Relating the *Sub-Parker Spiral Structure of the Heliospheric Magnetic Field* to the *Dynamic Sources of Solar Wind*

N. A. Schwadron

Southwest Research Institute

Also, Boston University

Is there a physical link between heliospheric field structure and solar wind sources?

- *Organization of solar wind*: steady fast wind, unsteady slow wind
- *Heliospheric Field Structure:* departures from Parker spiral, particularly in rarefactions
- *Coronal Hole Boundaries*: Changes in Solar Wind Source, Composition, and Field Structure
- Energetic Particles also possibly linked through topology

Possible Link through Footpoint Motion

- Footpoint motion (Fisk, JGR, 1996)

  1. High Lat Coronal Holes rotate at *Equatorial Rotation Rate* but the photosphere rotates more slowly (differential rotation)

  2. Asymmetry of High Lat Coronal Holes

  3. Super-radial expansion

  1 => Causes footpoint motion through coronal holes

  ,2&3 => Footpoint motion on pressure balance surface in longitude **& latitude**

- The Difference between Fast & Slow Solar Wind (Fisk et al., 1999; Schwadron et al., 1999)

  2 => Motion of footpoints through coronal hole boundaries

  => Interchange reconnection between open field lines and large loops allows open field footpoints to circulate beyond coronal hole

  => Consistent with source region of slow wind

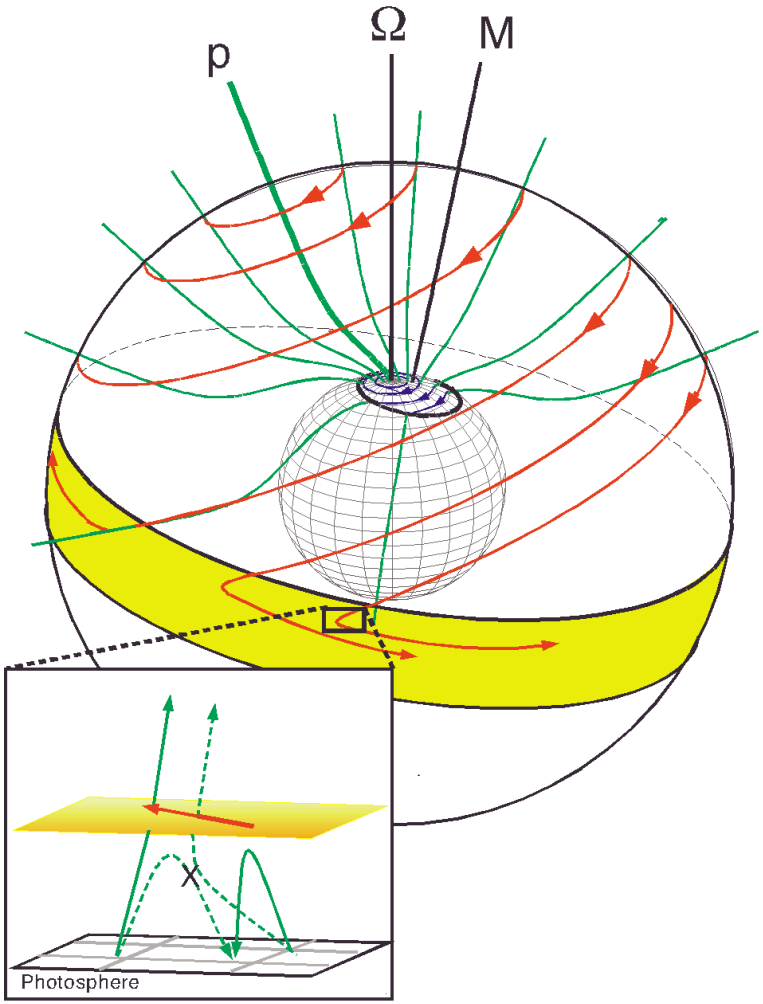
- Media Diffusion (Fisk and Schwadron, 2001)

  - Footpoint motion is fundamentally a combination of systematic (differential motion) and random motions (interchange reconnection) described by a non-standard diffusion equation (media diffusion):

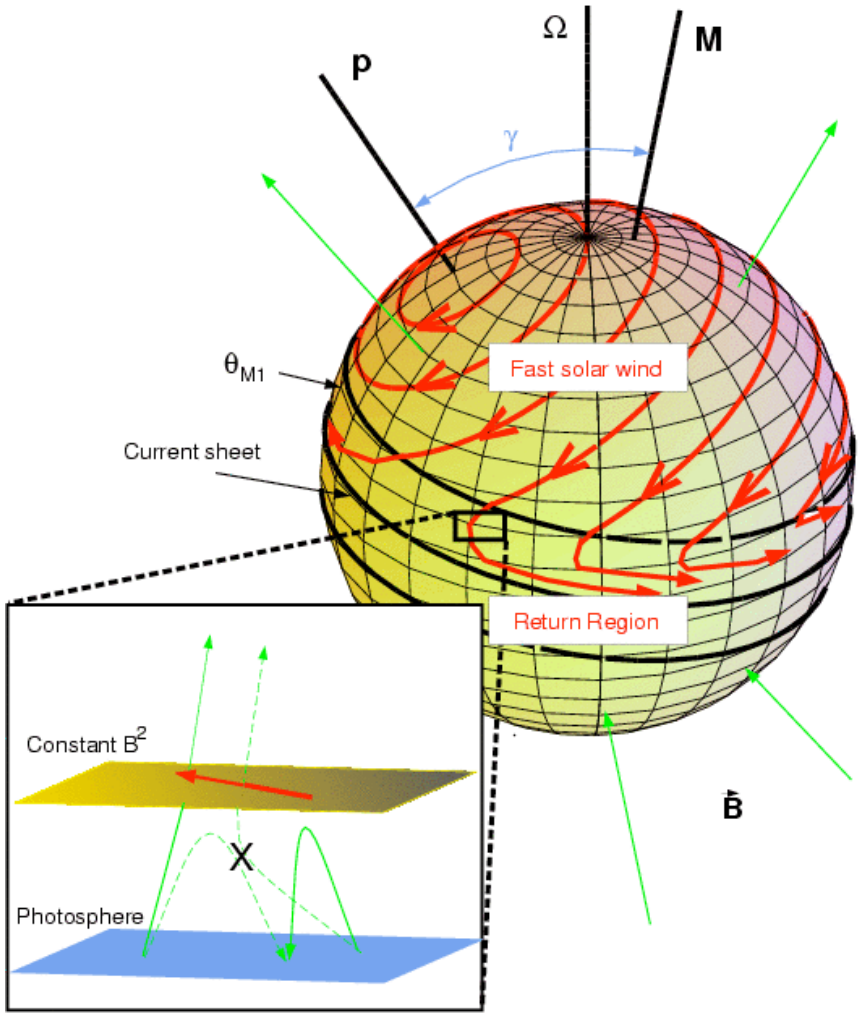
$$\frac{\partial |B_0|}{\partial t} + \nabla \bullet \left(\vec{u}_d |B_0| \right) - \nabla^2 \left(\kappa |B_0| \right) = 0 \qquad \kappa \approx \left\langle \frac{\delta h^2}{2 \delta t} \right\rangle$$

Principles of Footpoint Motion

- Footpoint motion
- The Difference between Fast & Slow Solar Wind
- Interchange Reconnection

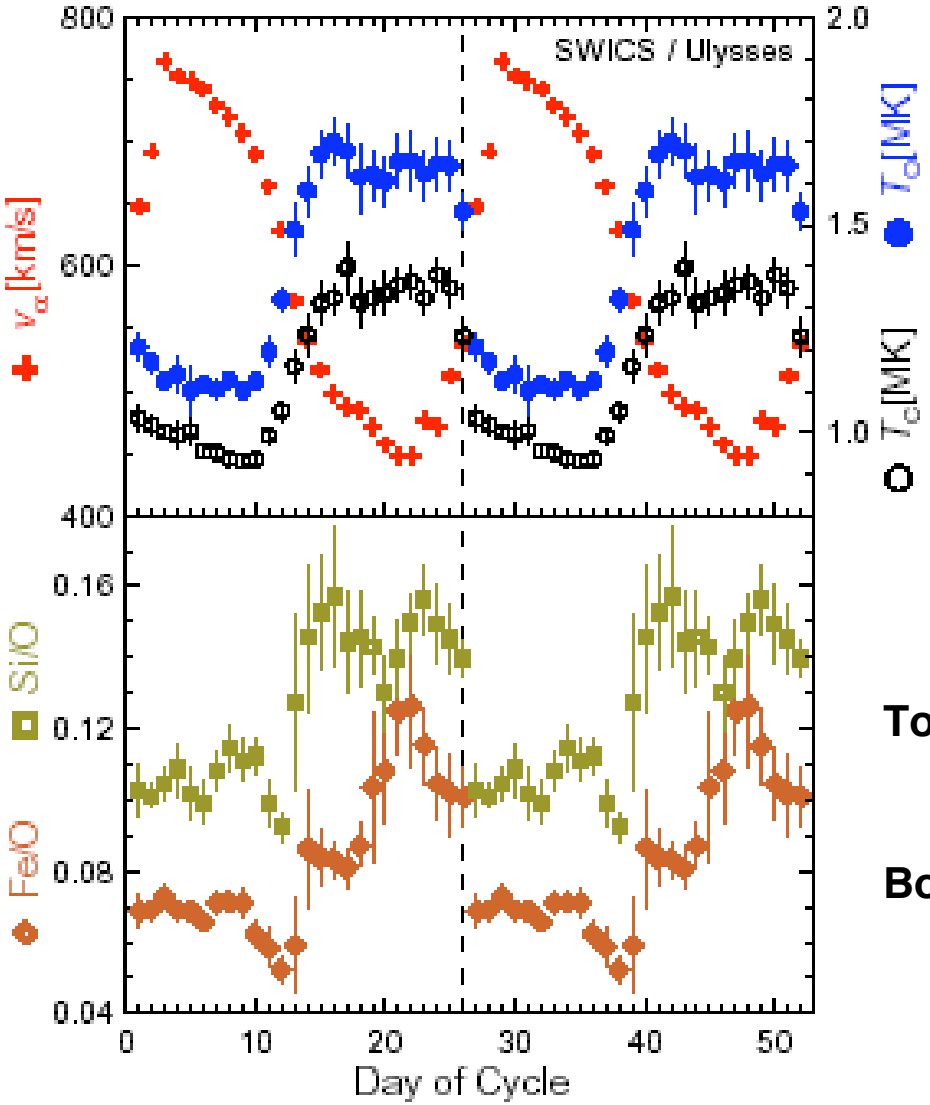


Schwadron et al., ApJ, 1999



Fisk et al., ApJ, 1999

Transition from Fast to Slow Wind Observed in CIRs



- Fundamental Composition Distinction between sources of slow and fast wind
  - Charge-state, 1.5-2.5 Rs
  - Elemental, beneath transition region!

Top Panel: Solar wind speed (red data points), and oxygen (blue points) and carbon (black points) in a co-rotating interaction region.

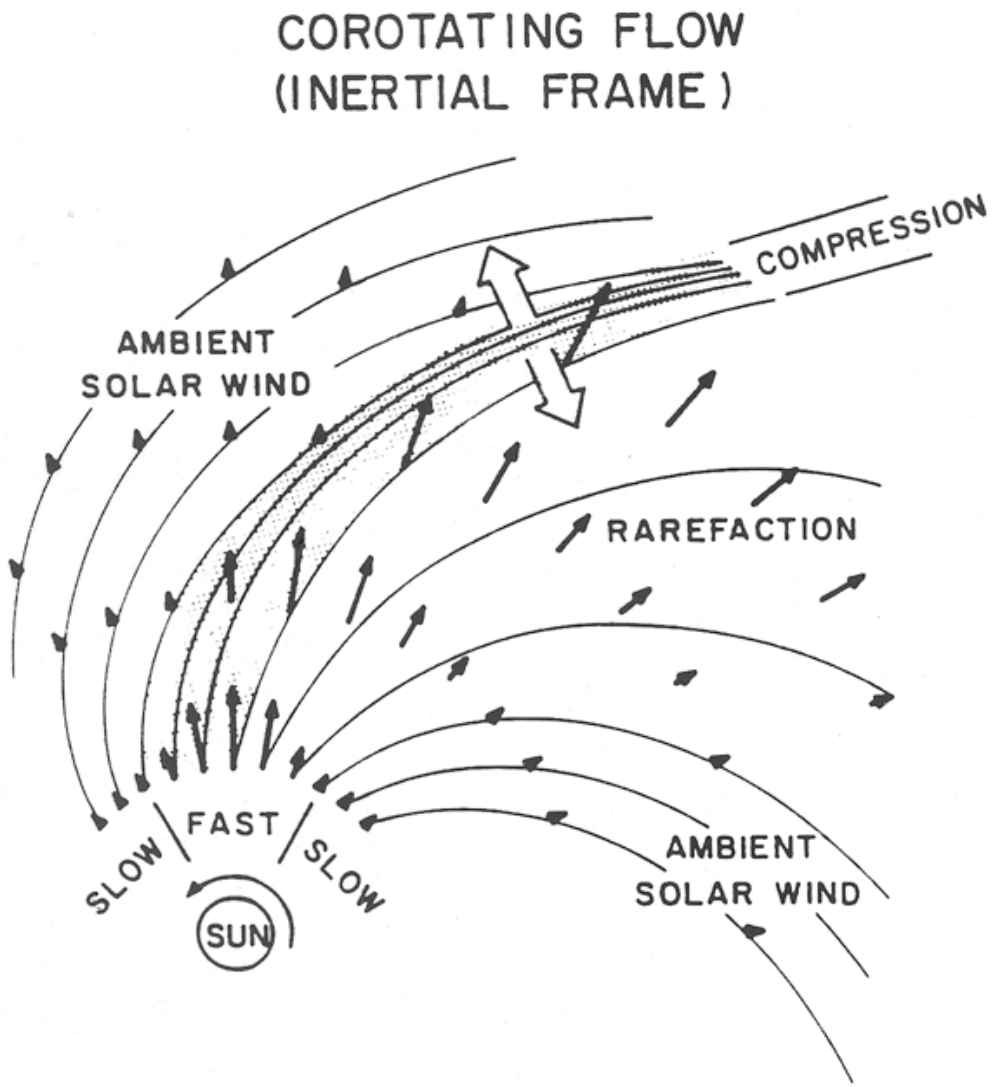
Bottom Panel: Elemental abundances of several low First Ionization Potential (low-FIP) elements Fe and Si relative to O. [Figure from **Geiss et al., 1995; von Steiger et al., 2000].**

Loop Sources of Solar Wind

Source Region	T [K]	FIP Bias	Lifetime	Length	Height
1. QS, CH	0.03-0.7 MK	1.5-2	100-500s	10-20 arcsec	7-14 Mm
2. QS	0.7-1.2 MK				<20 Mm
3. QS	1.2-1.6 MK	3-4	1-2 days	10-100 arcsec	150-250 Mm (grav. Sett)
4. CH	0.7-1.1 MK (0.8±0.1)MK, 35 Mm (1.0±0.1)MK, 70-140 Mm	1-1.5			70-200 Mm
		Feldman et al, JGR, 2005 (and ref therein)			
Fast Wind	**C6+/5+: 0.8-1.0 MK** **O7+/6+: 1.0-1.2 MK**	**1-2**			
Slow Wind (not one state)	**C6+/5+: 1.2-1.4 MK** **O7+/6+: 1.5-1.7 MK**	**3-4**			
		von Steiger et al., JGR, 2000 (and ref therein)			

- Similarity between composition signatures from remote loop observations and *in situ* solar wind observations
- Does all solar wind emanate from loops? ***Intrinsically dynamic sources!***

Structure of the Co-rotating Interaction Region (CIR)



Pizzo, 1978

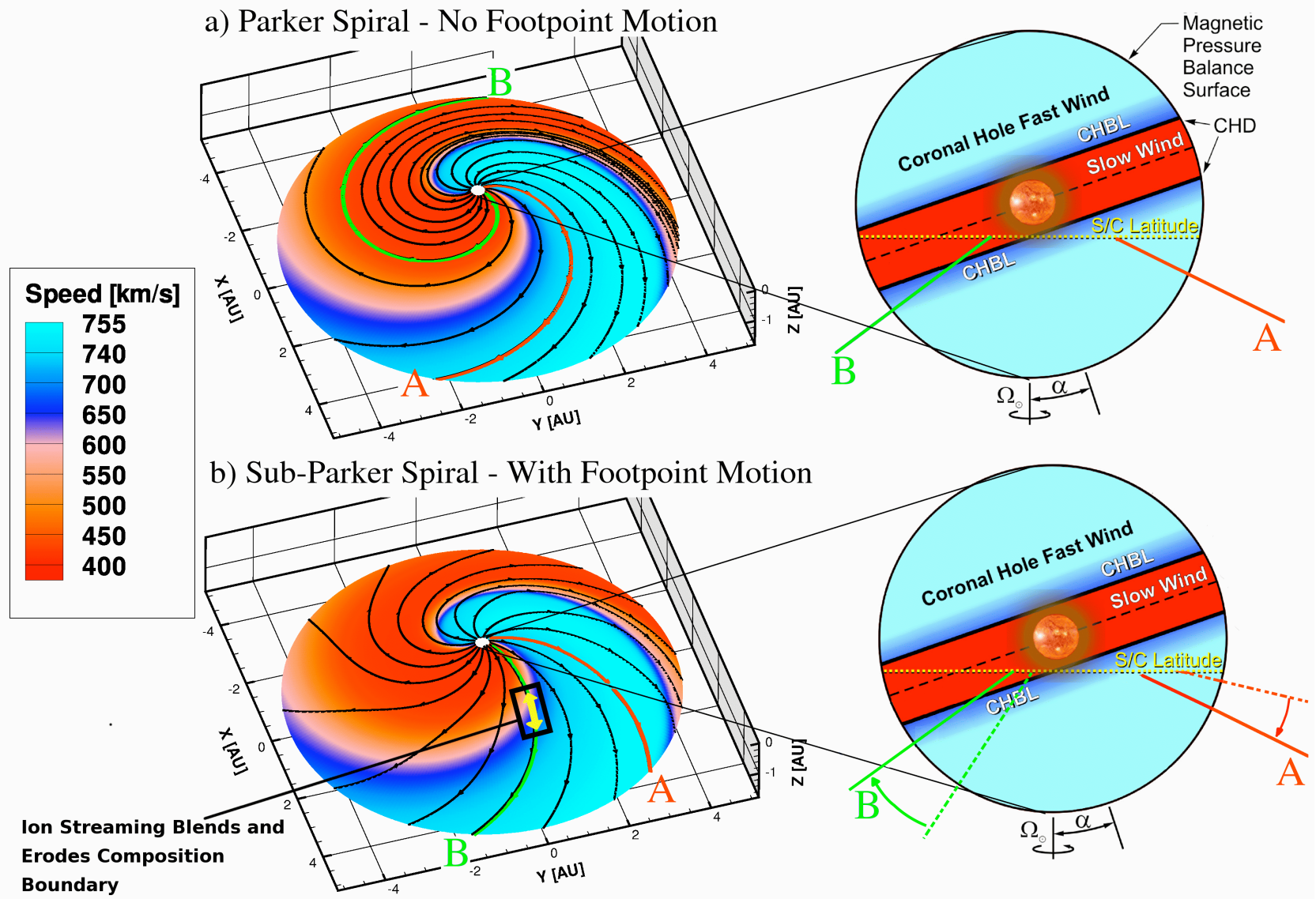
The Link between Field Structure and Solar Wind Sources

- Fast solar wind from coronal holes:
  - Footpoint motion driven by differential motion
  - Resembles photospheric abundances
  - Cool freezing-in temperatures
  - Small source structures within the supergranular network
- Slow wind from beyond coronal holes
  - Footpoint motion through interchange reconnection with large loops
  - Strong Low-FIP enhancements
  - Larger, less-steady sources from large loops

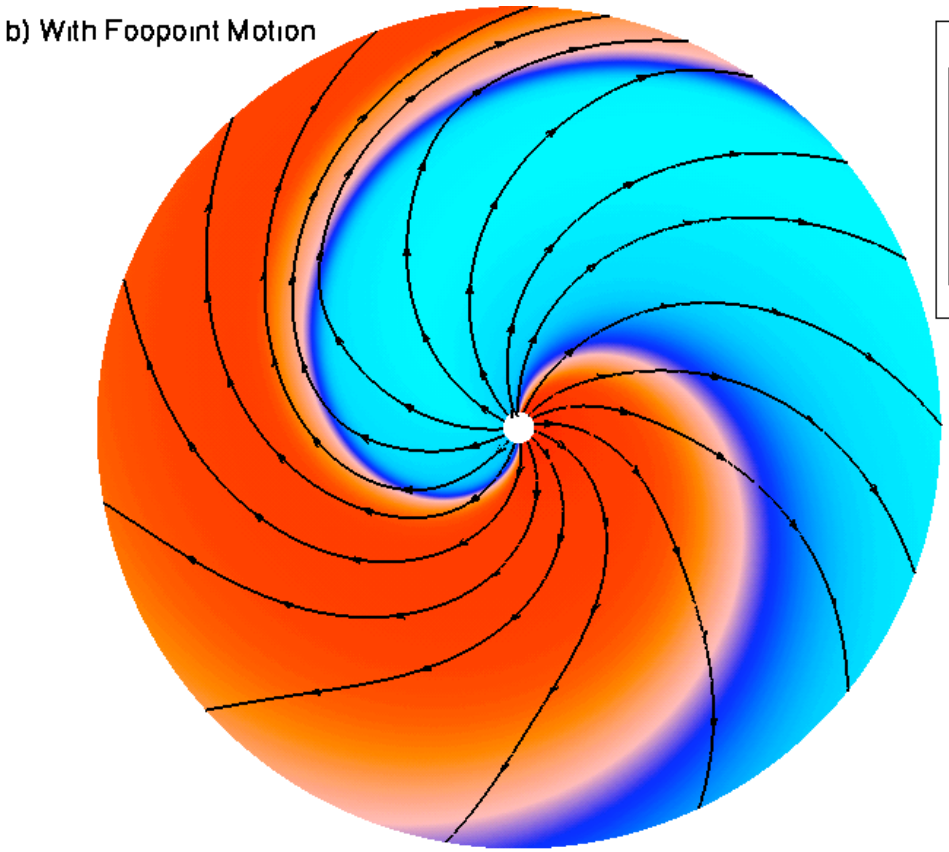
Evidence that the Link is Valid

- Sub-parker structure of the heliospheric magnetic field caused by footpoint motion at the Sun
- Composition structure of coronal hole boundaries

Parker/Sub-Parker Spirals

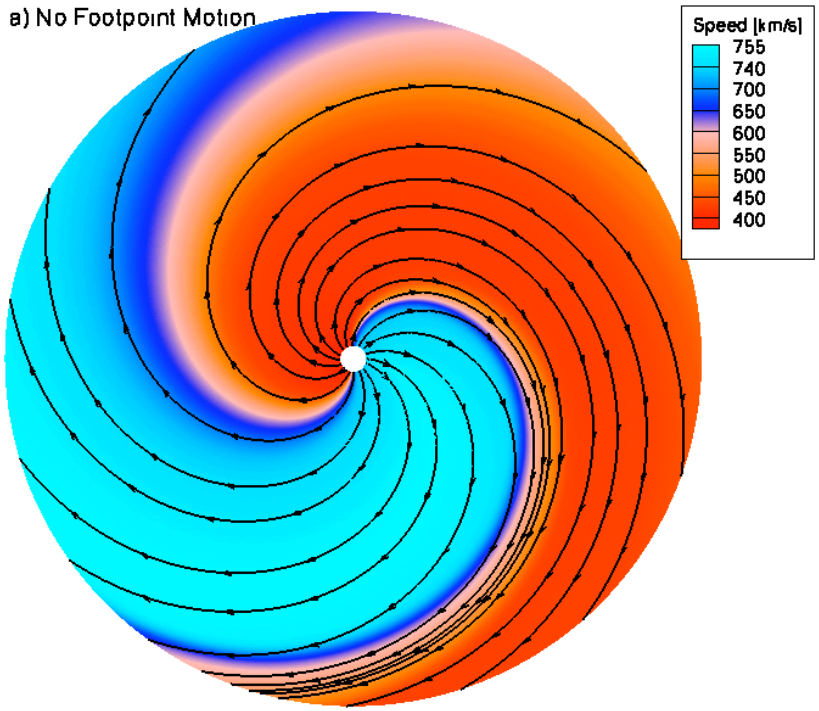


Schwadron et al., JGR, 2005

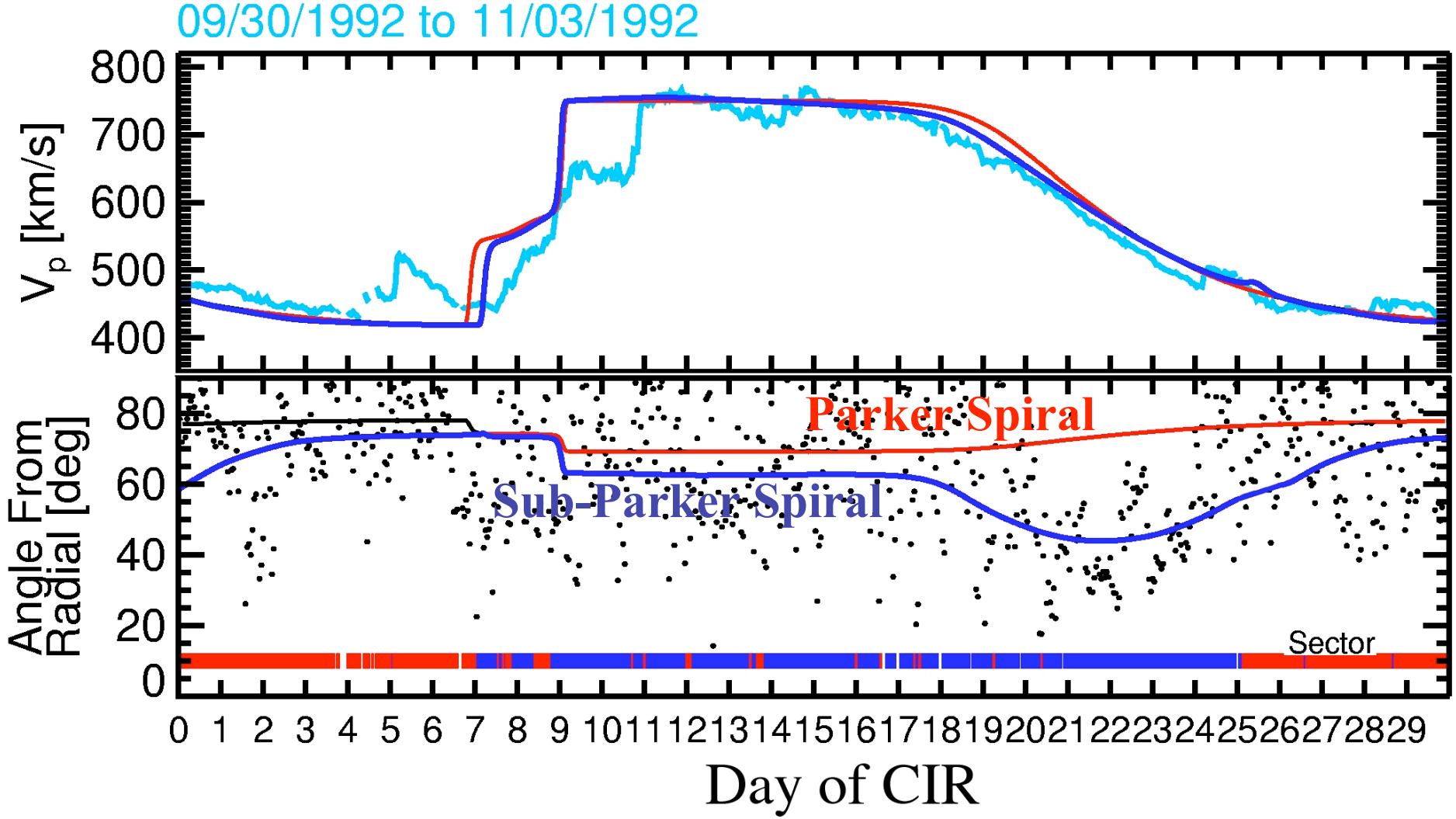


Sub-Parker Spiral

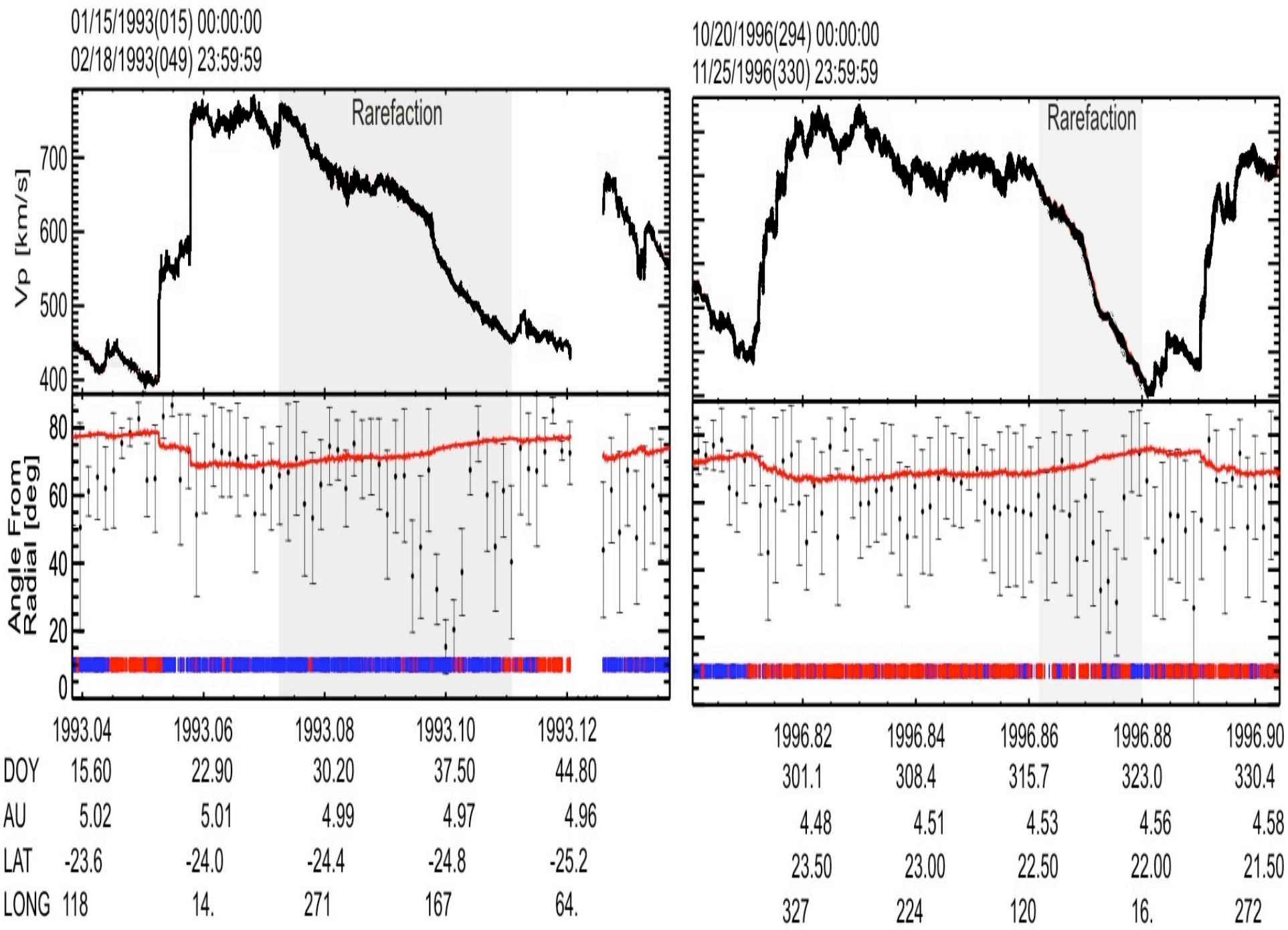
Parker Spiral



Sub-Parker Spiral Observed



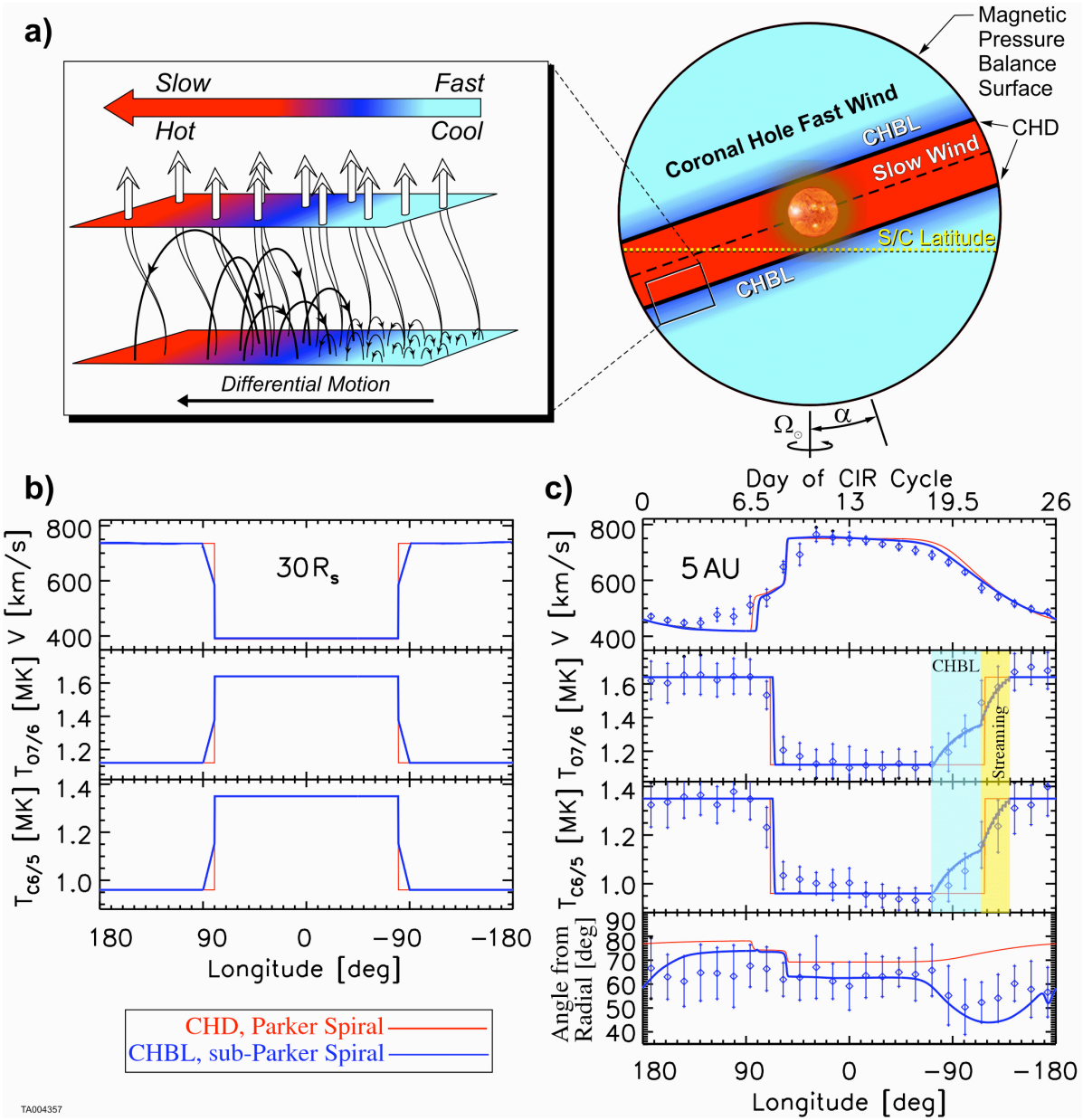
Schwadron et al., GRL 2005


01/15/1993(015) 00:00:00
02/18/1993(049) 23:59:59
Rarefaction
Vp [km/s]
700
600
500
400
Angle From Radial [deg]
80
60
40
20
0
1993.04
1993.06
1993.08
1993.10
1993.12
DOY 15.60 22.90 30.20 37.50 44.80
AU 5.02 5.01 4.99 4.97 4.96
LAT -23.6 -24.0 -24.4 -24.8 -25.2
LONG 118 14. 271 167 64.
10/20/1996(294) 00:00:00
11/25/1996(330) 23:59:59
Rarefaction
1996.82
1996.84
1996.86
1996.88
1996.90
301.1 308.4 315.7 323.0 330.4
4.48 4.51 4.53 4.56 4.58
23.50 23.00 22.50 22.00 21.50
327 224 120 16. 272

Sub-Parker Spiral Summary

- Sub-Parker spiral caused by footpoint motion on the Sun through coronal hole boundary
- Field stretched and less transverse in rarefaction regions of CIRs
  - Good agreement with MHD model results
- Generality of sub-Parker spiral
  - Greater than 90% (17/18) of CIR rarefactions observed by Ulysses from 1992-1997 had the sub-Parker spiral
- Non-ideal behavior due to Alfven waves and possible interchange reconnection

Structure of Coronal Hole Boundaries



- Coronal Hole Boundary Layer (CHBL)
  - Speed: 600->740 km/s
  - $T_{O7/6}$: 1.4-> 1.1 MK
  - $T_{C6/5}$: 1.16->0.96 MK

$$\Delta\varphi'_{CHBL} \sim 10°$$

$$\Delta\varphi_{CHBL} \sim 4°$$ W/out expansion

- Coronal Hole Discontinuity (CHD)
  - Speed: ~350->600 km/s
  - $T_{O7/6}$: 1.7-> 1.4 MK
  - $T_{C6/5}$: 1.4->1.16 MK

Schwadron et al.,JGR, 2005

Coronal Hole Boundaries

- CHBL: Over the escape time, footpoints are moved differentially through the coronal hole boundary

$$\Delta\varphi_{CHBL} \sim \omega\tau_{esc} \sim 4^\circ$$

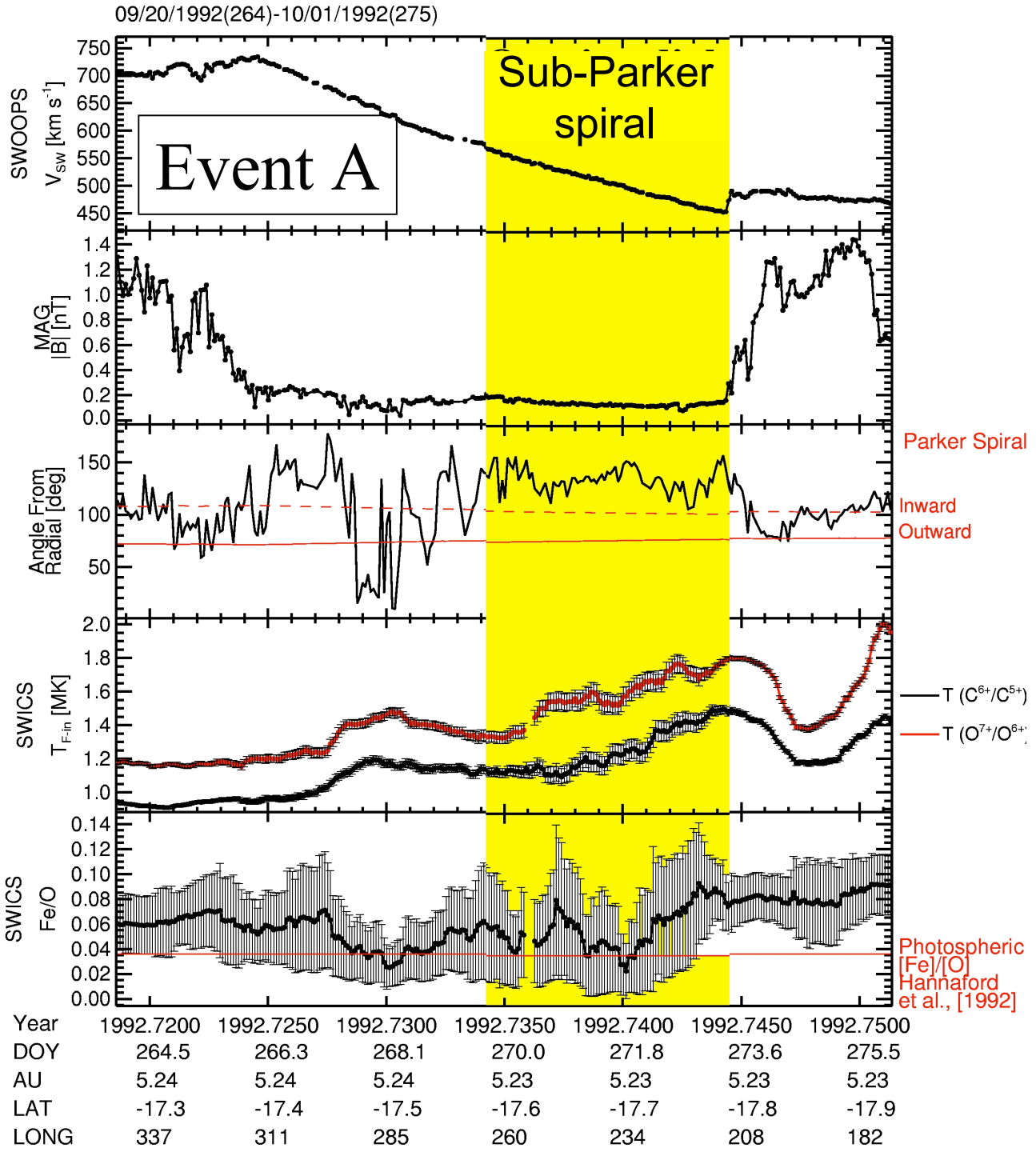
$$(\omega \sim 4^\circ/day; \quad \tau_{esc} \sim day)$$

- CHD: Transition into large-loop sources undergoing interchange reconnection (plasma released ballistically from loop tops)

- *Stronger expansion on edge on coronal holes?*
- *Transition in loop sizes?*

CHD:

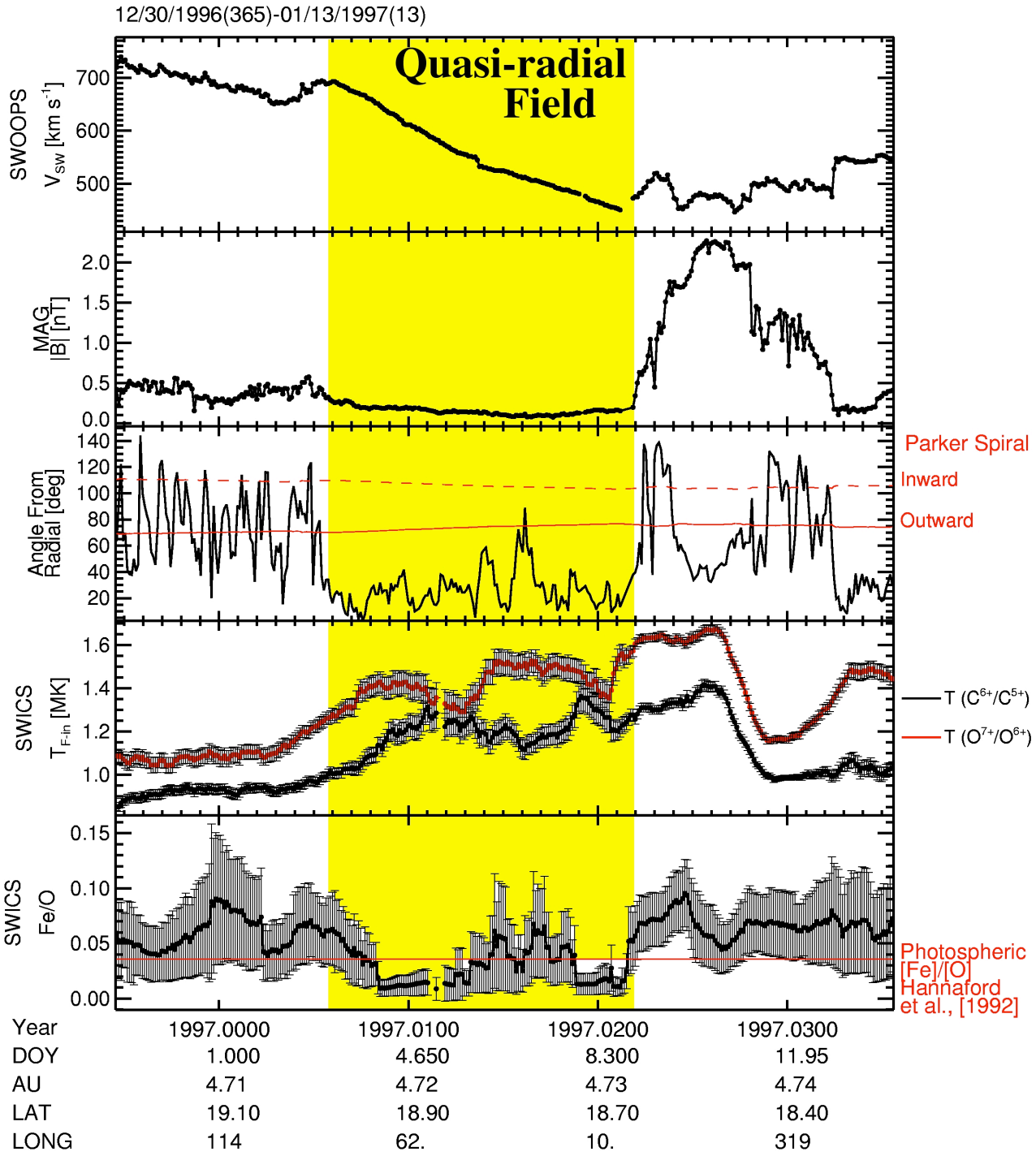
Onset of Interchange reconnection with large loops



CHD:

Onset of Interchange reconnection with large loops

Remarkably large, nearly radial event first identified by *Jones et al., GRL, 1998.*



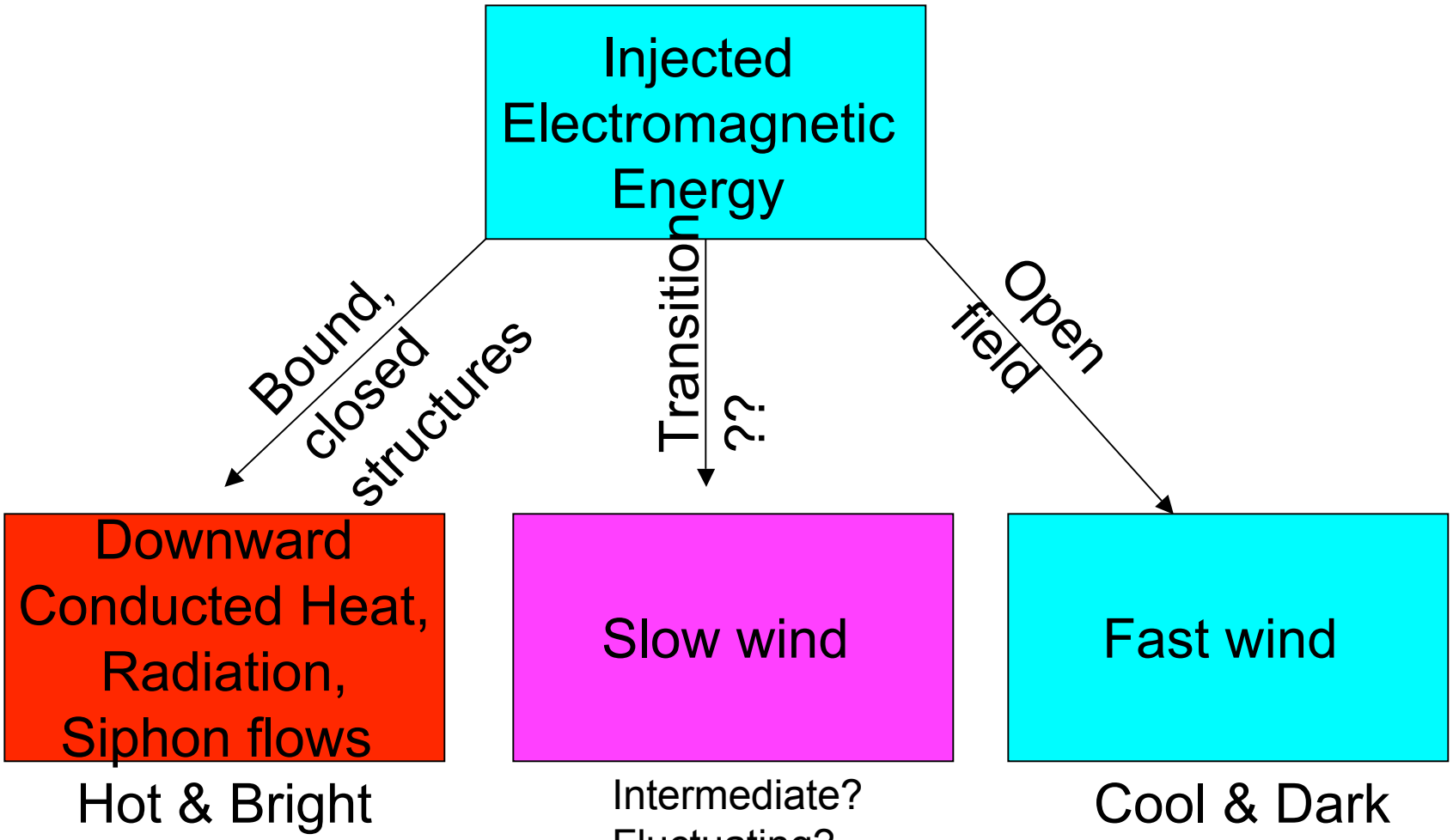
Interchange Reconnection with Large Loops just beyond Coronal Hole Boundaries

- Heavy ion depletions suggest gravitational loss
  - Consistent with recent results from ACE [Ipavich et al, 2005]
- Loops > 80 Mm, ~ 1 scale-height in 1 MK plasma
- Reconnection with legs of helmet streamer?
- Reconnection with large loops well beyond coronal hole boundary?

Summary

- ***Heliospheric field structure and solar wind sources intrinsically linked through footpoint motion at the Sun***
- ***Compelling evidence that the Link is valid:***
  - Sub-Parker spiral indicates field line connection between fast and slow wind, footpoint motion through coronal hole boundaries
  - Coronal Hole Boundaries show two-part structure
    - Coronal Hole Boundary Layer (CHBL), wide smooth transition
    - Coronal Hole Discontinuity, onset into interchange reconnection with large loops

Paths for Deposited Coronal Energy

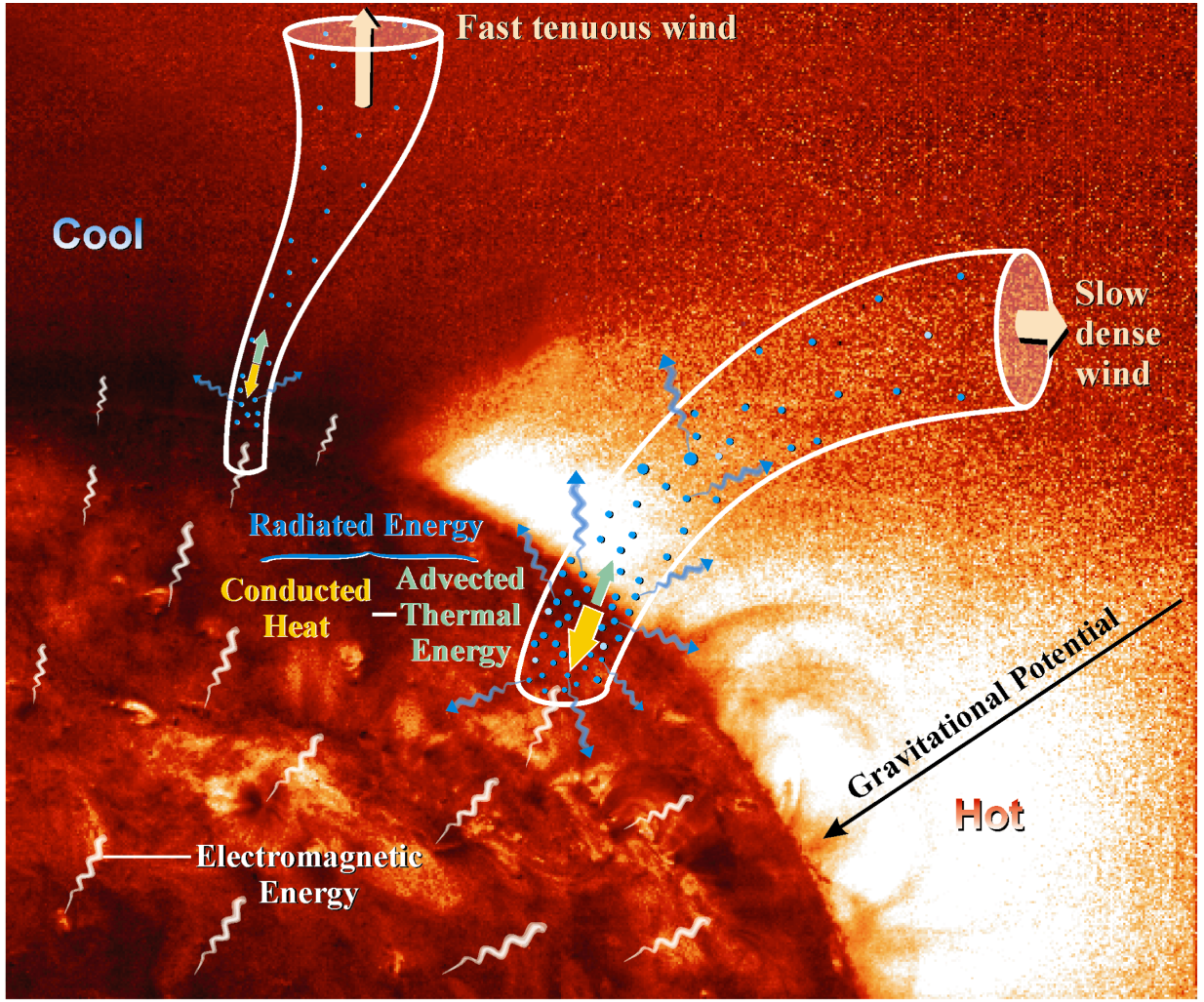


$$\frac{mu_f^2}{2} = \frac{c}{4\pi}\frac{\int d\mathbf{S}_0 \cdot \langle \mathbf{E} \times \mathbf{B} \rangle_0}{\delta \dot{N}} - \frac{\int_{r_0}^{r_1} dV \langle \dot{E}_{\mathrm{Rad}} \rangle}{\delta \dot{N}} - \frac{GM_s m}{R_s}$$

Paths of deposited Energy

- Solar Wind Scaling Law
- Electron heat conduction and radiative losses

Fast wind
Cool, Dark
Slow wind
Warm,Brighter
Radiative Loss
Hot, Bright

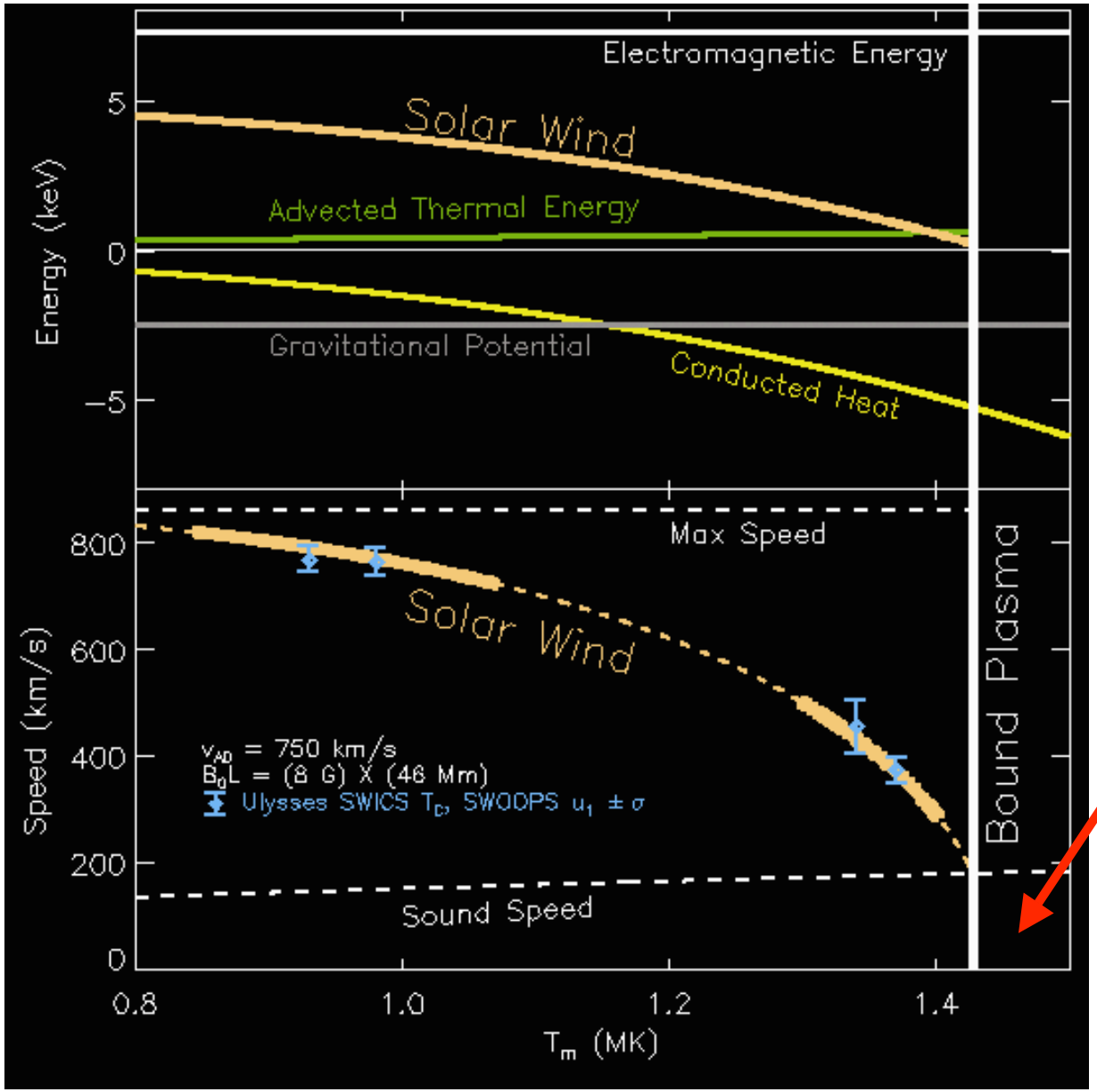


Schwadron and McComas, ApJ, 2003

Energy	Electro-magnetic Energy	−	(Conducted Heat	−	Advected Thermal Energy)	− Gravitational Potential	= Wind Energy
Scaling Law	$m\bar{v}_{a0}^2$	−	$\left(C_0 \frac{K_0 T_m^{7/2}}{f_0 L} \right.$	−	$\left. C_1 k T_m \right)$	− $\frac{GM_S m}{R_S}$	= $\frac{mu_f^2}{2}$

TA003805

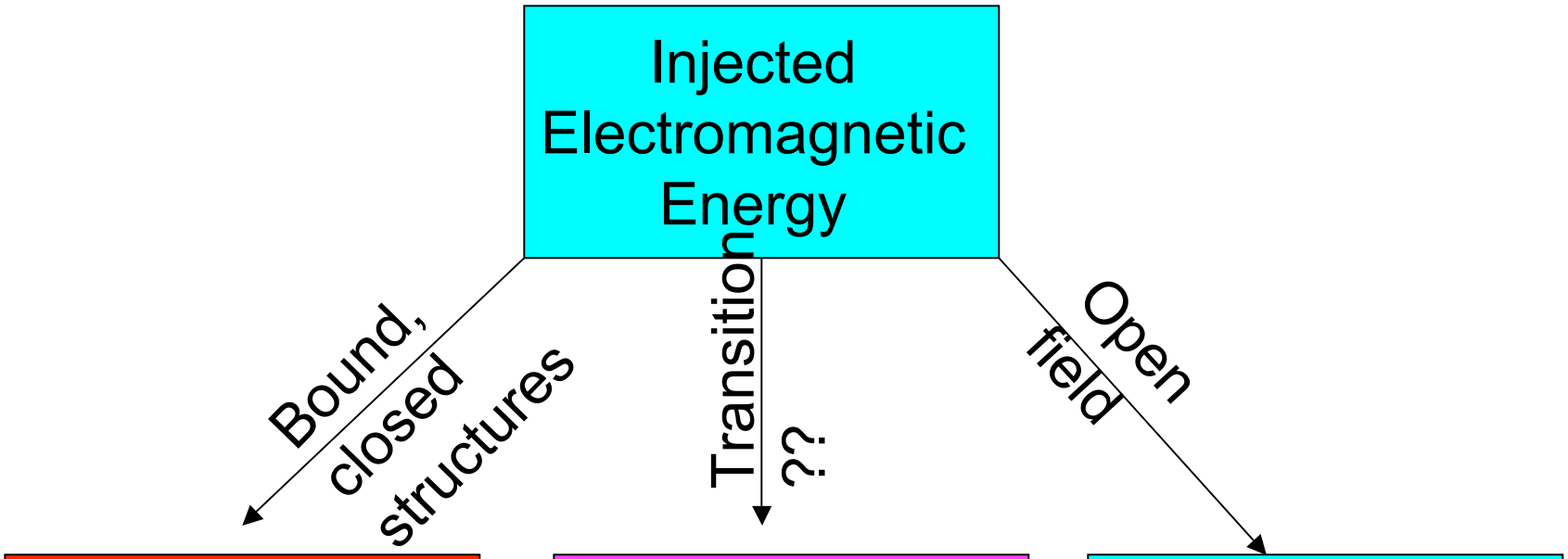
A Constant Energy Source



Schwadron and McComas, ApJ, 2003

The suprathermal seed population

Paths for Deposited Coronal Energy



Hot & Bright

Strong field fluct
Stronger FIP
Strong suprathermal tails

Intermediate?
Fluctuating?

Cool & Dark

Weak field fluct
Weak FIP
Little suprathermal tails