SOLAR AND INTERPLANETARY MAGNETIC FIELD TOPOLOGY

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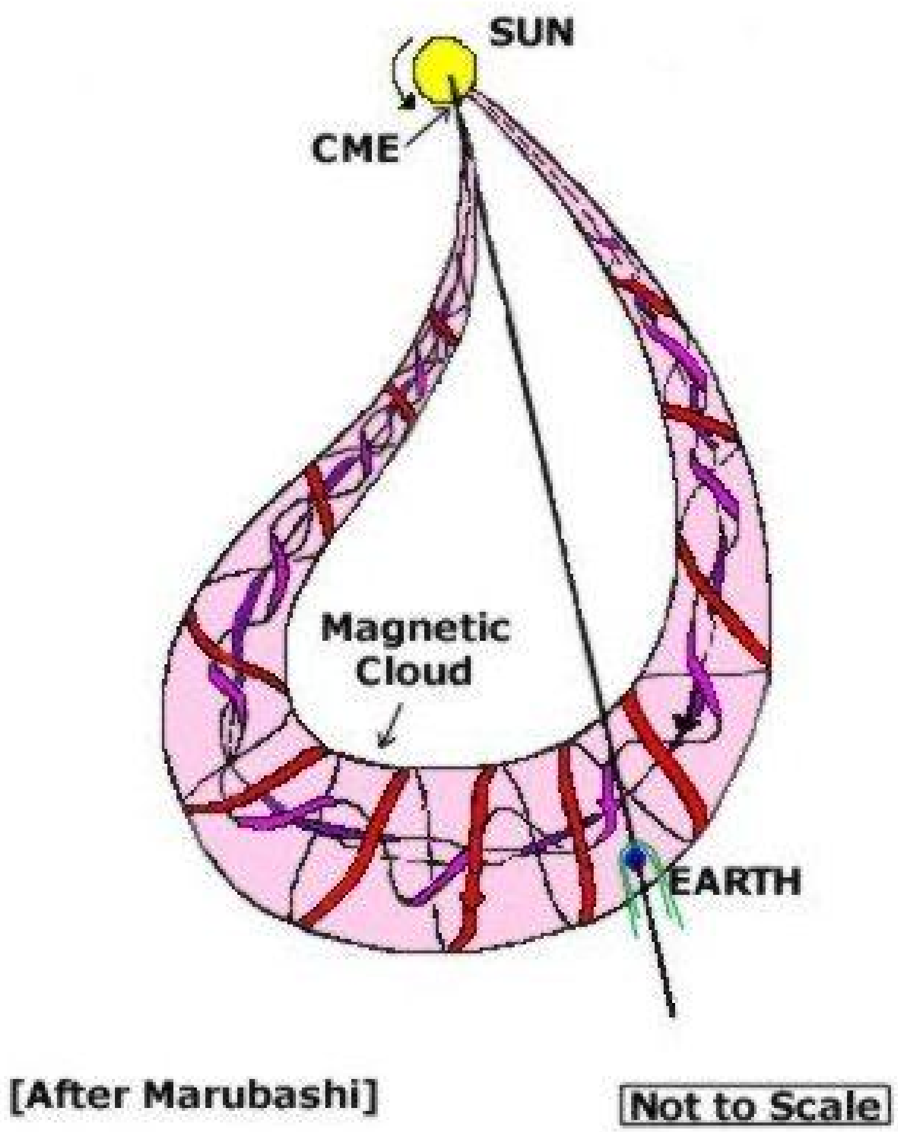
Magnetic Clouds and Solar Progenitors

- Focus on MCs associated with AR-related CMEs
- Approach: lfff
- For MC/AR pairs, determine:
  - magnetic flux
  - electric current
  - magnetic helicity
- Conclusion: MCs formed by reconnection of ARs with their surroundings
- Future: Quantitative application of mutual and self helicity



MC Model (Leamon et al. [JGR, in press]

- Lepping *et al.* [1990]: assume force-free, cylindrical:

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} = \mu_0 \mathbf{j}$$

- Lundquist [1950]:

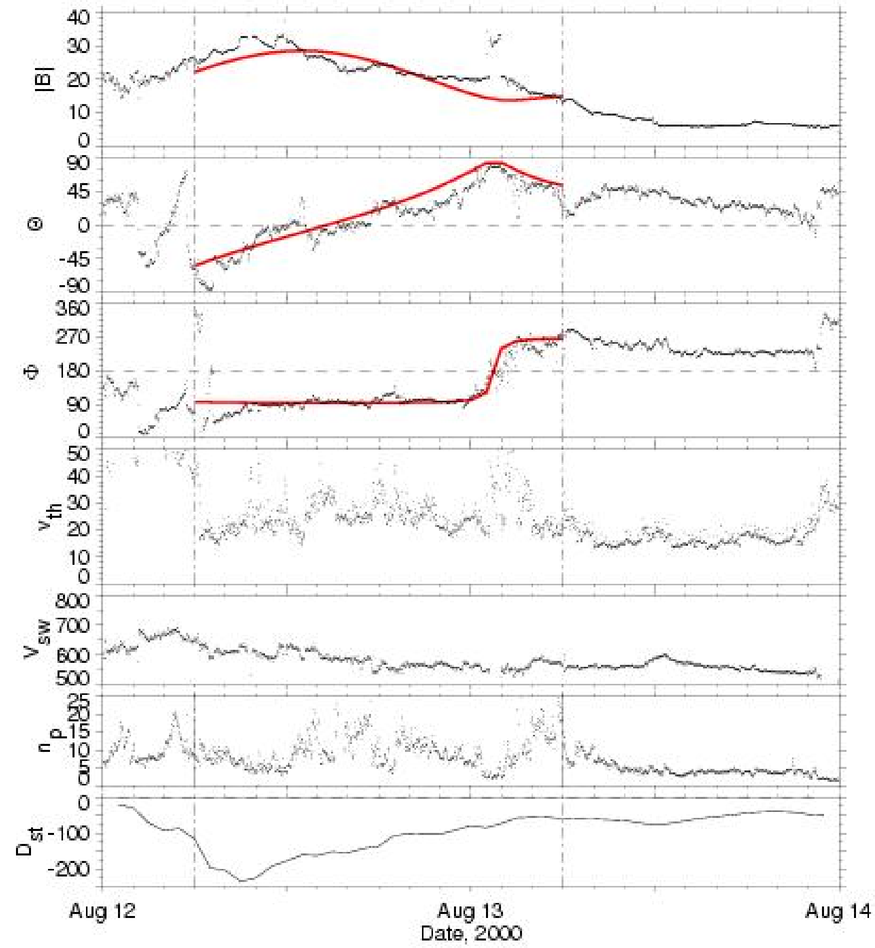
$$\begin{aligned} B_A &= B_0 J_0(\alpha r) \\ B_T &= H B_0 J_1(\alpha r) \\ B_R &= 0 \end{aligned}$$

- Find least squares fit by downhill Simplex method:

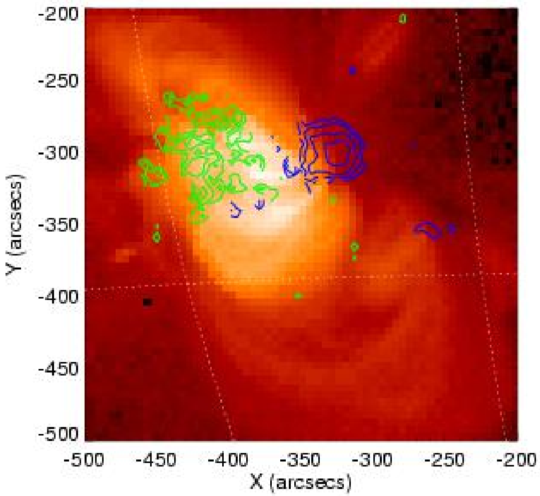
$\alpha_{MC} = 2.2048/R_0$

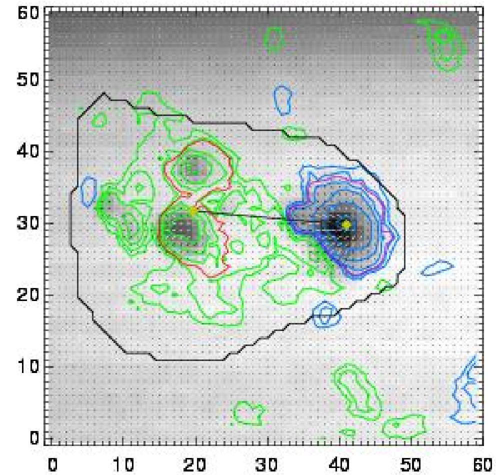
$I_{MC} = 2\pi(0.51915)\mu_0{}^{-1} B_0 R_0$

$\Phi_{MC} = 2\pi(0.21588) B_0 R_0^2.$



AR Model (Pevtsov et al. [1995])





- The total unsigned current $I_{AR} = \Sigma_i |j_z(i)| S_p/2$ and unsigned magnetic flux $\Phi_{AR} = \Sigma_i |B_z(i)| S_p/2$ are derived from vector magnetograms for active region area S_p using Ampère's Law $\frac{4\pi}{c} j_z = (\nabla \times \mathbf{B}) \cdot \hat{\mathbf{z}} = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}$.
- The linear force-free field parameter α_{AR} is derived from the best least-squares fit to the observed B_x and B_y field in the vector magnetogram, constrained by the observed B_z distribution.
- The dipole length scale ℓ is determined from the separation of the flux-weighted centroids of positive and negative flux.

Data and Analysis – MCs and ARs

- Missions / Instruments
  - WIND/MAG, SWE (thermal plasma)
  - Yohkoh/SXT
  - SOHO/MDI and SOHO/LASCO
  - MSO/HSP
- Identify associated MCs and ARs
  - ID LASCO halo or partial halo CMEs occurring at about the time calculated from the constant velocity transit time based on the average solar wind speed observed in the interplanetary ejecta
  - Exclude events where there are two (or more) possible sources that erupted within less than a day of one another.
  - Exclude events for which there is no SXT evidence for flaring or eruption
  - Exclude events for which there is evidence that CME interaction plays a role
- Number of events in the dataset: 12!

Results: Interplanetary

No.	Year	Cloud Times: Start	End	θ_0 (deg)	ϕ_0 (deg)	B_0 (nT)	R_0 (10^6 km)	H	χ^2/B_0^2	I_{MC} (10^9 A)	Φ_{MC} (10^{12} Wb)	α_{MC} (Gm^{-1})
1	1995	Feb 08 03h	Feb 08 22h	−18	81	12.7	16.6	−	0.016	0.55	4.74	0.15
2	–	Mar 04 11h	Mar 05 04h	−55	154	11.8	14.2	−	0.035	0.44	3.26	0.17
3	–	Dec 16 05h	Dec 16 22h	39	50	11.6	34.2	−	0.023	1.03	18.5	0.07
4	1998	Feb 17 10h	Feb 18 18h	−5	310	17.6	19.0	+	0.032	0.87	8.69	0.13
5	–	May 02 12h	May 03 17h	−9	357	10.5	33.6	+	0.035	0.91	16.0	0.07
6	1999	Feb 18 14h	Feb 19 12h	41	58	16.8	35.4	−	0.011	1.54	28.6	0.07
7	–	Aug 09 10h	Aug 10 16h	59	270	12.8	23.5	−	0.023	0.78	9.59	0.10
8	–	Sep 21 21h	Sep 22 05h	6	90	14.7	7.08	−	0.011	0.27	0.99	0.34
9	2000	Jul 15 19h	Jul 16 09h	1	62	48.1	26.4	−	0.015	3.29	45.5	0.09
10	–	Jul 28 21h	Jul 29 11h	5	319	14.6	16.4	−	0.026	0.62	5.33	0.15
11	–	Aug 01 00h	Aug 01 16h	18	118	12.3	40.9	−	0.012	1.31	27.9	0.06
12	–	Aug 12 06h	Aug 13 05h	−11	82	29.1	25.1	+	0.024	1.90	24.9	0.10

Results: Solar

No.	Year	Event Times: Eruption	Magnetogram	AR	I_{AR} (10^{12} A)	Φ_{AR} (10^{12} Wb)	ℓ (Mm)	α_{AR} (Gm^{-1})	AR Tilt (deg)
1	1995	Feb 04 15:56	Feb 04 01:51	7834	0.97–2.28	12.8–20.2	42.2	−5.1	−30
2	–	Feb 28 08:46	Feb 27 17:17	7846	1.26–3.82	18.0–31.7	40.7	−0.7	45
–	–	–	Feb 28 19:45	–	1.91–3.39	29.2–39.4	61.3	−9.4	−6
3	–	Dec 11 03:31	Dec 10 17:22	7930	0.63–2.36	6.64–12.1	35.5	34.8	−17
–	–	–	Dec 11 17:15	–	0.48–1.56	7.25–13.8	34.0	24.4	−33
4	1998	Feb 14 02:29	Feb 12 17:33	8156	1.34–2.28	29.4–36.9	44.1	−12.3	−5
5	–	Apr 29 16:58	Apr 28 16:38	8210	0.85–3.14	23.7–37.8	60.7	17.2	79
–	–	–	Apr 29 16:39	–	1.02–2.25	24.7–37.1	29.9	27.0	−20
6	1999	Feb 14 11:16	Feb 11 19:26	8457	1.39–2.92	32.8–53.8	62.3	−4.7	29
7	–	Aug 04 04:11	Aug 02 16:36	8651	6.10–10.5	148.0–191.0	90.2	−7.5	−29
8	–	Sep 17 22:28	Sep 20 17:00	8700	0.15–2.12	3.51–29.3	70.1	−5.4	−15
9	2000	Jul 14 09:27	Jul 11 16:52	9077	4.73–5.43	66.5–72.6	102.5	−48.4	0
–	–	–	Jul 14 16:39	–	5.03–5.79	47.6–80.4	65.6	−52.9	10
–	–	–	Jul 17 16:32	–	0.73–1.66	19.0–30.6	34.9	−29.2	−75
10	–	Jul 25 02:48	Jul 21 20:28	9097	4.40–4.75	84.3–88.4	57.8	−15.6	17
11	–	Jul 27 22:18	Jul 26 16:33	9097	2.64–5.00	26.0–50.1	53.3	16.9	29
–	–	–	Jul 28 16:40	–	0.51–1.39	10.9–21.0	41.4	−17.5	63
12	–	Aug 09 16:30	Aug 08 16:37	9114	1.42–2.51	32.6–41.3	85.3	−12.7	−17
–	–	–	Aug 11 16:58	–	1.88–2.94	42.1–52.4	77.9	−9.8	83

Results: Solar - Interplanetary Comparison

No.	Year	Event Times: Eruption	Event Times: Magnetogram	AR	I_{MC}/I_{AR} $\times 10^{-3}$	Φ_{MC}/Φ_{AR} %	$(\alpha L)_{AR}$	$(\alpha L)_{MC}$
1	1995	Feb 04 15:56	Feb 04 01:51	7834	0.15–0.53	20–38	−0.34	−53.2
2	–	Feb 28 08:46	Feb 27 07:17	7846	0.05–0.30	8–18	−0.01	−62.2
–	–	–	Feb 28 19:45	–	0.12–0.28	8–12	−0.91	–
3	–	Dec 11 03:31	Dec 10 17:22	7930	0.13–1.25	115–279	1.94	−25.8
–	–	–	Dec 11 17:15	–	0.58–4.02	122–314	1.30	–
4	1998	Feb 14 02:29	Feb 12 17:33	8156	0.30–0.66	22-30	−0.85	+43.1
5	–	Apr 29 16:58	Apr 28 16:38	8210	0.09–0.83	35–69	1.64	+26.3
–	–	–	Apr 29 16:39	–	0.36–1.19	40–72	1.27	–
6	1999	Feb 14 11:16	Feb 11 19:26	8457	0.36–1.07	43–89	−0.46	−25.0
7	–	Aug 04 04:11	Aug 02 16:36	8651	0.06–0.13	5–7	−1.06	−37.6
8	–	Sep 17 22:28	Sep 20 17:00	8700	0–0.53	0–13	−0.59	−124.8
9	2000	Jul 14 09:27	Jul 11 16:52	9077	0.58–0.71	61–69	−7.79	−33.5
–	–	–	Jul 14 16:39	–	0.55–0.68	52–112	−5.45	–
–	–	–	Jul 17 16:32	–	1.78–6.12	138–274	−1.60	–
10	–	Jul 25 02:48	Jul 21 20:28	9097	0.13–0.14	6.0–6.4	−1.42	−53.9
11	–	Jul 27 22:18	Jul 26 16:33	9097	0.19–0.49	40–106	1.42	−21.6
–	–	–	Jul 28 16:40	–	0.83–4.00	121–317	−1.14	–
12	–	Aug 09 16:30	Aug 08 16:37	9114	0.59–1.35	56–79	−1.70	+35.2
–	–	–	Aug 11 16:58	–	0.60–1.14	46–62	−1.19	–

Discussion: Solar - Interplanetary Comparison

Consider three simple models of the solar genesis of the observed MC flux:

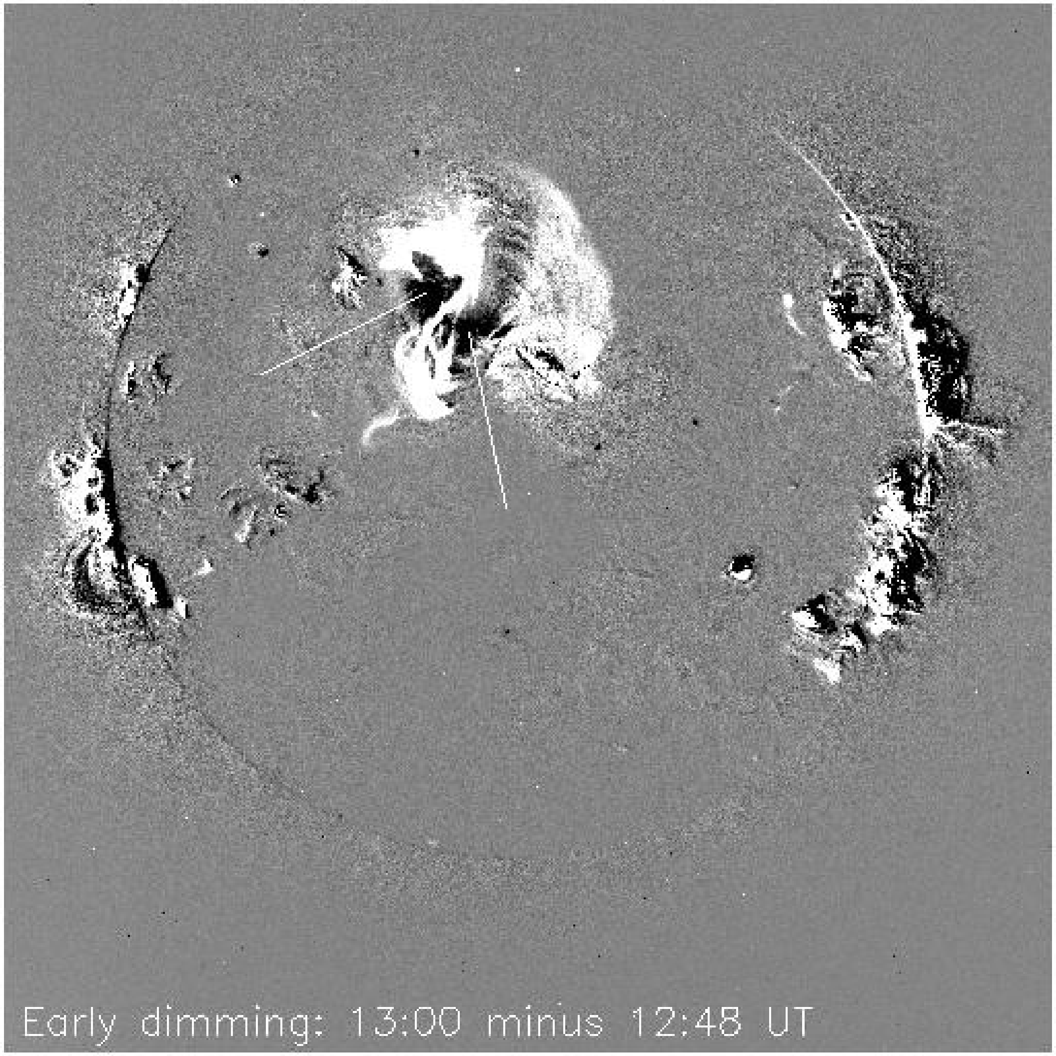
- The active region alone (the AR model);
- The overlying large-scale dipole alone (the LSD model);
- A region of reconnection of the active region and the large-scale dipole (the AR-LSD reconnection model).

Three basic results:

- The flux ratios Φ_{MC}/Φ_{AR} tend to be large.
- The current ratios I_{MC}/I_{AR} tend to be orders of magnitude less than the flux ratios Φ_{MC}/Φ_{AR}.
- There is a statistically significant proportionality between the flux ratios Φ_{MC}/Φ_{AR} and the current ratios I_{MC}/I_{AR}.

First Result: Large Flux Ratios

NB: No attempt to ID footpoints of dimming region (e.g., Lepping *et al.* [1997], Webb *et al.* [2000])



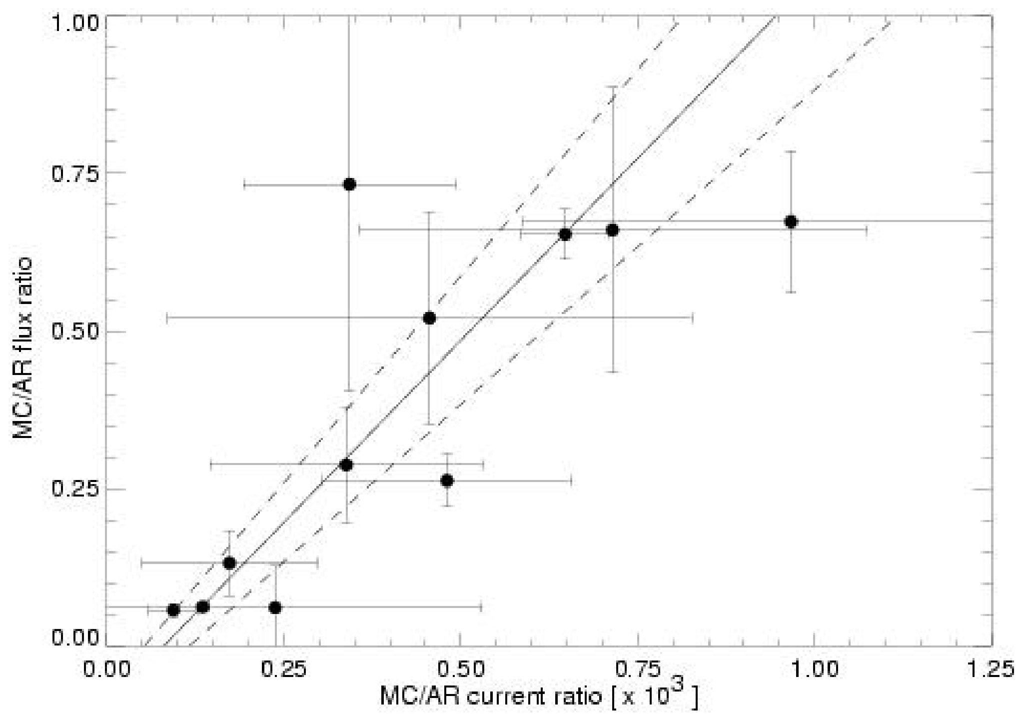
- The flux ratios Φ_{MC}/Φ_{AR} tend to be large.
- Inconsistent with the AR model
- Consistent with the LSD model
- Consistent with the AR-LSD reconnection model

Second Result: Current Ratios $<<$ Flux Ratios

- The current ratios I_{MC}/I_{AR} tend to be orders of magnitude less than the flux ratios Φ_{MC}/Φ_{AR}.
- Makes sense only in the context of the AR and AR-LSD reconnection models, if there is no significant current present outside the cores of active regions.
- Although this view is reasonable, it is hard to defend, since as a practical matter vector magnetographs lack sufficient sensitivity to measure currents beyond the strong-field areas of active regions.
- It remains possible that there exist on the Sun very extended regions outside ARs with current density that is low, but nevertheless not so low that their contribution to the total current of MCs is negligible.

Third Result: I_{MC}/I_{AR} grows with Φ_{MC}/Φ_{AR}

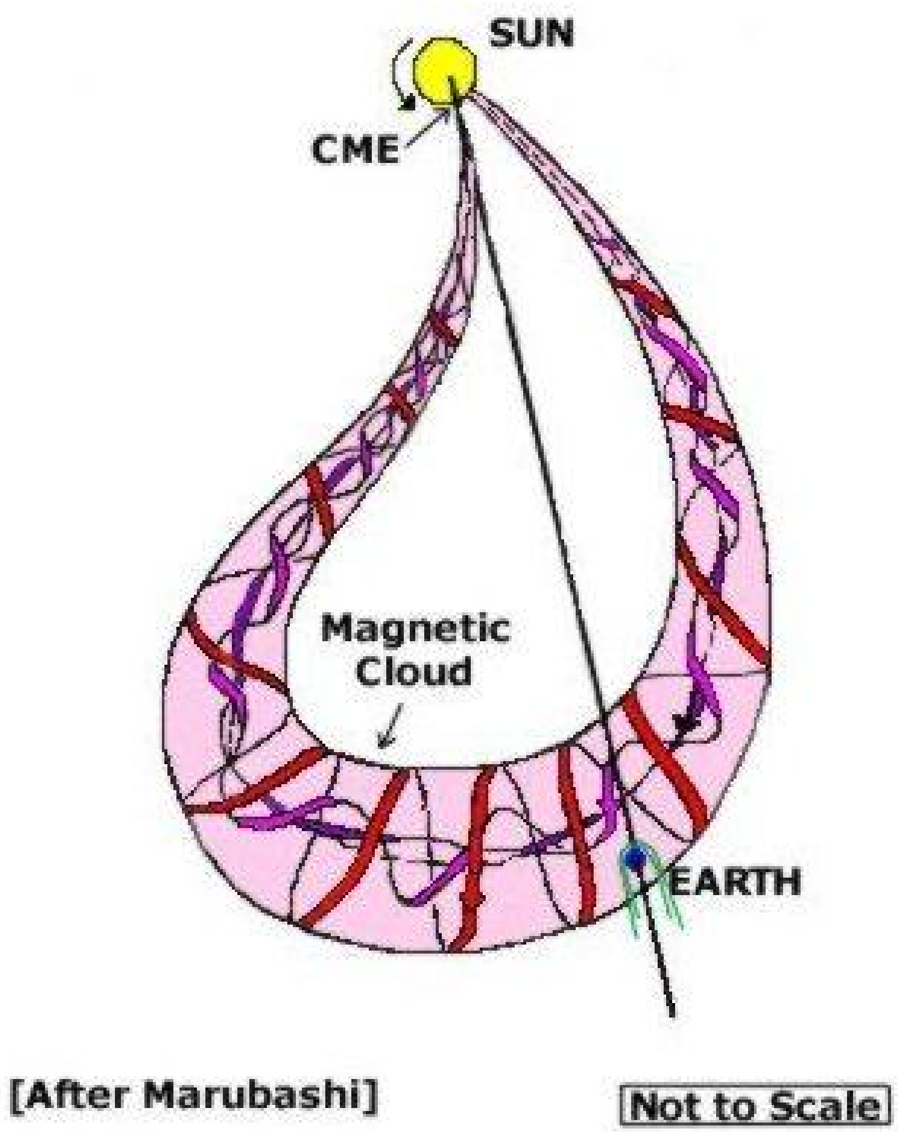
- Whether or not the relationship is linear, it is demonstrably real.
- Spearman rank-order correlation coefficient is 0.811, with confidence level 99.8%.
- This trend can most easily be explained in terms of the AR-LSD reconnection model.
- The combination of $I_{MC} \ll I_{AR}$ and $\Phi_{MC} \sim \Phi_{AR}$ argues against AR model.



Twist and Turns

NB:

- $\alpha L \sim$ total twist in length L.
- ARs: $L = \pi\ell/2$ from magnetograms.
- MCs: $L = 2.5$ AU (Larsen *et al.* [1997] case study.)
- $N_{\text{turns}} = \alpha L/(2\pi)$.



Two basic results:

- $(\alpha L)_{MC} \ \sim \ 10\ (\alpha L)_{AR}$.
- No systematic sign or amplitude relationship betwen $(\alpha L)_{MC}$ and $(\alpha L)_{AR}$.

Implications for the Simple Models

- $(\alpha L)_{MC} \;>>\; 1$ rules out AR and LSD models.
- Only the MC-LSD reconnection model can produce so many turns within the resulting magnetic cloud.
- Only the MC-LSD reconnection model can explain the lack of relationship between $(\alpha L)_{AR}$ and $(\alpha L)_{MC}$ (Zhang & Low [2003]).

Summary

Considering three simple models – that the flux of magnetic clouds originates in:

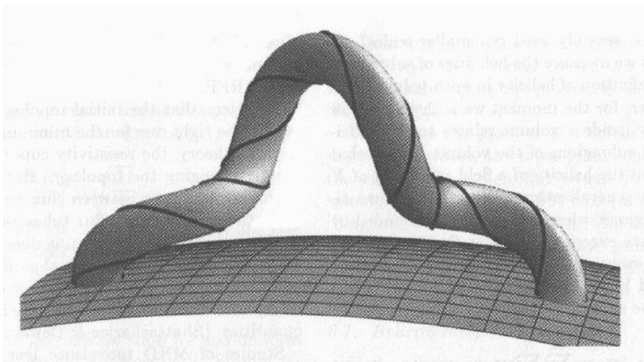
- Active regions alone (AR model);
- The overlying large-scale dipole alone (LSD model);
- A region that has experienced reconnection of the active region and the large-scale dipole (AR-LSD reconnection model).

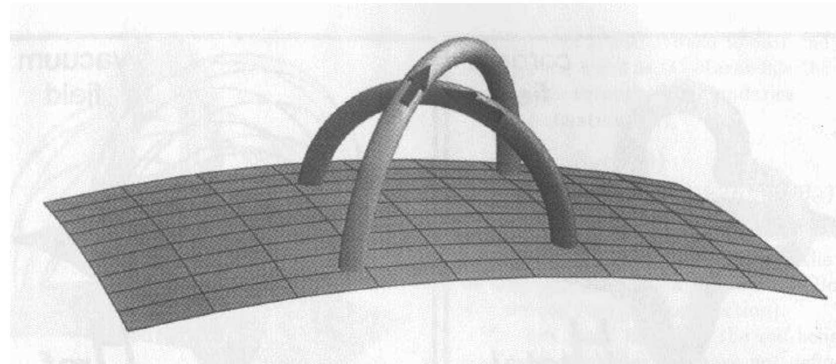
And the observational results that :

- Φ_{MC}/Φ_{AR} values are large
- $\Phi_{MC}/\Phi_{AR} >> I_{MC}/I_{AR}$
- I_{MC}/I_{AR} is proportional to Φ_{MC}/Φ_{AR}
- $(\alpha L)_{MC} >> 1$
- $(\alpha L)_{MC}$ and $(\alpha L)_{AR}$ unrelated in sign and amplitude

Only the AR-LSD reconnection model works!

Where to go ...





- Relative magnetic helicity (Finn & Antonsen [1985]):

$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A_P}) \cdot (\mathbf{B} - \mathbf{B_P}) d^3x.$$

- Self [AR] and mutual [AR-LSD] helicity (Berger [1999]):

$$H_{\mathcal{AR}}^{\mathit{self}} = \int_{\mathcal{AR}} \mathbf{A} \cdot \mathbf{B} \; d^3x, \quad H_{\mathcal{AR}-\mathcal{LSD}}^{\mathit{mutual}} = 2 \int_{\mathcal{AR}-\mathcal{LSD}} \mathbf{A_P} \cdot \mathbf{B} \; d^3x.$$

- Discrete flux tubes with linking number L_{ij}, twist $\mathcal{T}$ and writhe $\mathcal{W}$:

$$H = \sum_{i=1}^{N} \sum_{j=1}^{N} L_{ij} \Phi_i \Phi_j, \quad L = \mathcal{T} + \mathcal{W}.$$

- Magnetic helicity conservation.