In-Situ Signatures of Interplanetary Coronal Mass Ejections

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~Two dozen in-situ signatures frequently (but not necessarily exclusively) associated with ICMEs (solar wind manifestions of coronal mass ejections near the Sun).

Reviews include:

Gosling, J.T.: 1990, In: Russell, C. T., Priest, E. R., Lee, L. C. (eds.), Physics of Magnetic Flux Ropes, AGU Geophys. Monograph 58, 343.

Gosling, J.T.: 2000, In: Dingus, B. L., Kieda, D., Salamon, M. (eds.), Proc. 26th Int. Cosmic Ray Conf., AIP Conf. Proc. 516, 59.

Neugebauer, M., Goldstein, R.: 1997, In: Crooker, N., Joselyn, J.A., Feynman, J. (eds.), Coronal Mass Ejections, AGU Geophys. Monograph 99, 245.

Zurbuchen, T. H., Richardson, I. G.: 2006, Space Sci. Rev. 123, 31.

Signatures of ICMEs (Magnetic Field)

T. H. ZURBUCHEN AND I. G. RICHARDSON

TABLE I

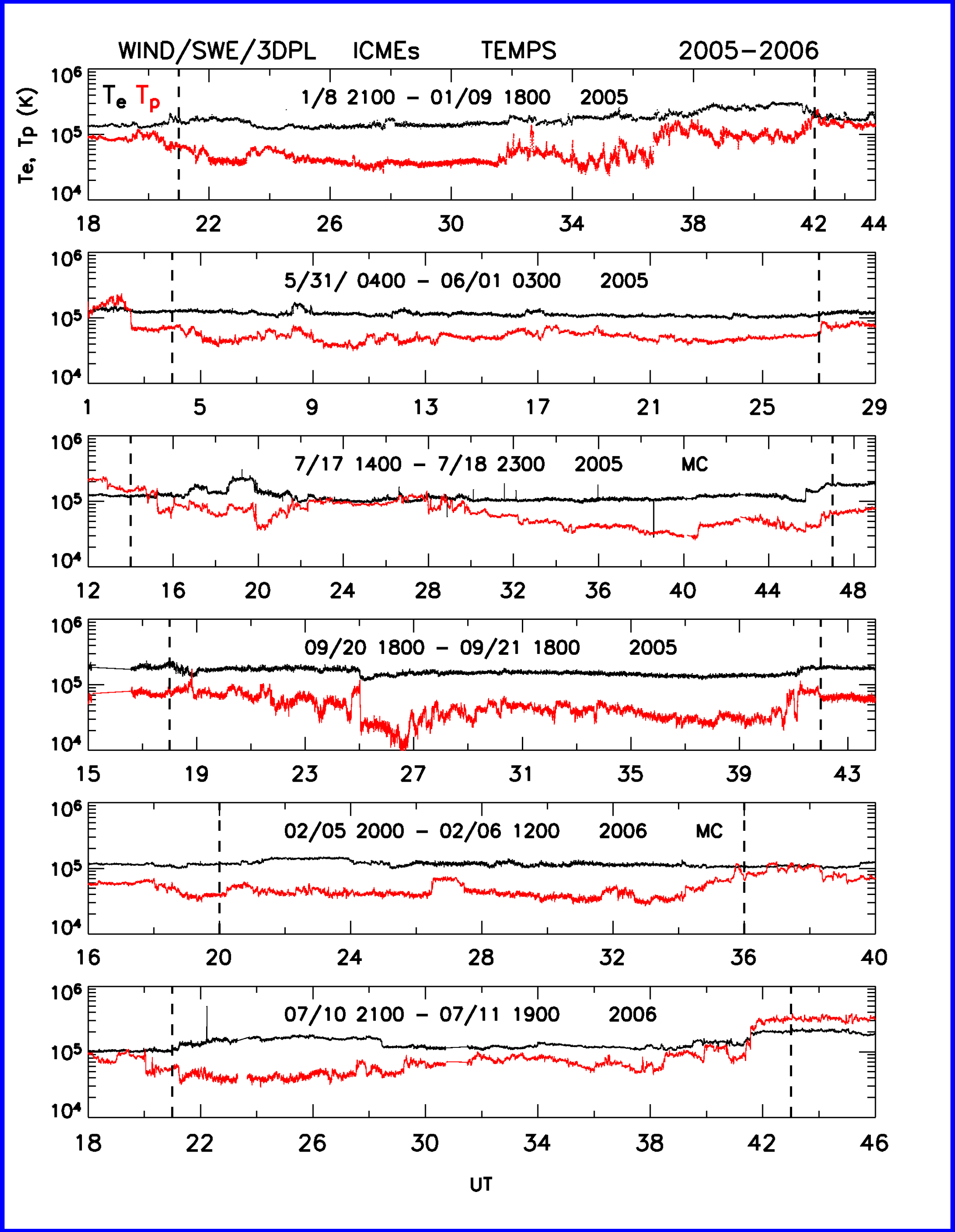
In-situ signatures of ICMEs (description applies to ~1 AU heliospheric distance) in the magnetic field (B), plasma dynamics (P), plasma composition (C), plasma waves (W), and suprathermal particles (S)

	Signature	Description	Selected references
★	B1: B Rotation	$\gg 30°$, smooth	Klein and Burlaga (1982)
★	B2: B Enhancement	>10 nT	Hirshberg and Colburn (1969); Klein and Burlaga (1982)
★	B3: B Variance decrease		Pudovkin *et al.* (1979); Klein and Burlaga (1982)
★	B4: Discontinuity at ICME boundaries		Janoo *et al.* (1998)
	B5: Field line draping around ICME		Gosling and McComas (1987); McComas *et al.* (1989)
★	B6: Magnetic clouds **~30% of events**	(B1, B2 and $\beta = \frac{\sum nkT}{B^2/(2\mu_0)} < 1$)	Klein and Burlaga (1982); Lepping *et al.* (1990)

★ Useful signature

Signatures of ICMEs (Plasma)

★	P1: Declining velocity profile/expansion	Monotonic decrease	Klein and Burlaga (1982); Russell and Shinde (2003)
	P2: Extreme density decrease	≤ 1 cm^{-3}	Richardson *et al.* (2000a)
★	P3: Proton temperature decrease **Most events**	$T_p < 0.5T_{exp}$	Gosling *et al.* (1973); Richardson and Cane (1995)
	P4: Electron temperature decrease	$T_e < 6 \times 10^4$ K	Montgomery *et al.* (1974)
	P5: Electron Temperature increase **T_e>2T_p (Richardson et al., 1997)**	$T_e \gg T_p$	Sittler and Burlaga (1998); Richardson *et al.* (1997)
★	P6: Upstream forward shock/"Bow Wave"	Rankine-Hugoniot relations	Parker (1961)



Comparison of WIND T_e (black) and T_p (red) in a sample of ICMEs in 2005-2006 (from C. J. Farrugia)

$T_e > T_p$; ($n_e kT_e > n_p kT_p$ i.e., don't ignore the electron pressure in ICMEs!)

Greater variability in T_p

$T_e = T_p$ often occurs close to the ICME boundaries suggested using other data (dashed lines, Richardson and Cane ICME list)

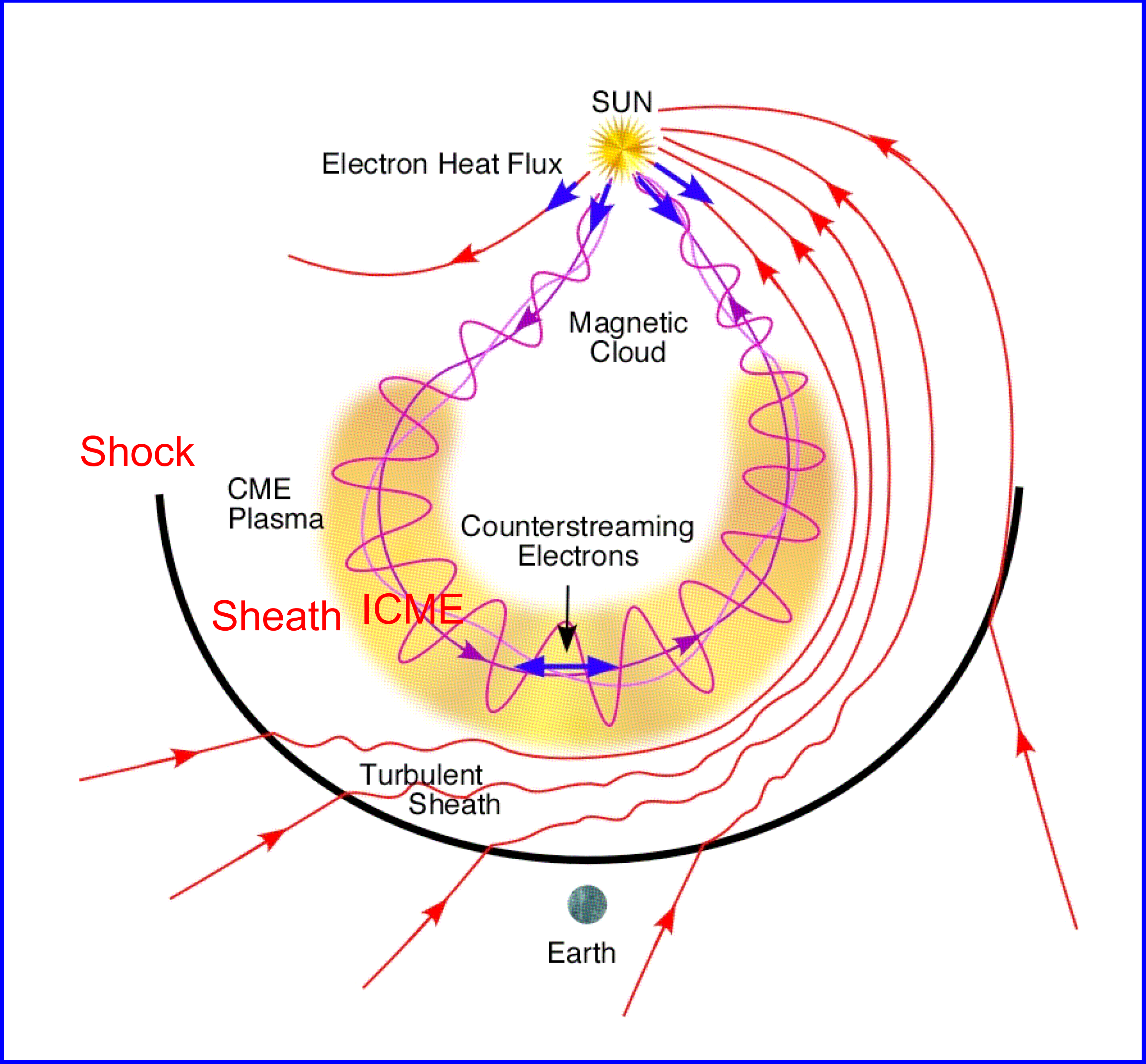
Signatures of ICMEs (Solar Wind Abundances/charge states, Plasma Waves)

C1: Enhanced α/proton ratio	$He^{2+}/H^{+} > 8\%$	Hirshberg *et al.* (1972); Borrini *et al.* (1982a)
C2: Elevated oxygen charge states	$O^{7+}/O^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003)
C3: Unusually high Fe charge states	$\langle Q \rangle_{Fe} > 12$; $Q_{Fe}^{\geq 15+} > 0.01$	Bame *et al.* (1979); Lepri *et al.* (2001); Lepri and Zurbuchen (2004)
C4: Occurrence of He^{+} **Rare; handful of events**	$He^{+}/He^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
C5: Enhancements of Fe/O	$\frac{(Fe/O)_{CME}}{(Fe/O)_{photosphere}} > 5$	Ipavich *et al.* (1986)
C6: Unusually high $^{3}He/^{4}He$	$\frac{(^{3}He/^{4}He)_{CME}}{(^{3}He/^{4}He)_{photosphere}} > 2$	Ho *et al.* (2000)
W1: Ion acoustic waves		Fainberg *et al.* (1996); Lin *et al.* (1999)

Signatures of ICMEs (Energetic Particles)

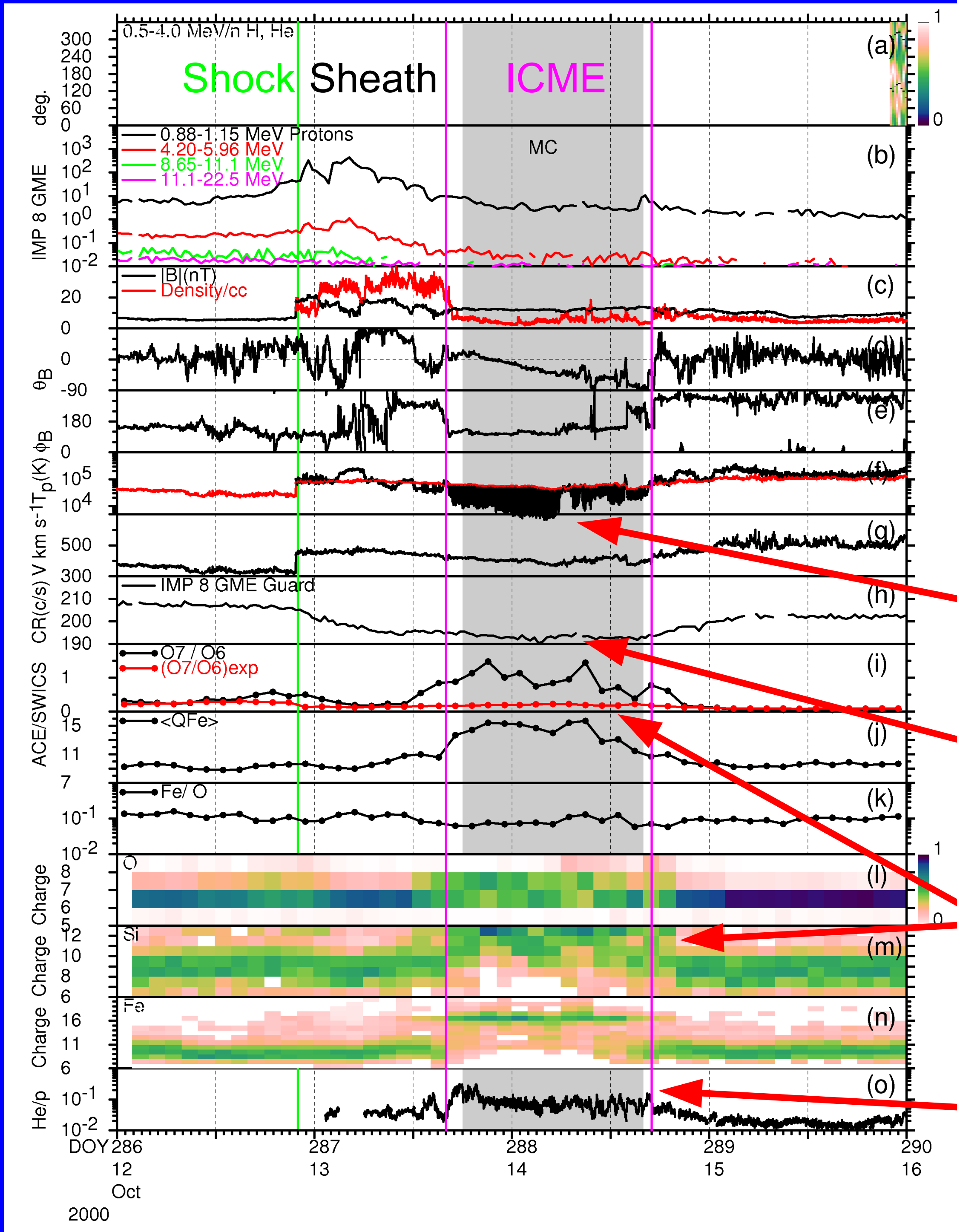
		(1999)
★ S1: Bidirectional strahl electrons		Gosling *et al.* (1987)
★ S2: Bidirectional ~MeV ions	2nd harmonic >1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
★ S3: Cosmic ray depletions	Few % at ~ 1GeV	Forbush (1937); Cane (2000)
S4: Bidirectional cosmic rays	2nd harmonic >1st harmonic	Richardson *et al.* (2000b)

“Textbook” Configuration of Interplanetary Coronal Mass Ejection and Upstream shock



***Zurbuchen & Richardson*, SSR, 2006**

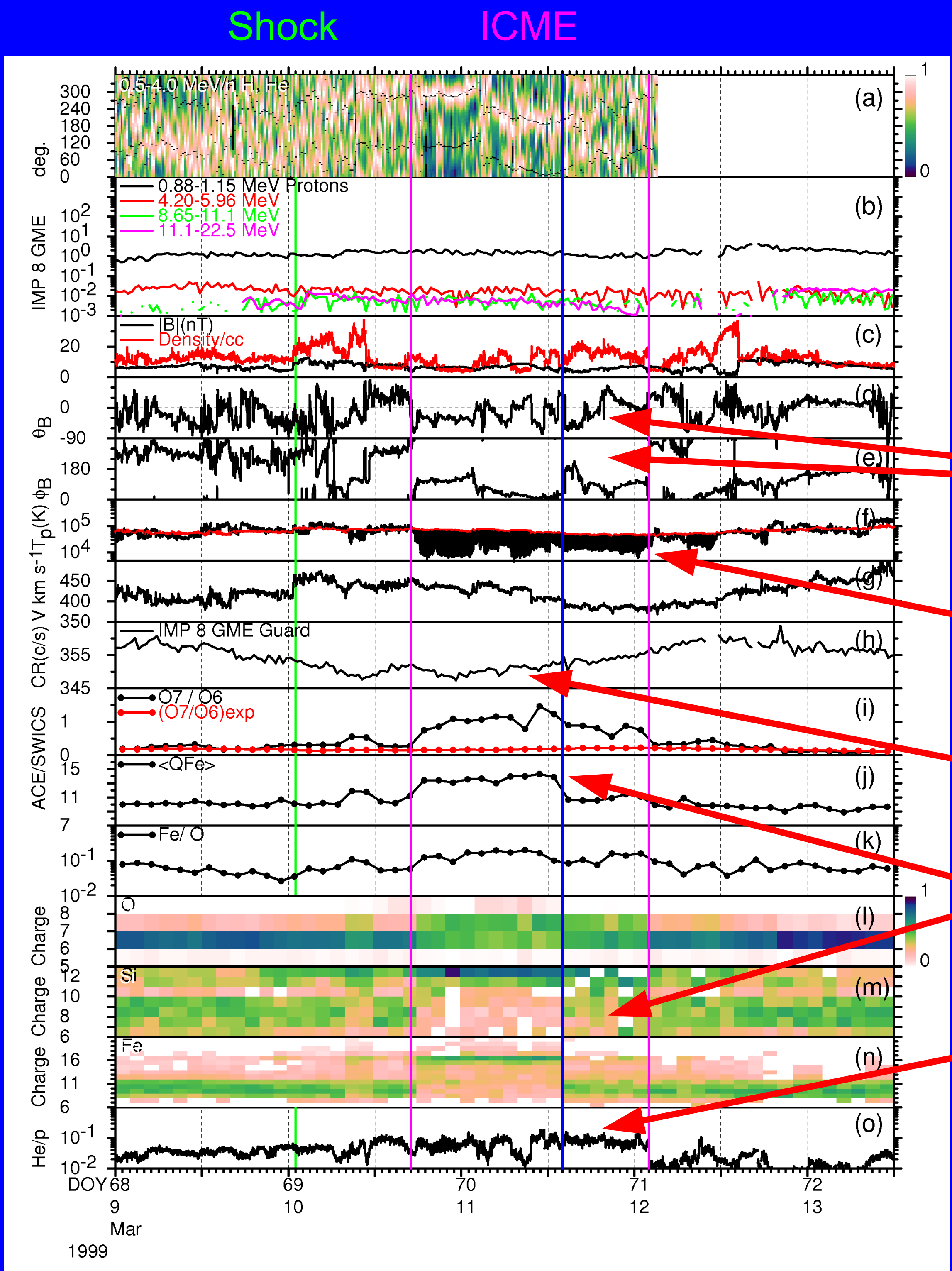
~ "Textbook" ICME



Richardson and Cane, Sol. Phys., 2010

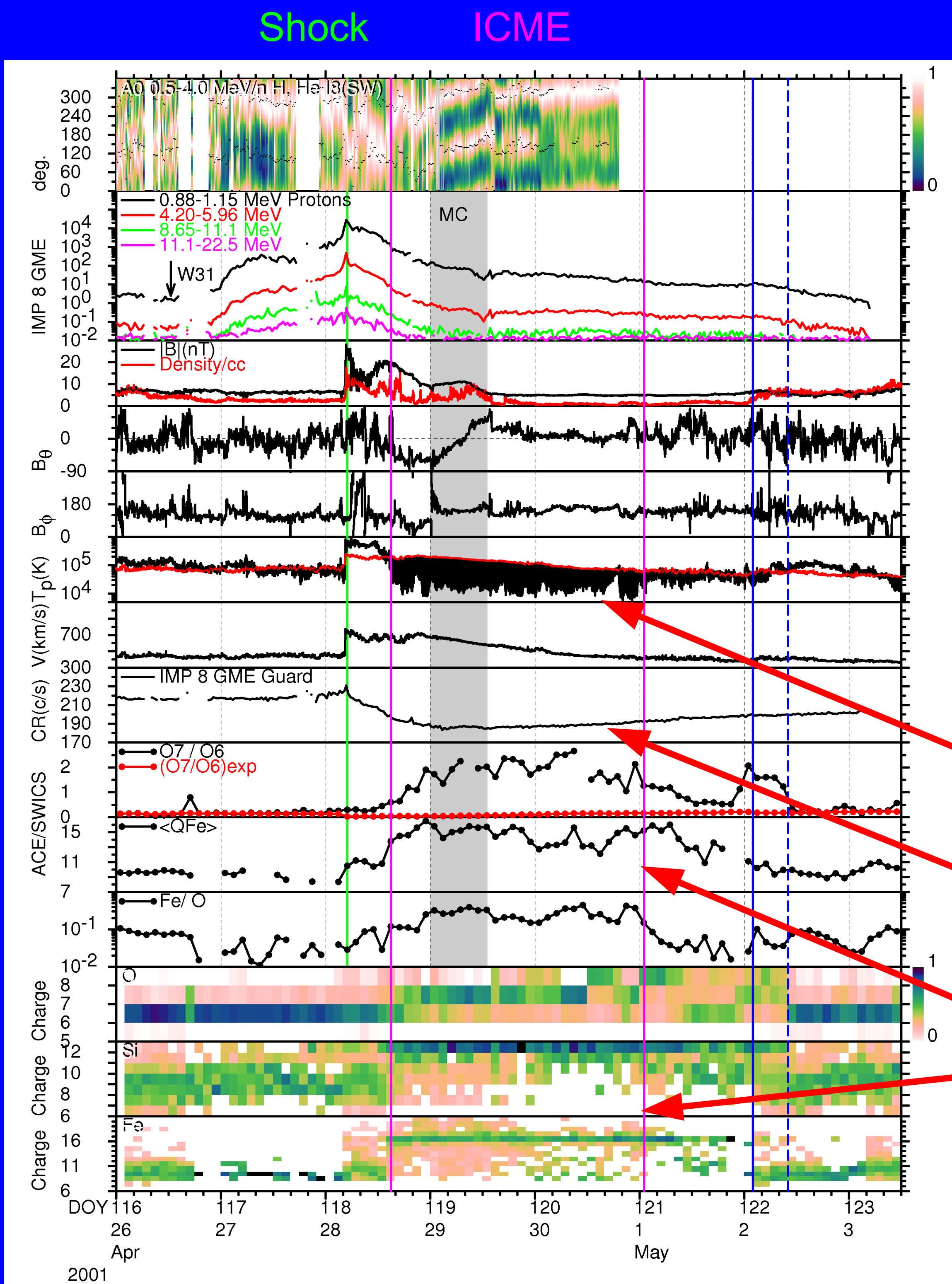
- Follows shock with a few hours delay (sheath);
- WIND Magnetic cloud (grey shading);
- Low T_p (< 2 T_{exp});
- Cosmic ray depression
- Enhanced solar wind ion charge states;
- Enhanced He/p;
- Signatures ~co-located.

Similar ICME, But No Magnetic Cloud Magnetic Signatures



- Follows shock;
- Weak magnetic field, fluctuating direction
- Low T_p
- Cosmic ray depression
- Enhanced solar wind ion charge states
- Enhanced He/p
- Signatures ~co-located.

Richardson and Cane, Sol. Phys., 2010



Extended (~4 day) region of ICME like plasma following shock/sheath.

- Identified magnetic cloud (grey shading) is only a SMALL SUBSTRUCTURE of the total ICME region suggested by other signatures.
- Low T_p;
- Cosmic ray depression
- Enhanced solar wind ion charge states (=> heating to 2-3×10^6 K) extending ~1 day behind ICME and ~3 days behind MC;

- Interaction of multiple ICMEs? But the boundaries between component ICMEs are not too obvious across the multiple data sets (also noted by Burlaga et al.)

- Extended outflow of plasma heated to several Mk trailing some ICMEs?
  - ➔ Heating process at the Sun? A flare seems too brief!
  - ➔ Are extended outflows observed near the Sun following some CMEs/ICMEs?

- Could heliospheric imager data be used to identify features that correspond to the various in-situ structures and help infer their origin?

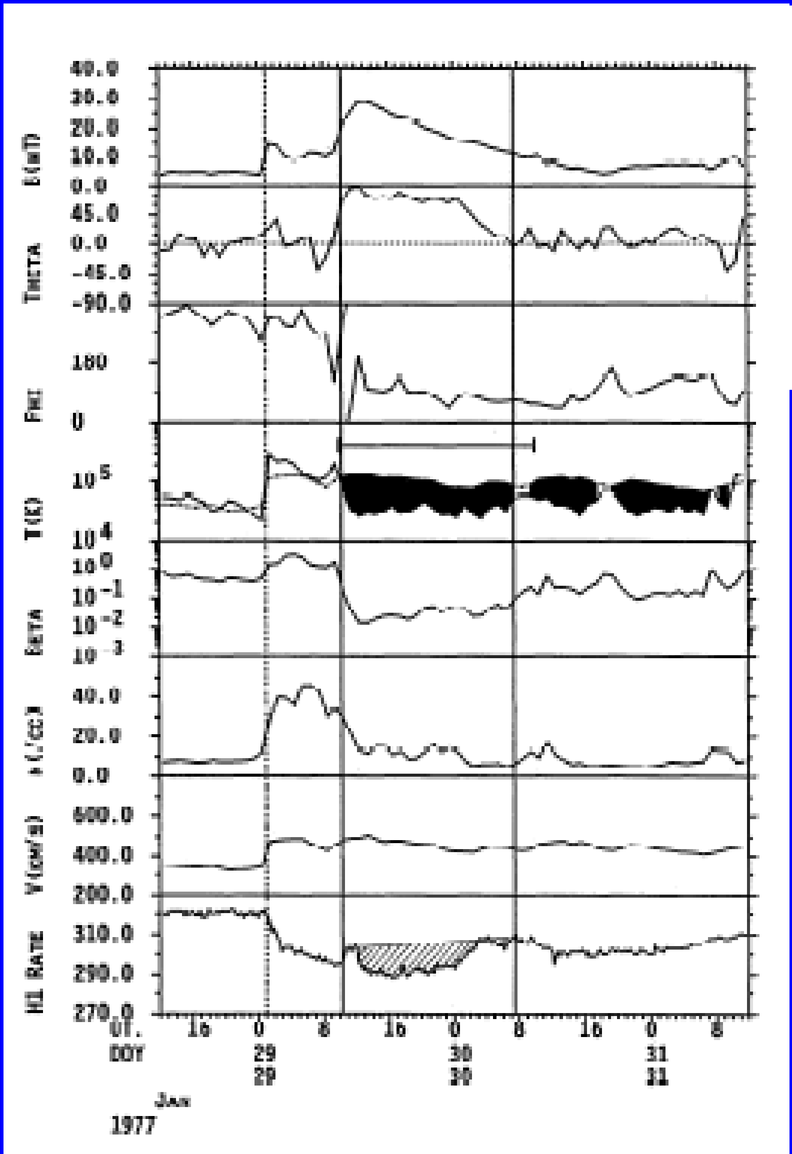
- The view that the in-situ magnetic cloud/flux rope, if present, is THE ICME, and that if no MC is detected, then there is only a glancing encounter with the ICME seems too simplistic.

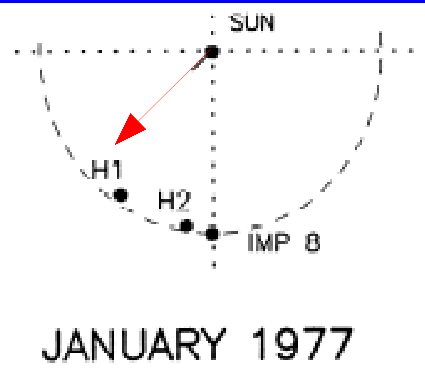
- Little hope of finding a unique parameter that indicates the presence of an ICME.

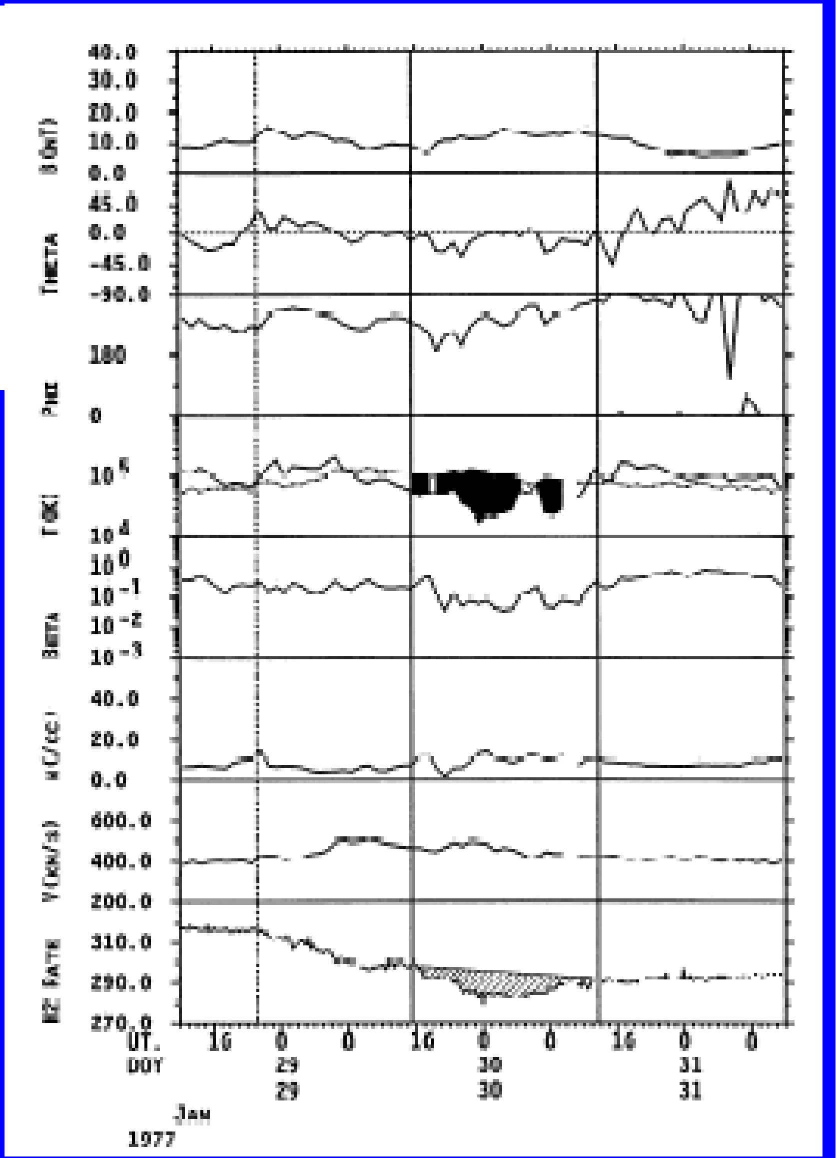
January 1977 ICME

Helios 1: Magnetic Cloud

Helios 2: Non-cloud ICME







Filament eruption at ~E50º

Helios 1, near eruption longitude, saw a MC;

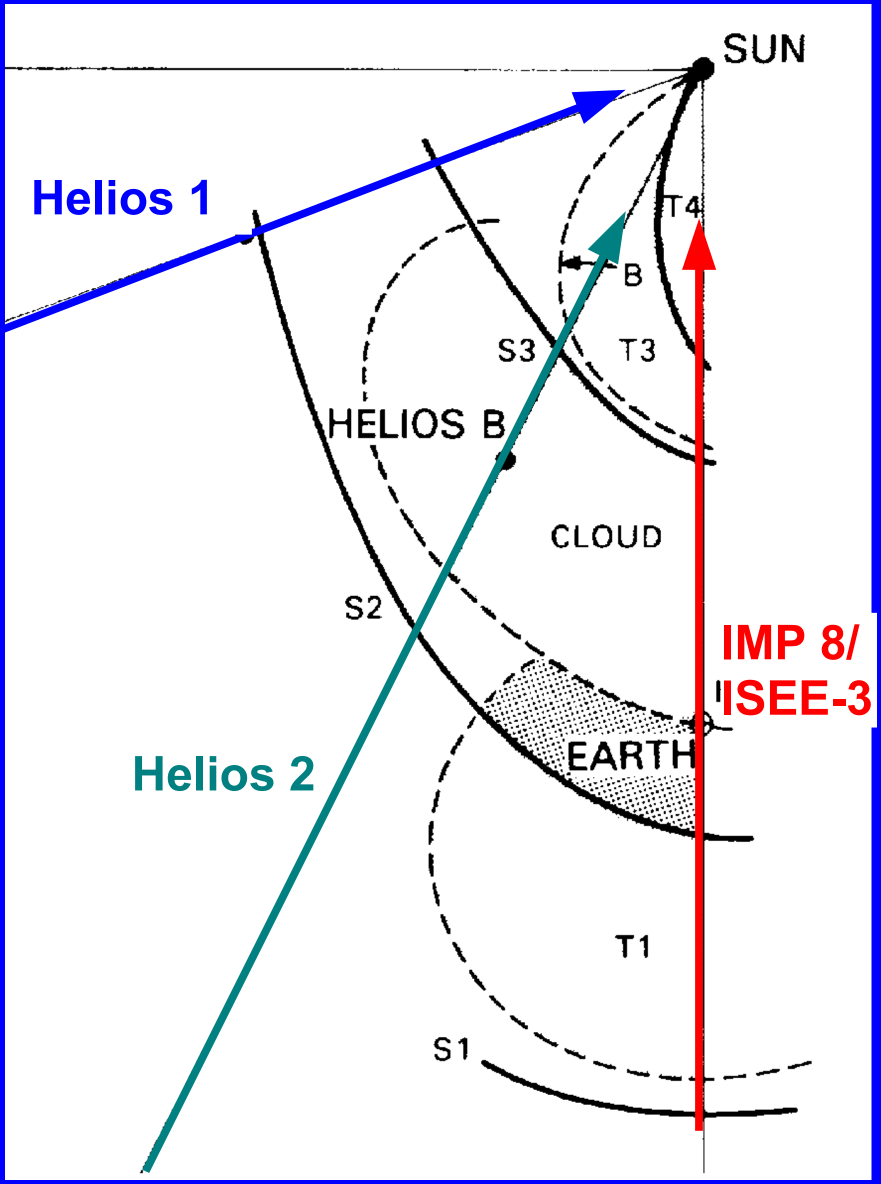
Helios 2 saw a non-cloud ICME

Also demonstrates that an MC may be a substructure of an ICME

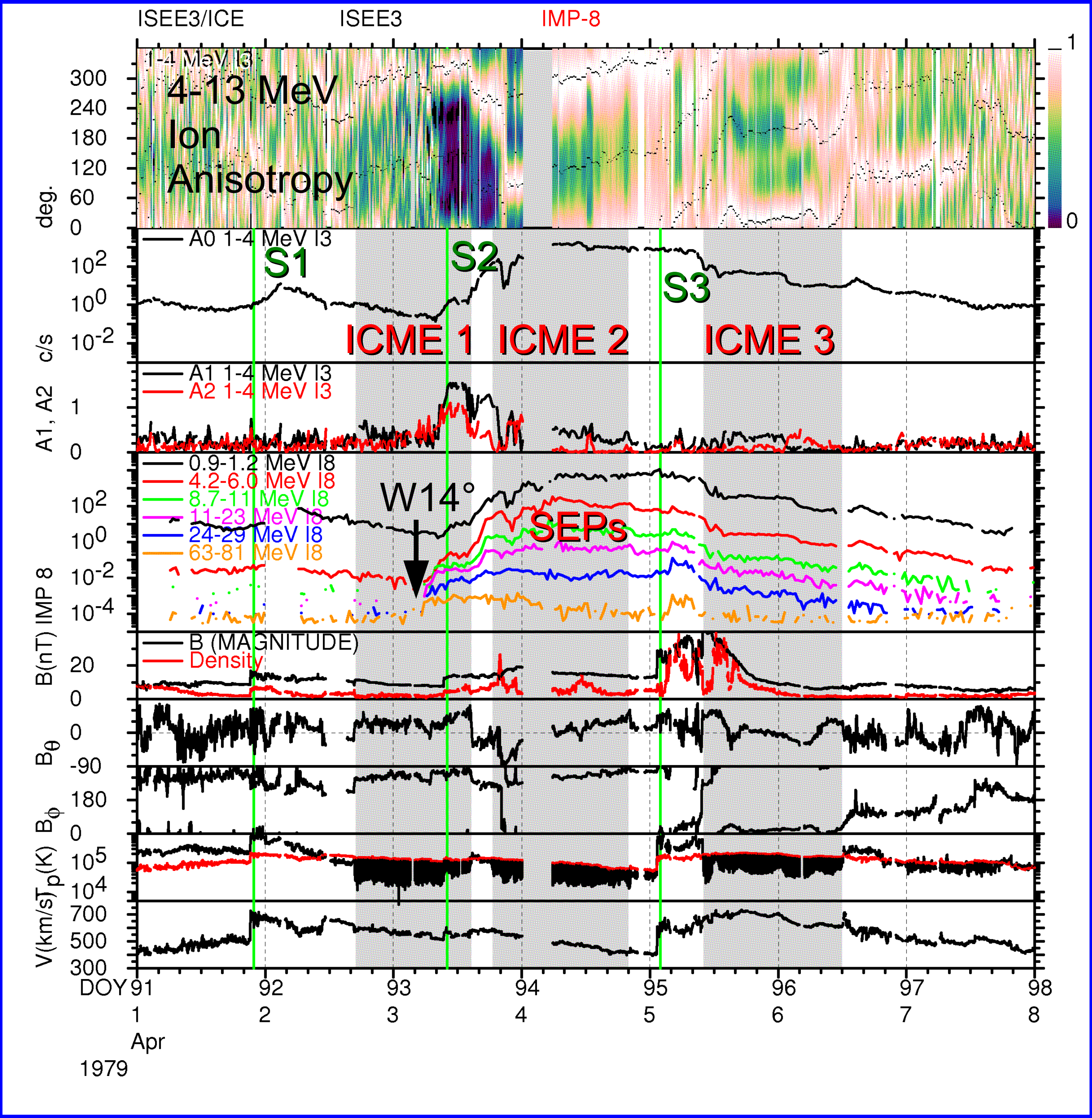
Cane, Richardson & Wibberenz, 1997

Configuration of Multiple Shocks and ICMEs, April 1979

Burlaga et al., 1987



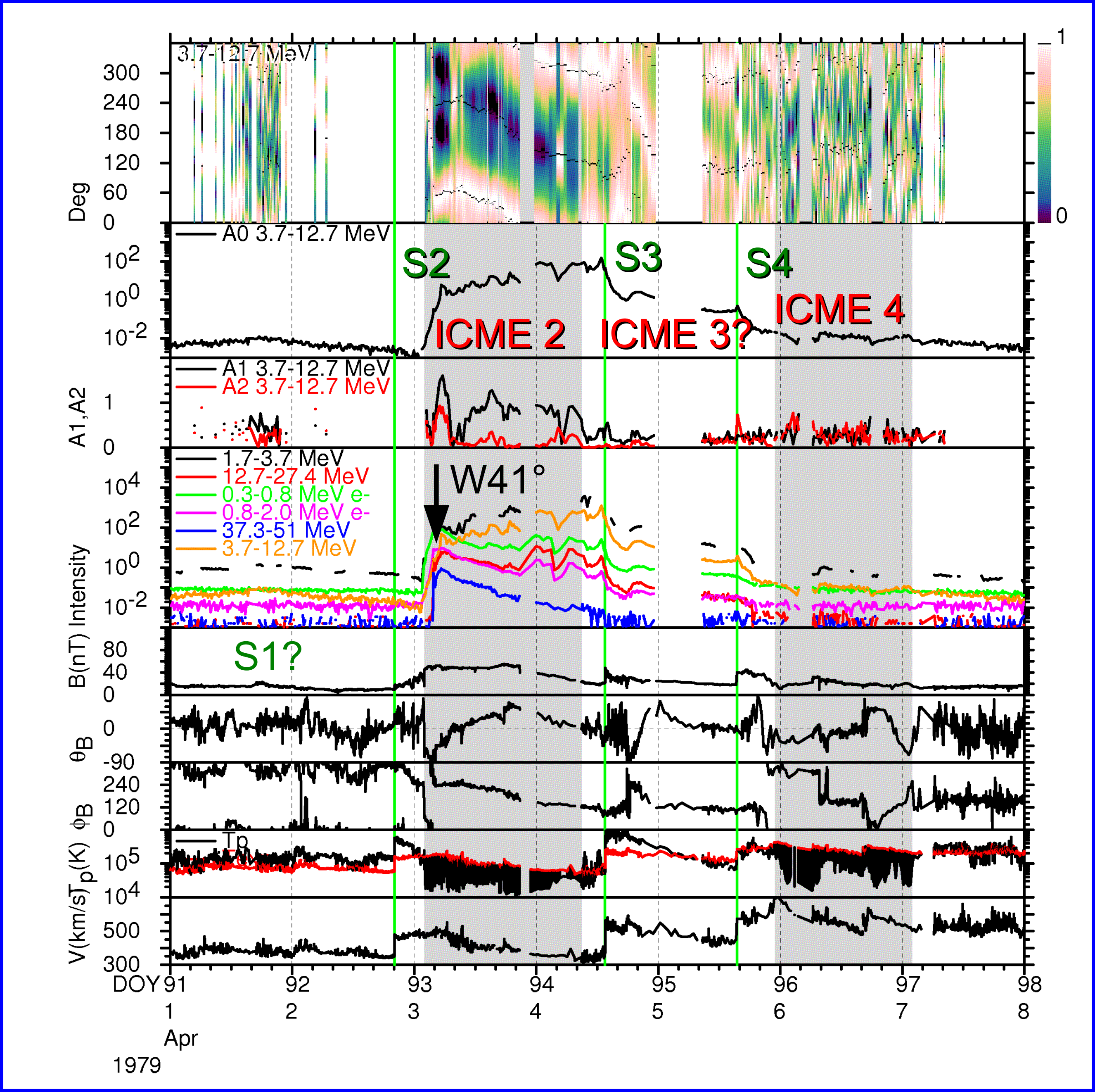
Observations at Earth, April 1-7, 1979



Three shocks (S1-3) followed by ICME drivers

Solar Particle onset on April 3rd from W14° event injected into ICMEs 1 & 2; related to S3 and ICME 3.

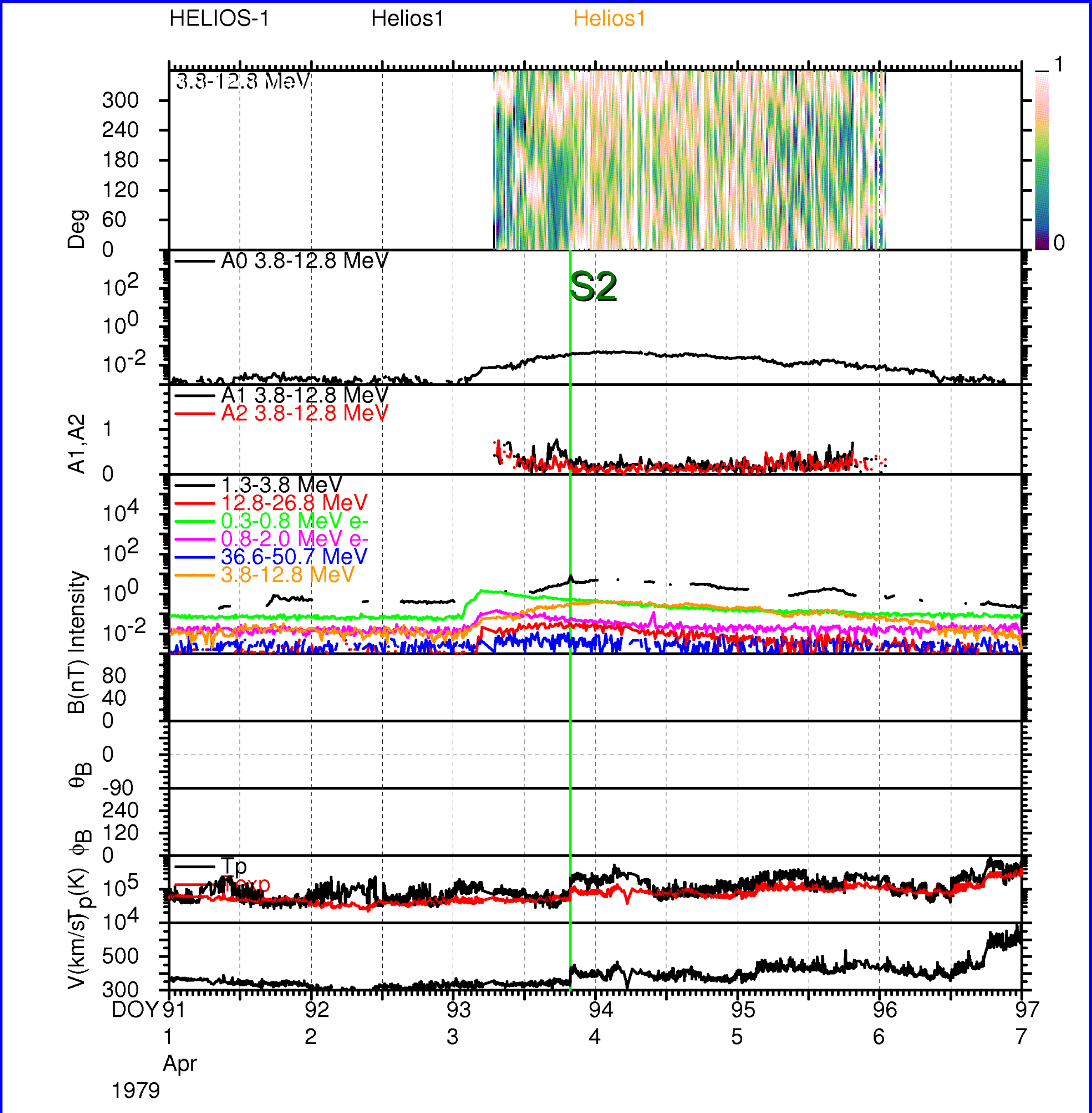
Observations at Helios 2 (0.67 AU, E27°)



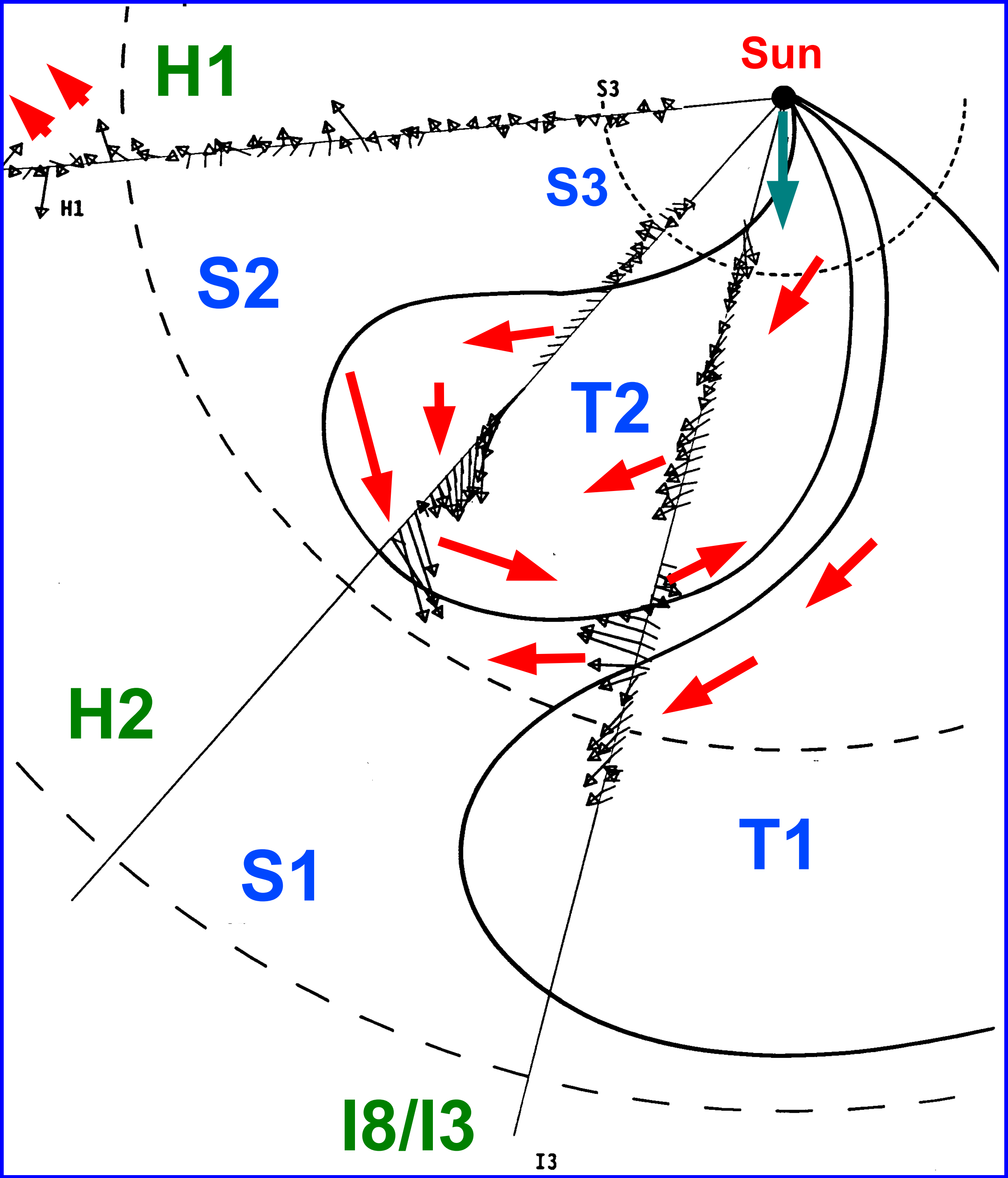
Three shocks (S2-4) probably followed by ICME drivers

Solar Particle onset on April 3rd from W41° event injected into ICME 2, but flow is from the EAST!

Observations at Helios 1 (0.74 AU, E70°)



- One shock (S2) (Schwenn); no ICMEs.
-
- W84° SEP event observed, but weak.



MeV proton Flows Following April 3, 1979 SEP Event

Note flow pattern in T2 suggestive of looped magnetic field lines.

Richardson and Cane [1996].

What is the relationship of “typical” ICMEs to “small” ICMEs?

Several studies have been made of smaller (shorter duration) structures that share some of the features of ICMEs.

e.g., Cartwright and Moldwin, JGR, in press, 2010:

- Small scale flux ropes, 10s of minutes-few hours,
- No expansion signature or depressed Tp.
- Formed in the solar wind or at the corona (or both)?
- Most often found near sector boundaries.
- Reconnection across the HCS or streamer blobs?

STEREO: ICMEs associated with “blobs” moving out through the HPS e.g., Kilpua et al.

- Are these the same phenomenon as “typical” ICMEs but on a smaller scale, or a different phenomena?

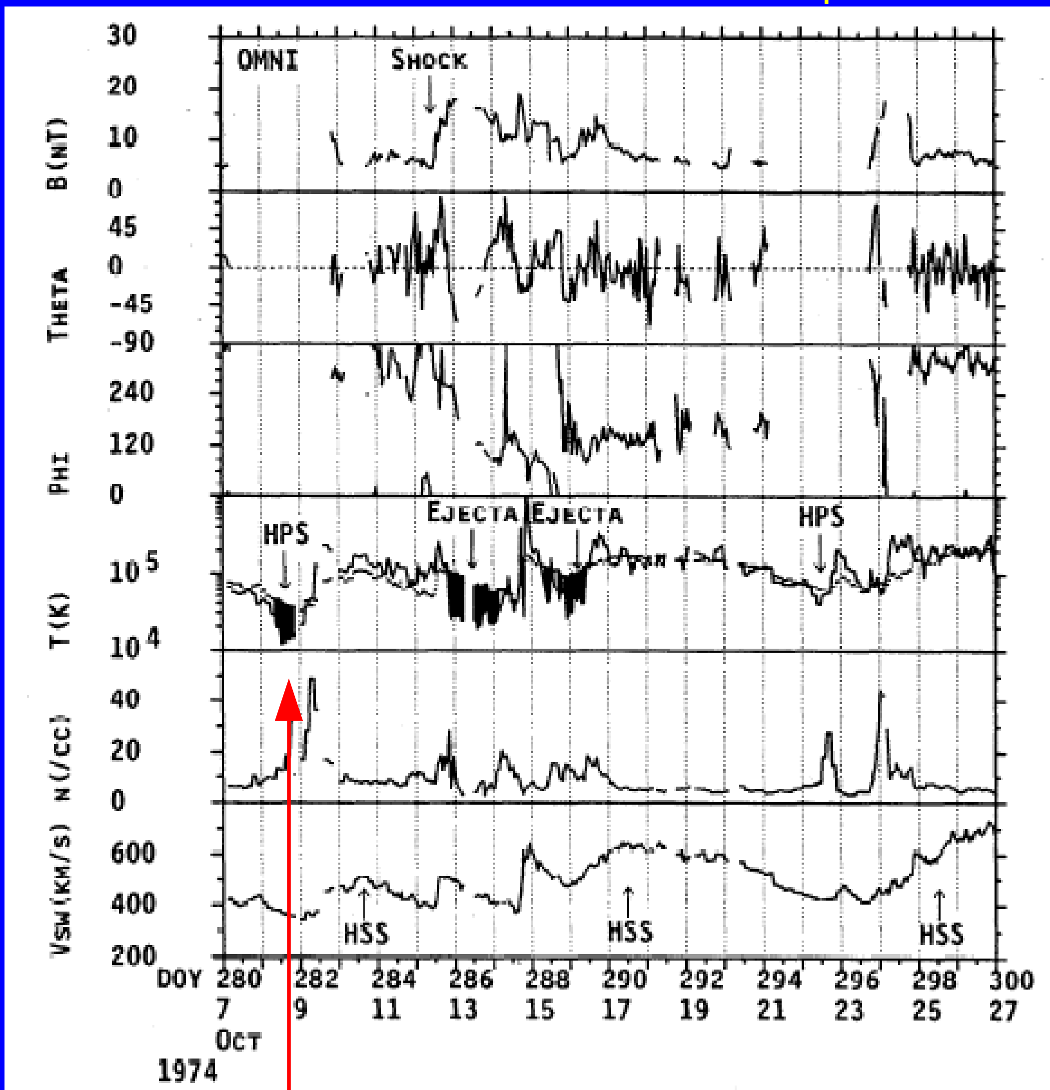
- Are the interplanetary signatures distinct in some way(s)?

- Should an “ICME” require a CME/energetic eruption/flare at the Sun? But many “typical” ICMEs don't have visible CMEs (at least in LASCO) and may lack clear solar signatures.

- If there are different production processes at the Sun, should the interplanetary manifestations all be called ICMEs?

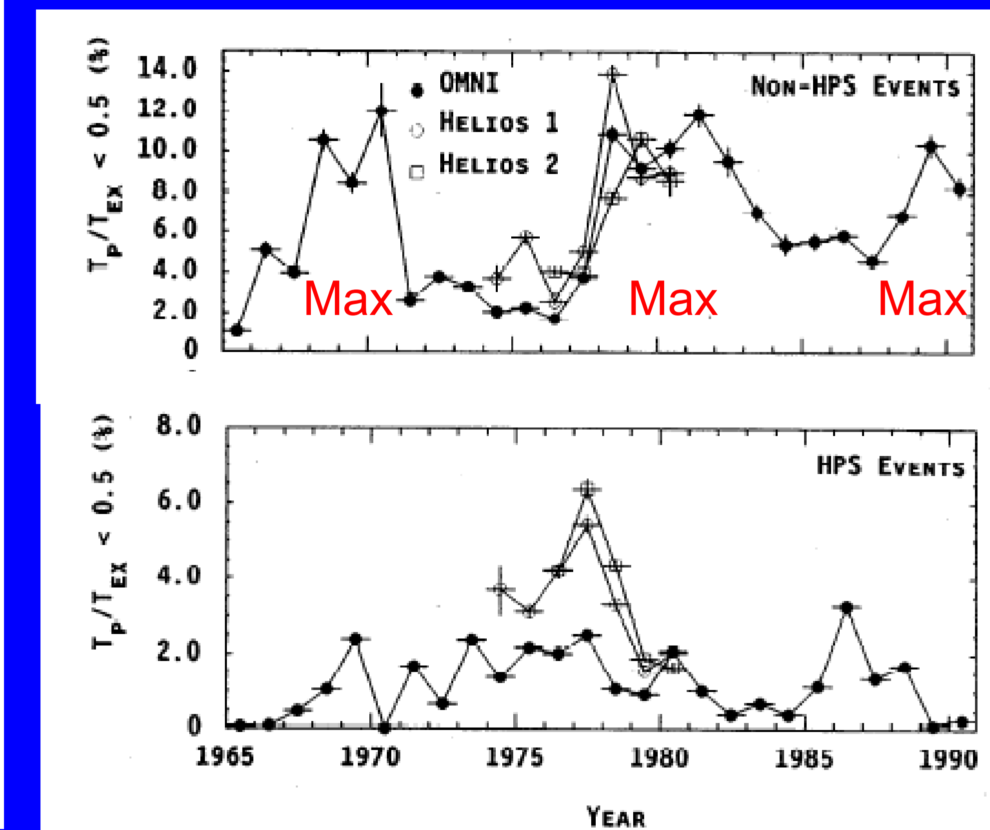
- But, if coronal material is ejected, why not call them all ICMEs?

Richardson and Cane, JGR, 1995: Low T_p regions in the HPS



Abnormally low T_p regions in the vicinity of the heliospheric plasma sheet

Occurrence rate of low T_p NOT associated with the HPS (1965-1990)



Occurrence rate of low T_p associated with the HPS

Association of low T_p regions within and outside the HPS with various "ICME-like" Signatures (Richardson and Cane, 1995)

Table 3. Number of $T_p/T_{ex} \leq 0.5$ Plasma Events Associated with Ejecta Signatures, Cosmic Ray Decreases, and Shocks, and Chance Association Rates

Non HPS HPS

	All Events		Non-HPS		HPS	
	All	≥10 hours	All	≥10 hours	All	≥10 hours
Bidirectional ~1 MeV ion flows						
IMP 8/ISEE 3[a]						
Events	197/554	123/184	161/406	103/153	36/148	20/31
Chance rate	10%	20%	11%	21%	8%	16%
Observed/chance	3.5	3.4	3.5	3.2	3.1	4.1
Helios 1						
Events	152/570	72/169	115/386	52/115	37/184	20/54
Chance rate	9%	23%	16%	24%	9%	21%
Observed/chance	2.9	1.9	3.1	1.9	2.3	1.8
Helios 2						
Events	72/246	39/77	48/159	26/49	24/87	13/28
Chance rate	5%	13%	6%	14%	5%	12%
Observed/chance	5.9	3.9	5.4	3.7	5.9	4.0
ISEE 3 bidirectional solar wind electron heat fluxes						
Events	65/240	44/97	60/188	43/86	5/52	1/11
Chance rate	15%	22%	16%	23%	12%	18%
Observed/chance	1.8	2.1	2.0	2.2	0.84	0.50 ± 0.50
ISEE 3 electron temperature depression ($T_e \leq 10^5$ K)						
Events	102/226	66/96	75/176	58/85	27/50	8/11
Chance rate	19%	31%	20%	31%	13%	24%
Observed/chance	2.4	2.3	2.1	2.2	4.2	3.1
ISEE 3 local electron temperature depression[b]						
Events	164/232	77/94	124/182	68/84	40/50	9/10
Magnetic cloud						
Events	41/566	24/191	35/401	22/148	6/165	2/43
Chance rate	1.4%	2.0%	1.5%	2.0%	1.3%	1.7%
Observed/chance	5.2	6.3	5.8	7.5	2.8 ± 0.5	2.7 ± 1.4
He abundance enhancement[c]						
Events	43/331	30/107	41/215	28/75	2/116	2/32
Chance rate	1.2%	2.8%	1.4%	3.0%	1.0%	2.1%
Observed/chance	10.8	10.0	13.6	12.4	1.8 ± 0.9	3.0 ± 1.5
Ion count rate depression >60 MeV/amu[d]						
IMP 8 Events	188/666	109/199	172/464	102/162	16/202	7/37
Helios 1 Events	180/680	83/176	143/436	72/118	37/244	11/58
Helios 2 Events	117/398	56/104	85/232	42/62	32/166	14/42
Neutron monitor decrease ≥4%						
Events	80/909	47/267	76/660	46/219	4/249	1/48
Chance rate	4.2%	5.5%	4.3%	5.6%	3.9%	5.0%
Observed/chance	2.1	3.2	2.7	3.8	0.4 ± 0.1	0.4 ± 0.4
Shock/sc within ~1.5 days before event						
Omni						
Events	164/909	96/267	155/659	94/219	9/249	2/48
Chance rate	13%	17%	14%	18%	12%	16%
Observed/chance	1.4	2.1	1.7	2.4	0.3 ± 0.05	0.3 ± 0.1
Helios 1						

Bidirectional ~1 MeV Ions

Bidirectional e heat flux

T_e depression

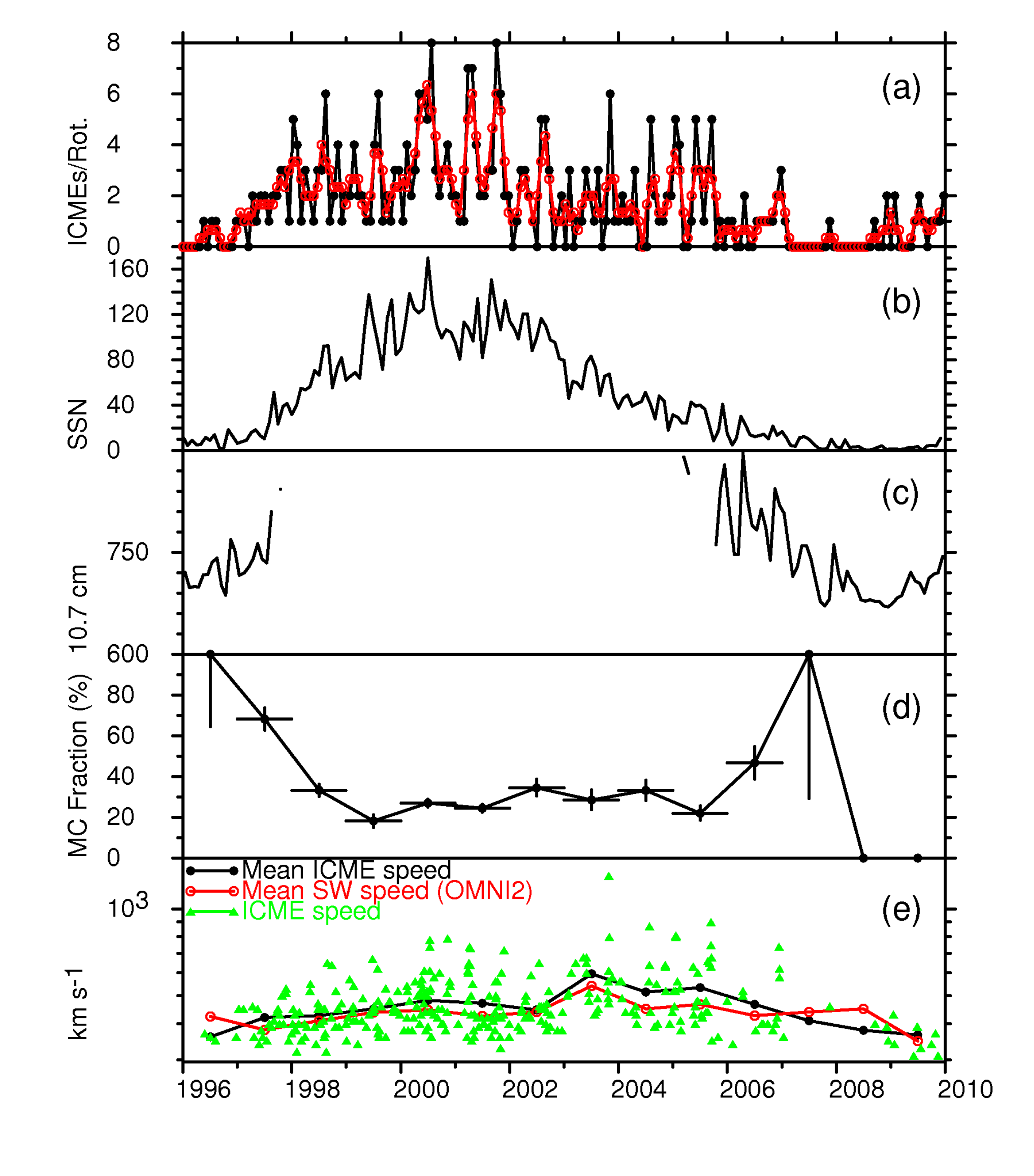
Magnetic Cloud

He enhancement

GCR decrease

Following IP shock?

ICME Properties 1996-2009



ICME rate/solar rotation

Sunspot number

10.7 cm flux

Fraction of magnetic clouds

Mean ICME and solar wind speeds, ICME speeds

Richardson and Cane, *Sol. Phys.*, 2010

Summary

- There are a plethora of ICME signatures resulting from processes at the Sun during CME formation and ejection and subsequent propagation through the solar wind.

- The individual signatures may or may not coexist. Not necessarily a “problem”, but a sign of interesting physics.

- Though there is an emphasis on magnetic clouds/flux ropes because they can be easily modeled in the solar wind and at the Sun, ICME-like material with multiple signatures may be found well beyond these structures.

- Heliospheric imaging and in-situ observations at multiple S/C may help to understand the origin of structures within ICMEs.

- What is the relationship of “typical” ICMEs with smaller structures with some ICME-like signatures?