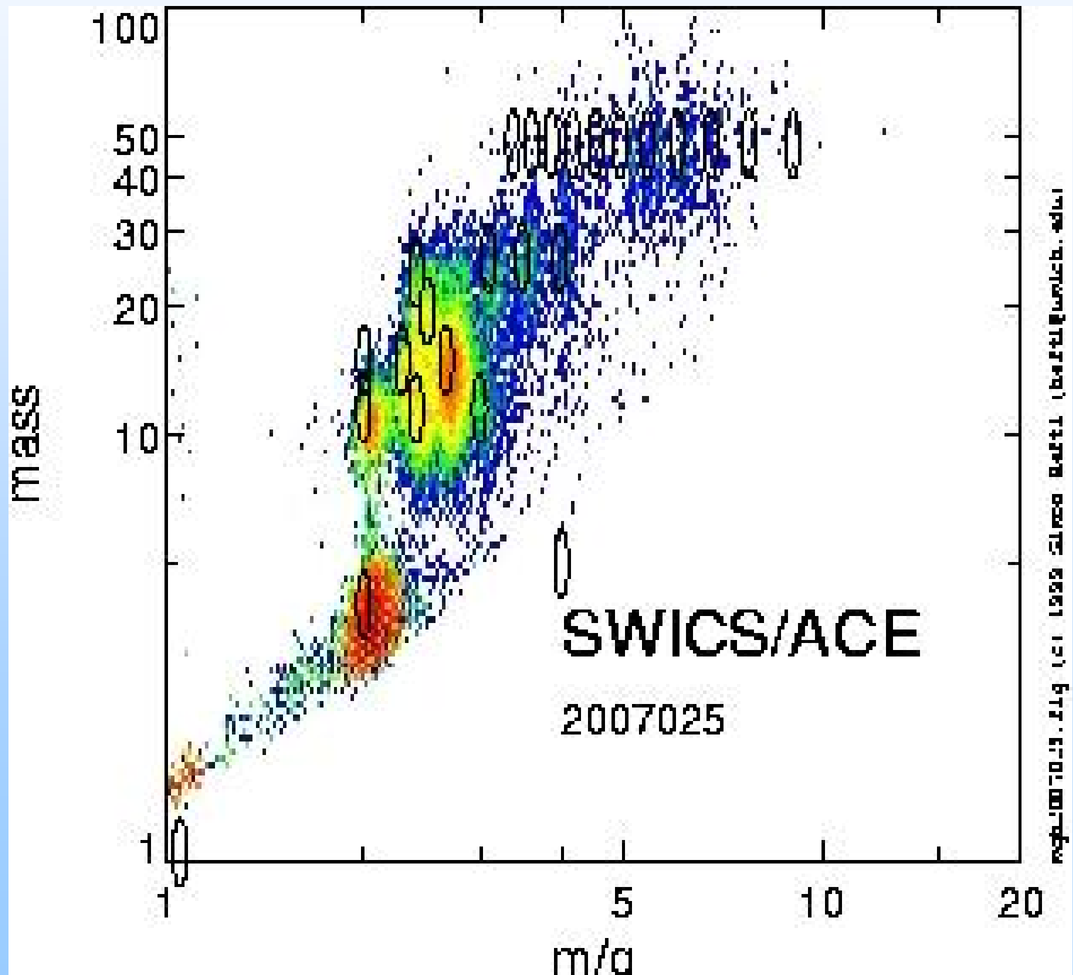
Lynch ’06 magnetic cloud ICMEs

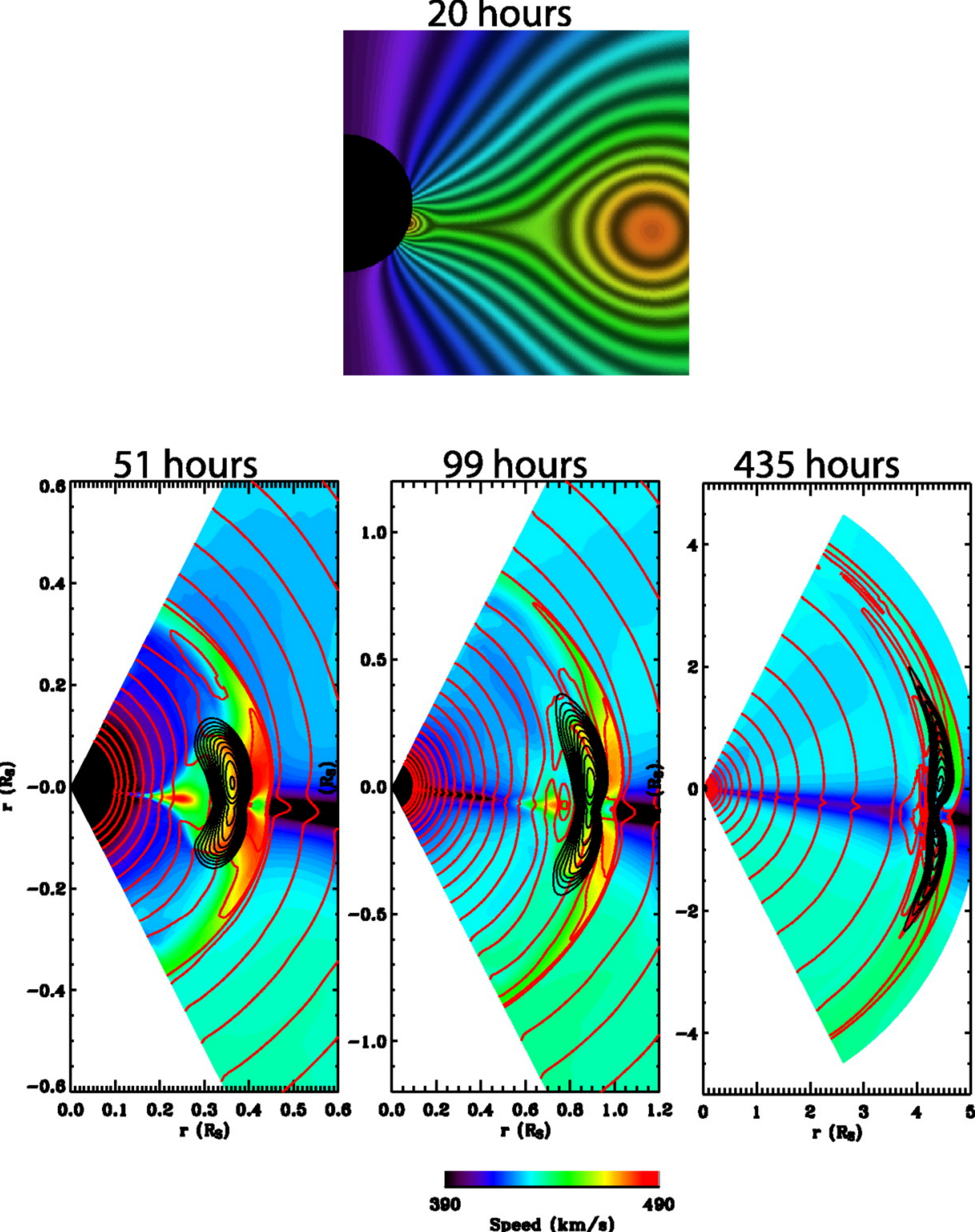
♦ Ugarte-Urra et al ’07 Halo-CMEs (break-out like)

Preliminary Results

Year	Day	Input Parameters v_f km s^{-1}	a km s^{-2}	v_i km s^{-1}	ρ_e 10^7cm^{-3}	T_e 10^6 K	$\frac{QE}{KE}$	Output Parameters $\rho_{10R_\odot}$ 10^3cm^{-3}	charge states O	Si	Fe
2002	173	425	0.1	10	10	1	0.7	10	6	7,8,6	8,9
2002	173	425	0.1	10	1	1	0	0.9	6	7,8,6	8,9,10
2000	178	500-850	0.1-0.15	10	10	1	9	15	6,7	10,11,12	16,15,17
2000	178	500-850	0.1-0.15	10	1	1	0	1.5	6	7,8,6	8,9,10
2000	210	500	0.1	20	10	2	5	30	7,6,8	12,11	16,17,15
2000	210	500	0.1	20	1	1.3	0	2.9	6	8,9,7	11,8,12,10,9
2001	351	500-800	0.1-0.25	10	5	1.8	6	7.0	6,7	12,11,10	14,15,13,16
2001	351	500-800	0.1-0.25	10	0.5	1.2	0	0.8	6	8,9,7	11,10,9,8
2003	129	700	0.1	10	10	1.2	2.6	11	6	9,10,8	13,12,14,15
2003	129	700	0.1	10	1	1.2	0	1.1	6	8,9,7	8,11,10,9
2000	262	700-900	0.1-0.15	15	10	2.5	3-2.5	17	7,8,6	12,11	16,15,14
2000	262	700-900	0.1-0.15	15	1	1.4	0	1.7	6	9,8,10	11,12,10,8
1998	268	750	0.1	15	10	2.3	8	16	7,8	12,11	16,17
1998	268	750	0.1	15	1	1	0	1.8	6	7,8	8,9,10
2003	302	1300-2500	0.2-1	20	10	2.3	4-8	15	7,8,6	12,11	16,17,15
2003	302	1300-2500	0.2-1	20	1	1.2	0	1.4	6	8,9,7	8,11,10,9

ACE Data





Flux rope evolution to 1 A.U.

Riley & Crooker 2004, ApJ, **600**, 1035