Energetics and driving currents of CMEs

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Subramanian, P., Vourlidas, A., 2008, to appear in ApJ, arXiv:0810.4210v1

Subramanian, P., Vourlidas, A., 2007, A&A, 467, 585

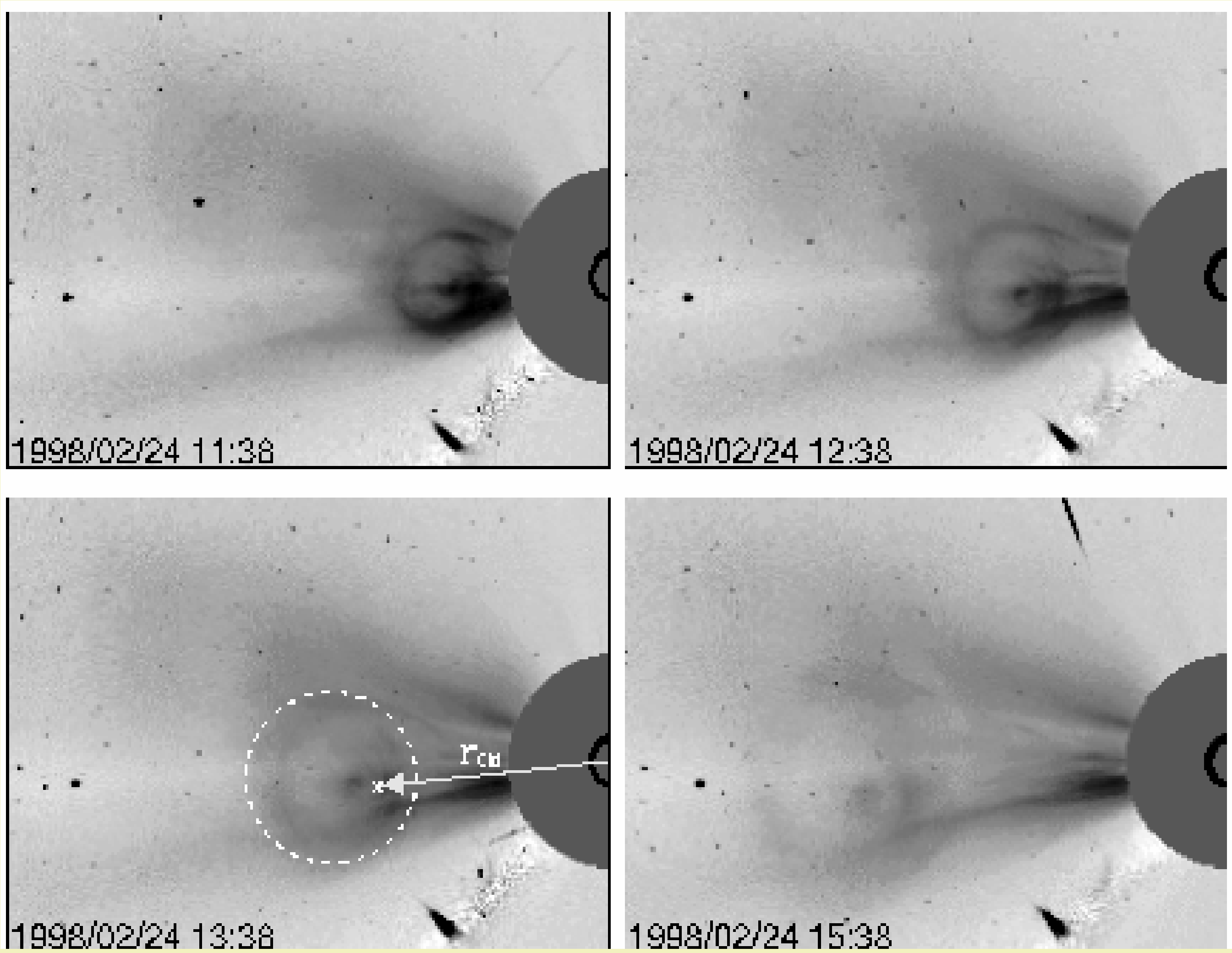
How are CMEs driven?

(distinction between initiation and "driving" $\sim$ 2–30 $R_\odot$)

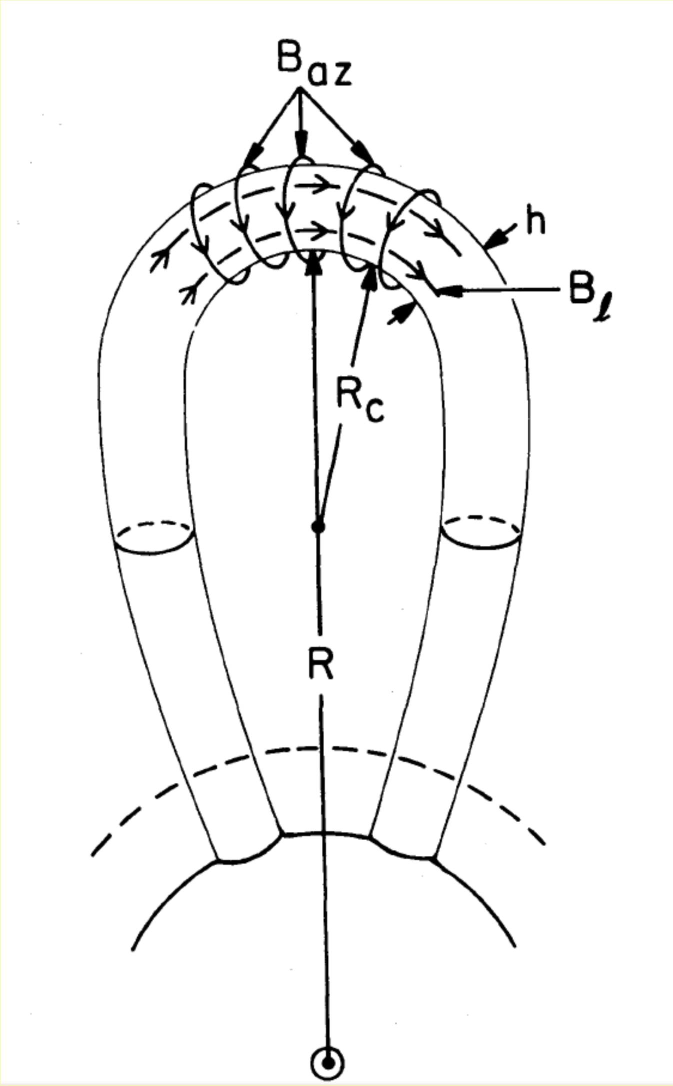
• By coupling to ambient solar wind, (i.e., does the solar wind mostly "drag" them along)

• or by release of magnetic energy associated with advected magnetic field?

Method

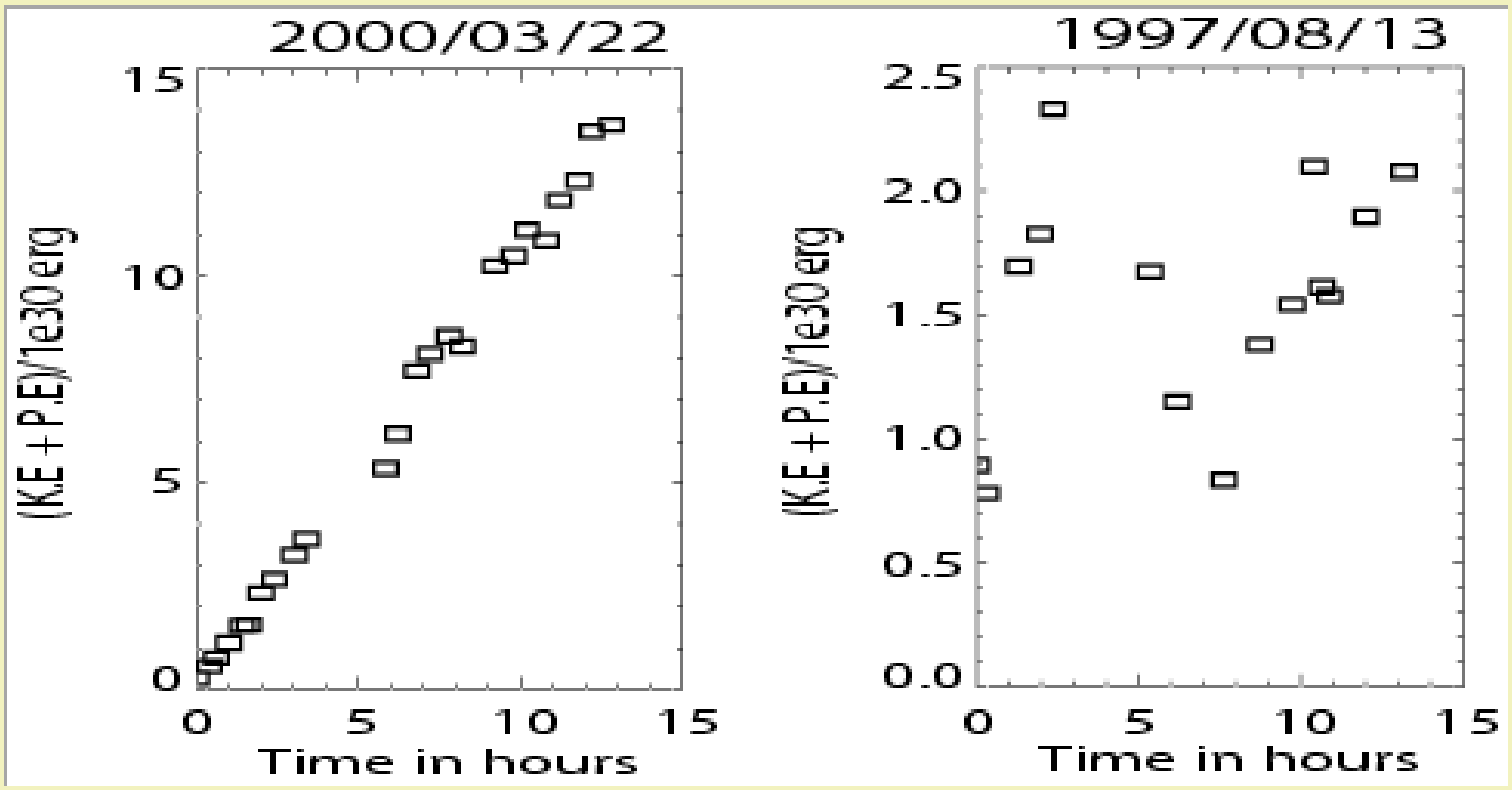


Examine energetics from mass images of 39 (best) flux-rope CMEs during 1996-2001.



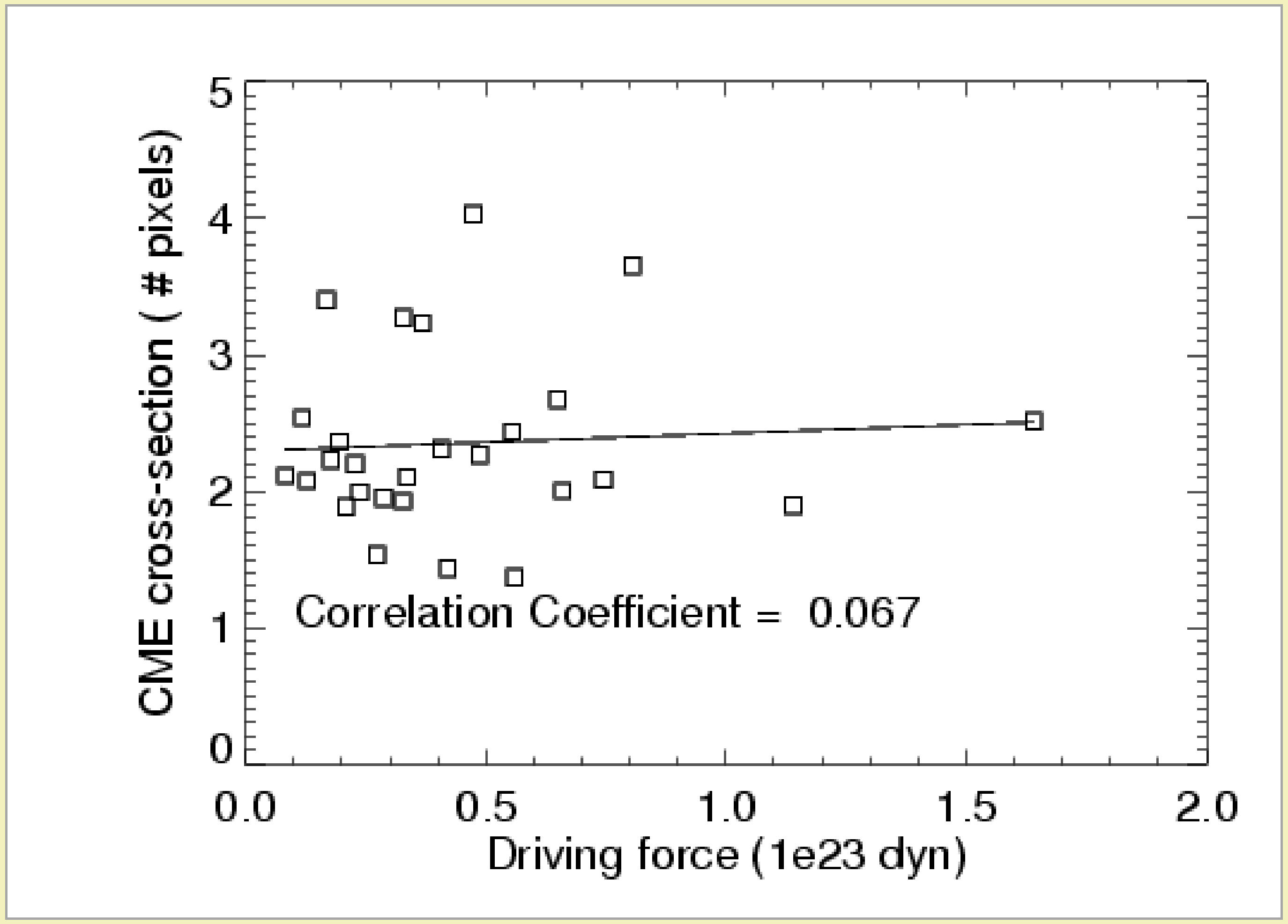
Mouschovias & Poland 1978

“Driven” CMEs



Consider only the driven CMEs (69% of CMEs in sample).

Dragged along by solar wind?



At large Reynolds nos. "drag"/propelling force ∝ cross-sectional area.

Available magn energy: upper limit

Bastian et al. (2001): from obs of “radio CME”: CME magnetic field 0.1–1 G. We use 0.1 G.

Available driving power

$$\widetilde{P_M} = \frac{d}{dt}\,\widetilde{E_M} = \frac{B^2}{8\,\pi}\,\frac{d}{dt}\,l\,A\,.$$

Compare w/ required driving power P_D?

$$\text{Average}\ \frac{\widetilde{P_M}}{P_D} \simeq 10 \pm 1$$

Available magn energy: lower limit

Assume flux to be frozen en route sun to earth. Estimate flux from near-earth magnetic clouds.

$$P_M = \frac{d}{dt}\, E_M = \frac{1}{8\,\pi}\,(\overline{B.A})^2\, \frac{d}{dt}\, \frac{l}{A}\,.$$

Compare with required driving power P_D:

$$\text{Average}\ \frac{P_M}{P_D} \simeq 0.74 \pm 1.3$$

Date	P_D	σ_D	P_M	σ_M	P_M/P_D	σ_{P_M/P_D}	$\widetilde{P_M}$	$\widetilde{\sigma_M}$	$\widetilde{P_M}/P_D$	$\sigma_{\widetilde{P_M}}$
97/11/01	0.23	0.02	0.62	0.92	2.7	4.0	5.9	0.67	25.6	3
97/11/16	2.42	0.2	0.3	0.43	0.12	0.71	24.5	2.6	10.1	1.
98/02/04	1.5	0.16	0.3	0.5	0.23	0.6	10.9	0.13	7.4	0.
98/02/24	0.3	0.1	0.5	0.76	1.7	2.5	6.6	0.808	21.686	2.6
98/05/07	3.295	0.355	0.494	0.739	0.150	0.751	8.145	1.554	2.471	0.4
98/06/02	7.274	0.656	0.718	1.086	0.098	0.926	23.054	3.809	3.169	0.5
99/07/02	0.835	0.127	0.187	0.278	0.224	0.757	18.826	3.061	22.550	3.6
99/08/02	0.478	0.023	0.324	0.481	0.678	1.009	7.200	0.682	15.053	1.4
00/03/22	1.060	0.017	0.312	0.463	0.295	0.441	3.147	0.409	2.975	0.3
00/05/05	0.358	0.038	1.120	1.665	3.122	4.646	1.324	0.160	3.693	0.4
00/05/29	0.488	0.052	0.528	0.783	1.082	1.608	2.311	0.274	4.733	0.5
00/06/06	1.153	0.031	0.659	0.979	0.572	0.851	4.750	0.622	4.121	0.5
00/06/08	0.705	0.095	0.840	1.269	1.190	1.802	9.941	1.364	14.088	1.9
00/07/23	0.747	0.208	0.740	1.106	0.989	1.505	3.566	0.581	4.770	0.7
00/08/02	3.557	0.099	0.562	0.843	0.158	0.295	28.542	3.970	8.025	1.1
00/08/03	3.789	0.200	0.839	1.271	0.221	0.411	30.443	4.224	8.035	1.1

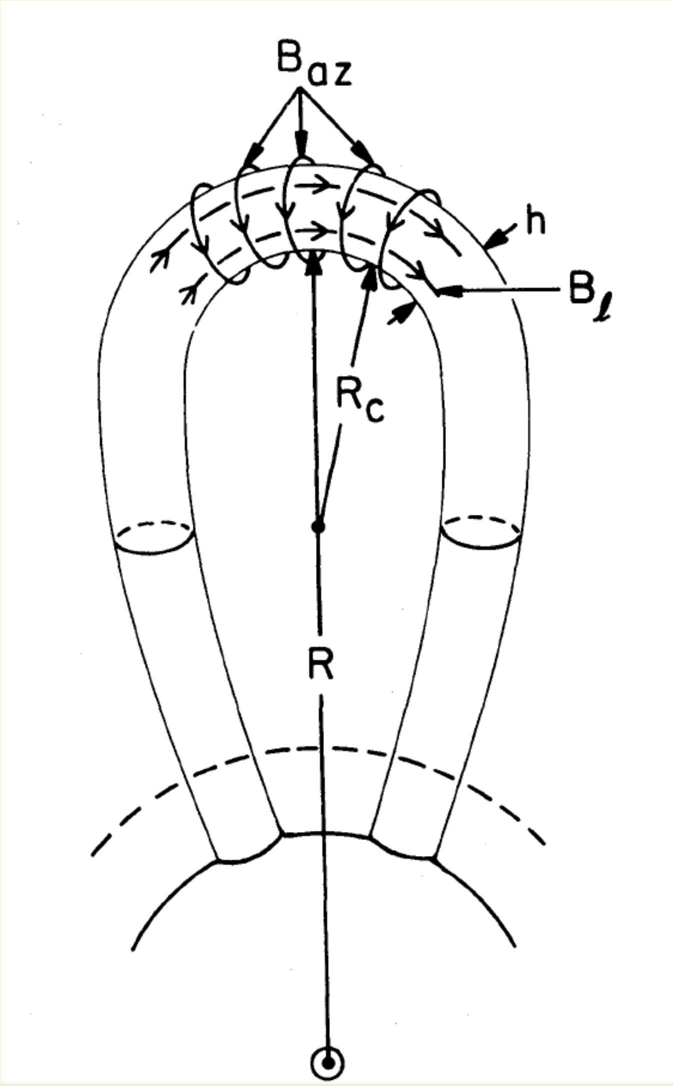
Date	P_D	σ_D	P_M	σ_M	P_M/P_D	σ_{P_M/P_D}	$\widetilde{P_M}$	$\widetilde{\sigma_M}$	$\widetilde{P_M}/P_D$	$\sigma_{\widetilde{P_M}}$
00/09/27	0.805	0.100	0.433	0.654	0.540	0.844	17.342	2.020	21.550	2.5
00/10/26	0.224	0.020	0.196	0.291	0.874	1.301	1.771	0.246	7.890	1.0
00/11/12	1.187	0.041	0.410	0.611	0.346	0.525	8.740	0.804	7.361	0.6
00/11/14	0.630	0.075	0.890	1.348	1.408	2.140	20.874	2.654	33.104	4.2
00/11/17	1.120	0.029	0.747	1.117	0.668	1.001	9.486	1.241	8.487	1.1
00/11/17	0.826	0.050	0.695	1.031	0.841	1.251	8.843	1.806	10.710	2.1
01/01/07	1.372	0.089	0.633	0.960	0.461	0.714	22.125	3.517	16.124	2.5
01/01/19	2.630	0.256	0.792	1.182	0.301	0.554	15.580	2.970	5.930	1.1
01/02/10	2.744	0.380	0.103	0.154	0.037	3.685	68.621	8.920	25.007	3.2
01/03/01	0.481	0.048	0.381	0.569	0.792	1.190	22.470	2.450	46.700	5.0
01/03/23	1.766	0.063	0.577	0.859	0.326	0.498	11.900	1.660	6.740	0.9
Averages	1.554	0.130	0.553	0.828	0.744	1.352	14.704	1.970	12.819	1.6

Conclusions: energetics

• Not much evidence for solar wind "dragging" CMEs along; driving force not $\propto$ cross-sectional area.

• On the other hand, CME magnetic fields can provide 74% (lower limit) to 10 times (upper limit) the power required to drive them.

• How can magnetic energy be converted into (directed) kinetic energy? Maybe $\vec{J} \times \vec{B}$ forces due to misaligned currents/fields.

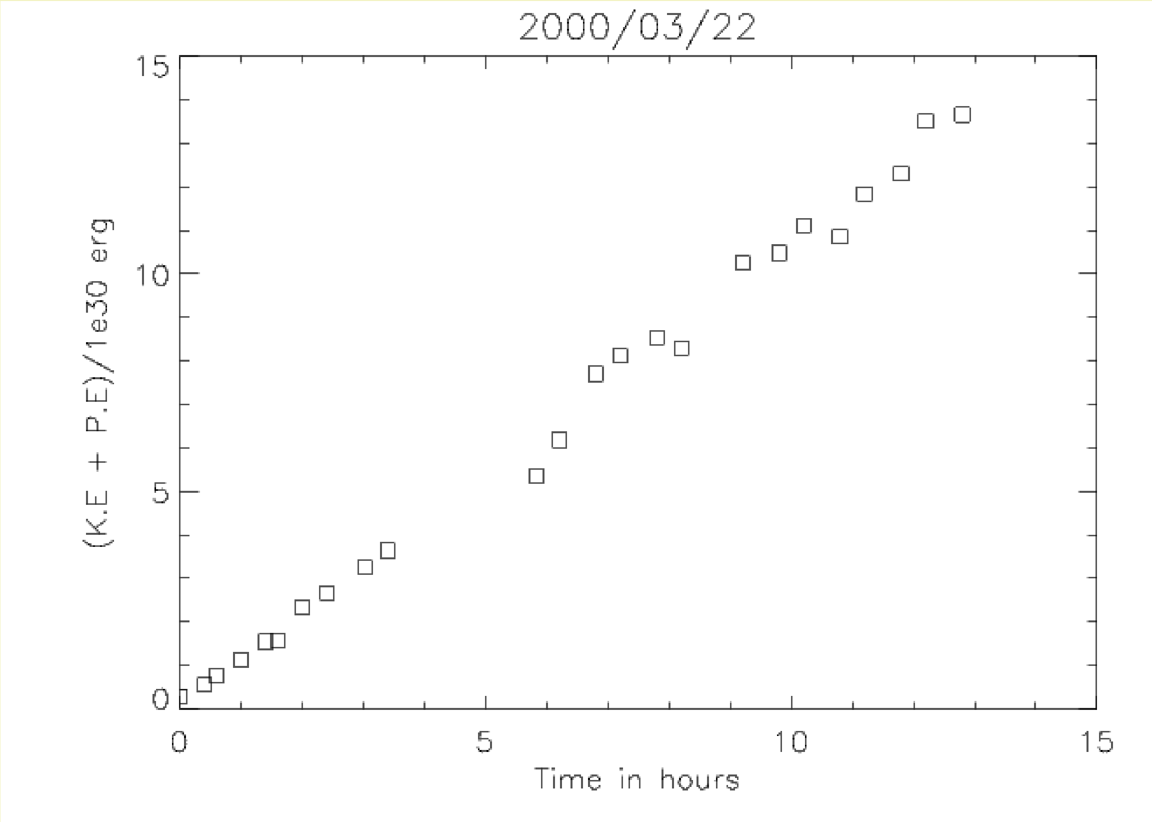


Mouschovias & Poland 1978

$$f = \frac{I_0^2}{c^2\, a}\left[\ln\left(\frac{8\, a}{r_0}\right) + \frac{l_i}{2} - \frac{3}{2}\right] + \pi\, r_0^2 (\vec{\nabla}\, P_\infty) + \vec{I} \times \vec{B}_\infty - \pi\, \rho\, r_0^2\, \frac{G\, M_\odot}{a^2}\,, \qquad (1)$$

- First term: Lorentz self-force.
- Second term: Pressure gradient force
- Third term: Lorentz force due to external B fields.
- Fourth term: graviational attraction due to sun

Only first term (Lorentz self-force) is important.



Slope of straight line = driving power P_D.
Driving force $F_{\rm D} = P_{\rm D}/v_{\rm CM}$ = Lorentz self-force $F_{\rm L}$.
$F_{\rm L} = \pi a \, \frac{I_0^2}{a\, c^2} \left[\ln\!\left(\frac{8\,a}{r_0} \right) - 1 \right]$.
Compute axial current I_0.

$$F_{\mathrm{D}} = F_{\mathrm{L}} = \pi a \, \frac{I_0^2}{a\, c^2} \left[\ln\!\left(\frac{8\, a}{r_0} \right) - 1 \right] \tag{2}$$

- All quantities known, save for axial current I_0.

- Compute I_0 for each driven flux rope CME in our sample.

Table 1: Average driving current enclosed by CMEs

Date	Time	$8a/r_0$	$\langle I_0 \rangle$/(10^{10} Amp)	$\phi/(10^{21}\mathrm{Mx})$
97/11/01	20:11	21	1	2
97/11/16	23:27[a]	19	1	10
98/02/04	17:02	18	2	6
98/02/24	07:28	26	0.5	2
98/05/07	11:05	22	2	7
98/06/02	08:08	14	3	10
99/07/02	17:30	14	1	7
99/08/02	22:26	26	1	4
00/03/22	04:06	18	2	6
00/05/05	07:26	23	1	2
00/05/29	04:30	20	1	5
00/06/06	04:54	21	1	5
00/06/08	17:07	13	1	3

Table 2: Average driving current enclosed by CMEs

Date	Time	$8a/r_0$	$\langle I_0 \rangle/(10^{10}$ Amp)	$\phi/(10^{21}\mathrm{Mx})$
00/07/23	17:30	16	1	4
00/08/02	17:54	14	2	5
00/08/03	08:30	15	2	5
00/09/27	00:50	15	1	4.2
00/10/26	00:50	17	1	4
00/11/12	09:06	22	1	11
00/11/14	16:06	19	1	1
00/11/17	04:06	20	1	2
00/11/17	06:30	18	1	3
01/01/07	04:06	14	1	3
01/01/19	17:06	18	1	5
01/02/10	23:06[a]	11	2	19
01/03/01	04:06	14	1	2
01/03/23	12:06	15	2	5

Conclusions: (axial) driving current

- Axial driving currents in CMEs $I_0 \simeq$ few $\times 10^{10}$ Amperes.
- Assuming force-free Lundquist solutions for flux rope,

these currents imply fluxes $\phi \sim$ few $\times 10^{21}$ Mx; these are a few $\times >$ average fluxes carried by near-earth magnetic clouds.

- $I_0 \simeq$ few $\times 10^{10}$ Amp: order of magnitude lower than estimates for currents in filaments. Currents in flaring loops $\sim 10^{10}$–10^{12} Amp. "Vertical" photospheric currents (vector magnetograms) $\sim 10^{12}$ Amp.