The Solar Wind and Heliosphere

Bob Forsyth - 23rd October 2017

TOPICS

Origin of the solar wind
Formation of the heliosphere
Outer boundaries of the heliosphere
Heliospheric spacecraft
The heliospheric magnetic field
Fast and slow solar wind flows
Evolution with the solar cycle
Corotating Interaction Regions
Coronal Mass Ejections


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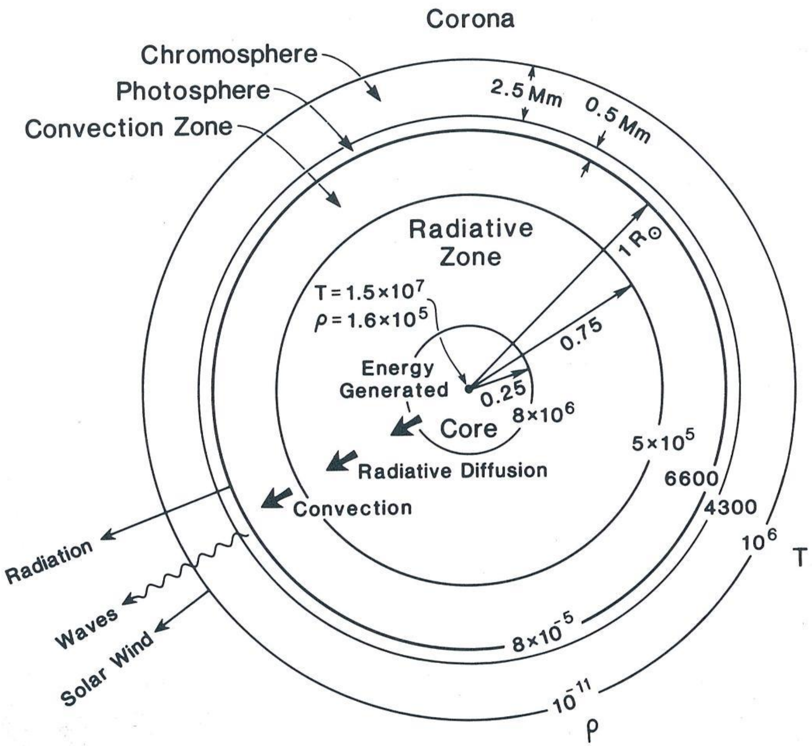
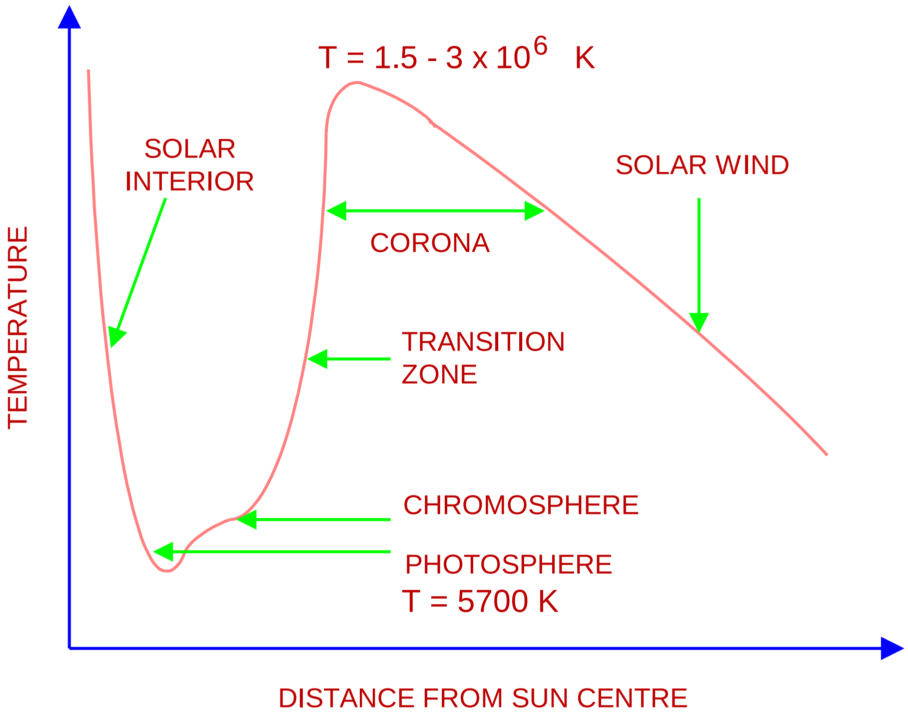
Overview of solar interior and atmosphere





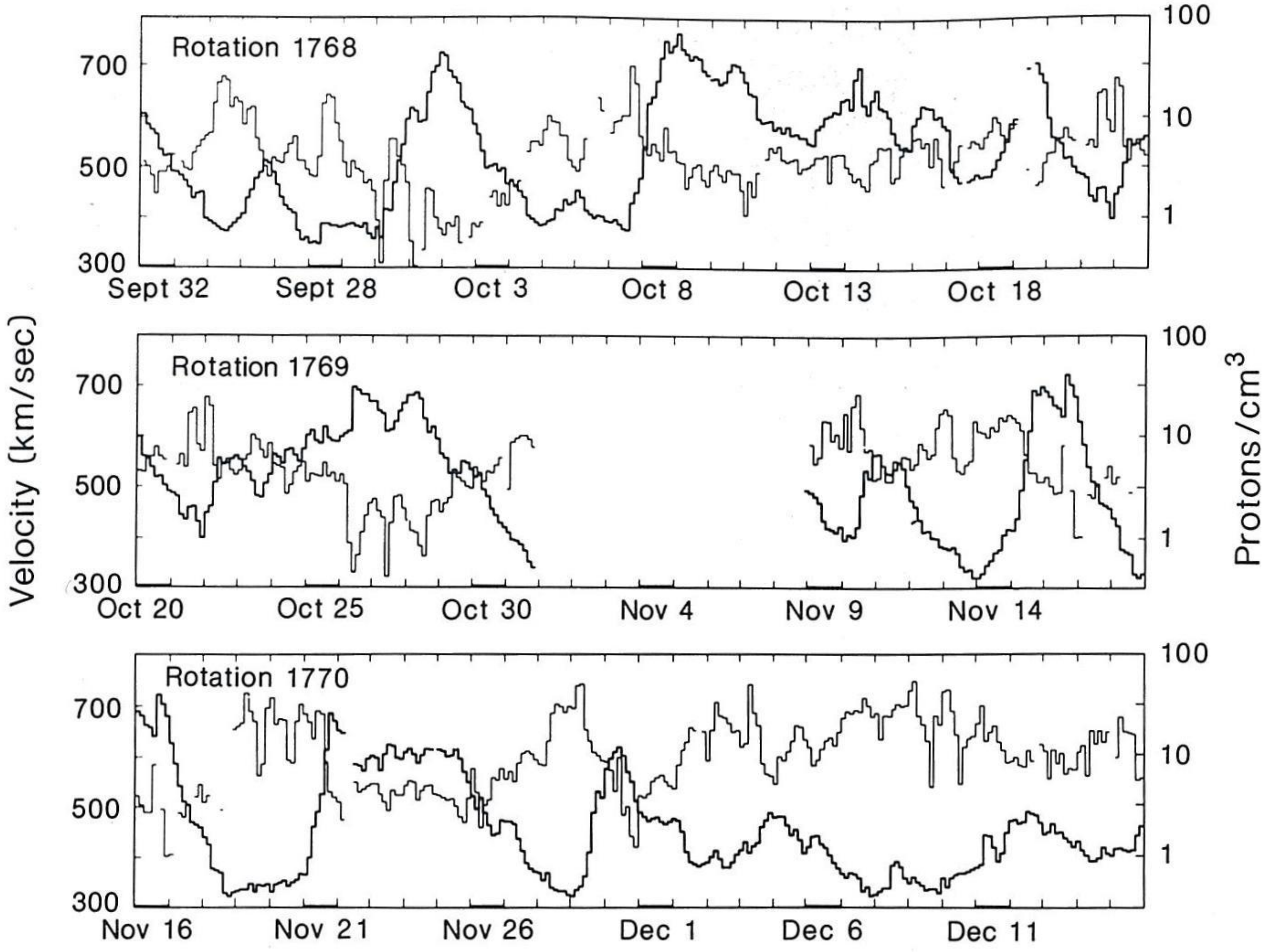
Priest (1995)

The solar wind

- The solar wind, consisting of ionised coronal plasma, flows supersonically and radially outward from the Sun due to the large pressure difference between the hot solar corona and the interstellar medium. The solar wind is a collisionless plasma.

Property at 1 AU	
Speed (v)	~400 km/s
Number density (n)	~10 cm^{-3}
Flux (nv)	~3×10^{8} cm^{-2} s^{-1}
Magnetic field (Br)	~3 nT
Proton temperature (Tp)	~4×10^{4} K
Electron temperature(Te)	~1.3×10^{5} K (>Tp)
Composition (He/H)	~1 – 30%
+ trace heavier elements	

Early solar wind observations from Mariner 2 in 1962



Hundhausen (1995)

Parker model of the solar wind

- Parker(1958) was the first to propose a model of the solar wind assuming a steady flow of plasma independent of time, as opposed to a static corona.
- He began from the mass and momentum conservation equations, taking time derivatives as zero since considering a steady flow…

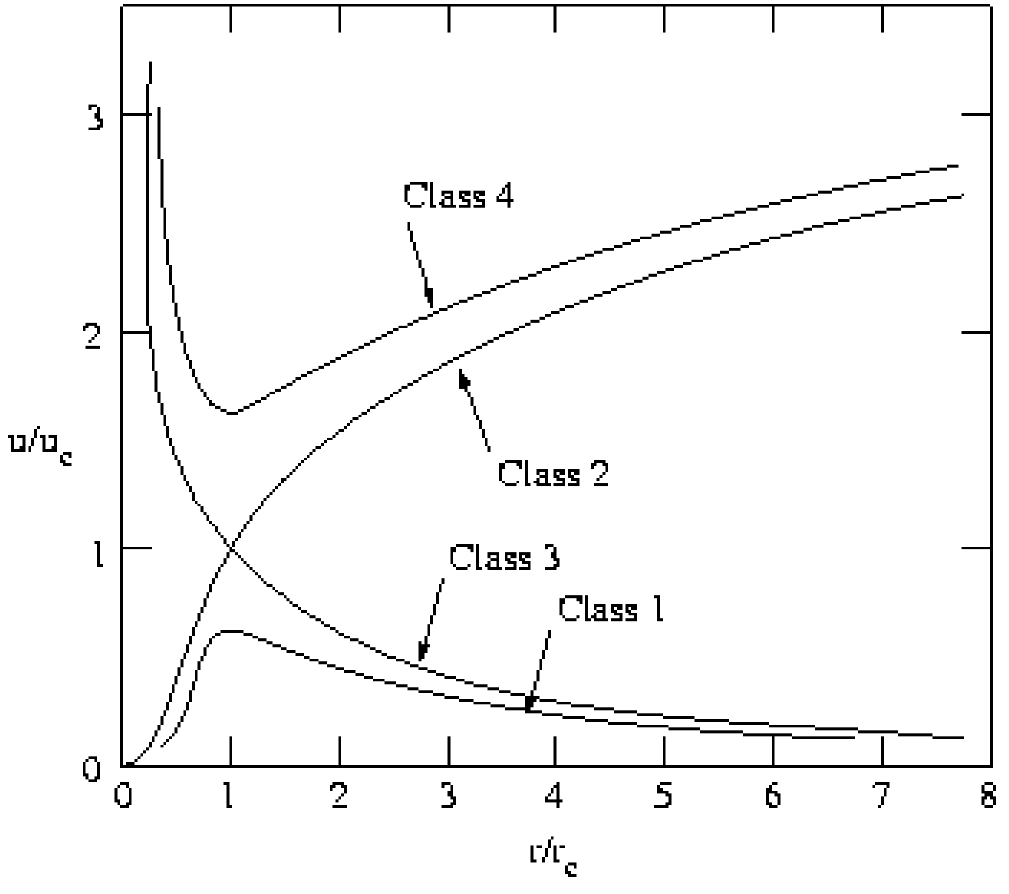
$$\nabla.\rho\mathbf{u} = 0$$

$$\rho\mathbf{u}.\nabla\mathbf{u} = -\nabla p + \mathbf{j}\times\mathbf{B} + \rho\mathbf{F}_g$$

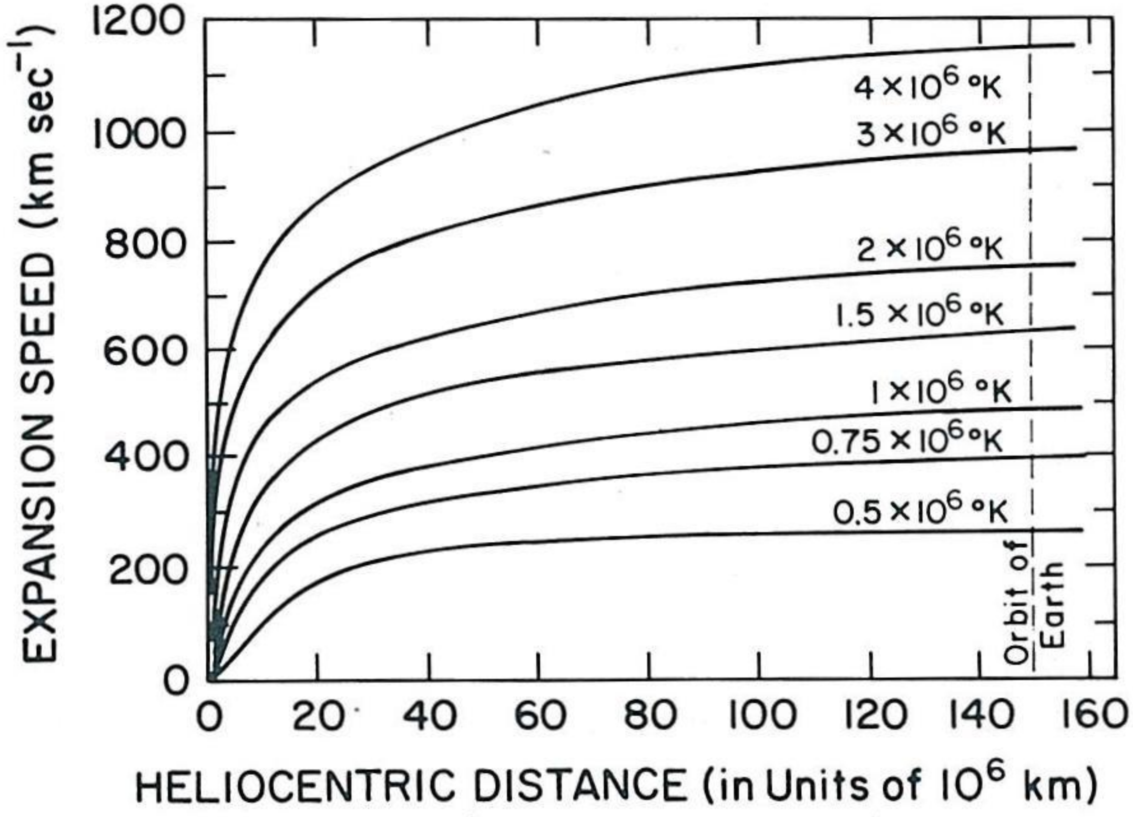
- Assuming isothermal and B=0 he found a solution of the form…

$$\left(u^2 - \frac{2k_B T}{m}\right)\frac{1}{u}\frac{du}{dr} = \frac{4k_B T}{mr} - \frac{GM_S}{r^2}$$

Possible solutions of the Parker solar wind equation

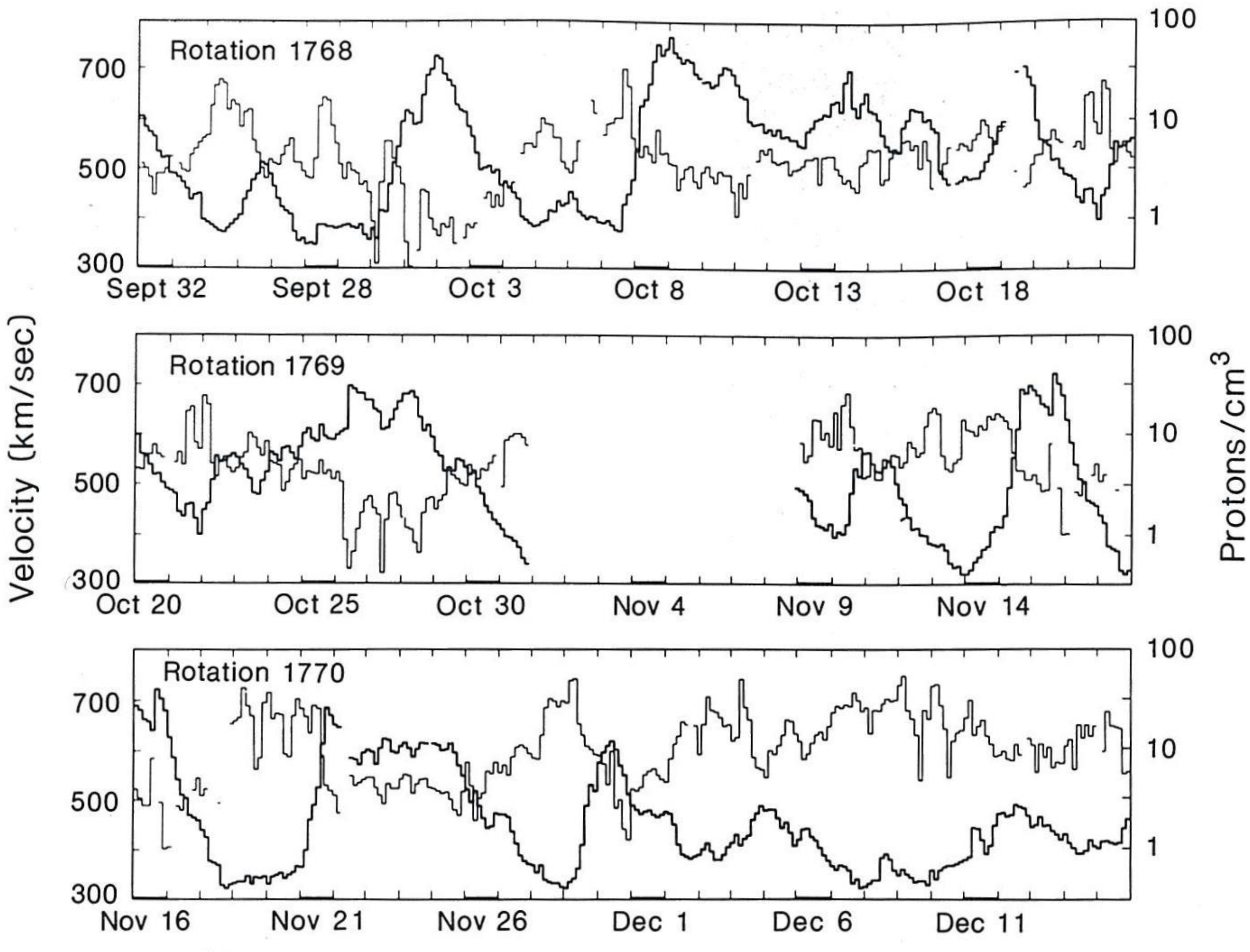


Parker solar wind solutions for a range of temperatures



Parker (1958)

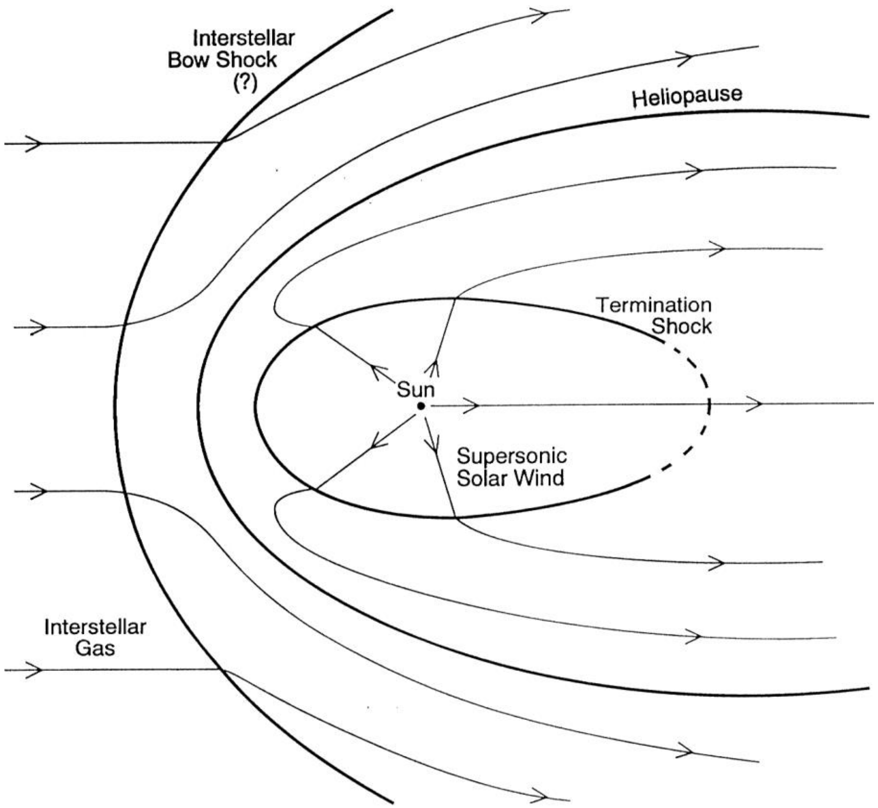
Early solar wind observations from Mariner 2 in 1962



Hundhausen (1995)

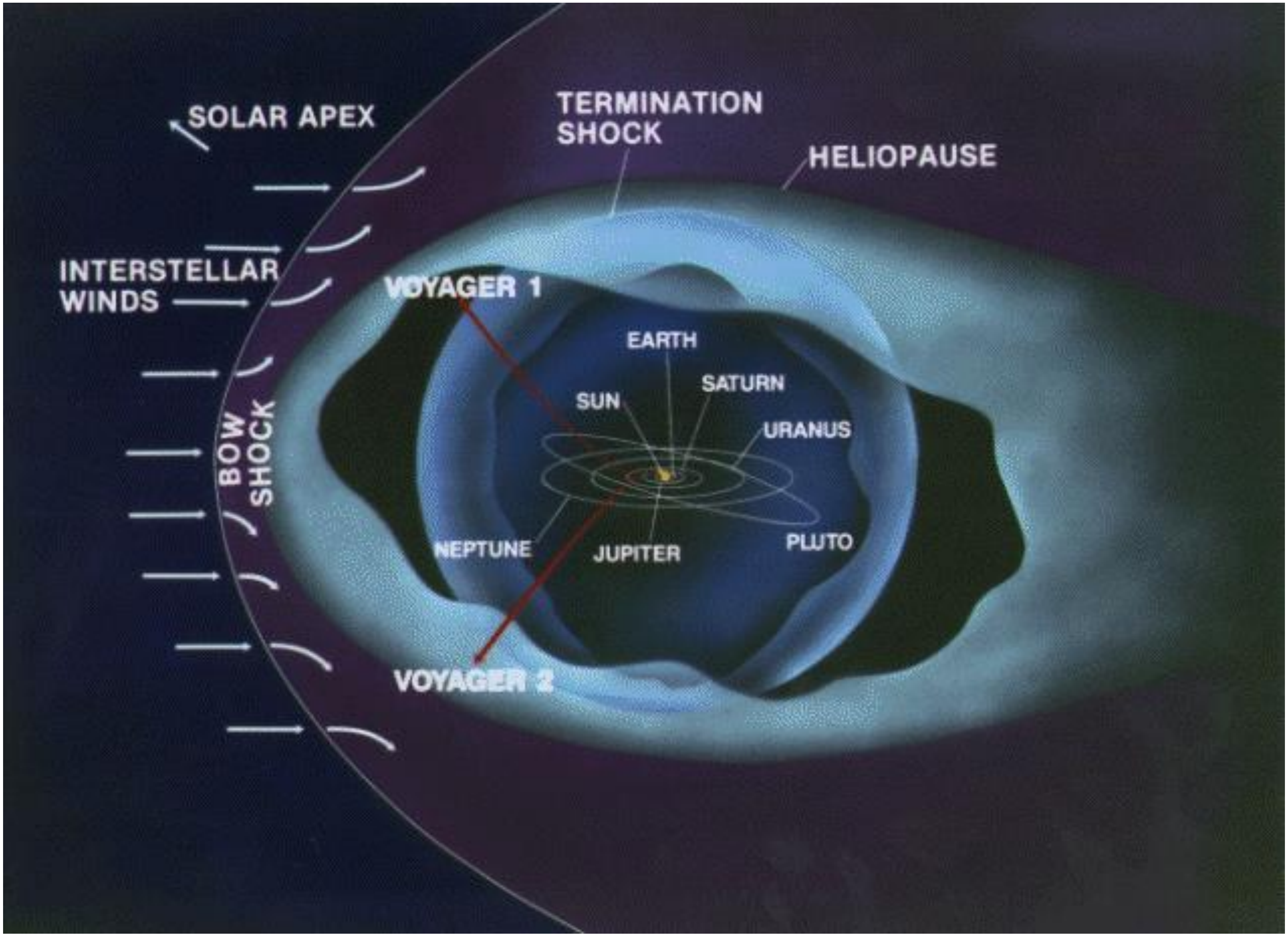
The Heliosphere

- The heliosphere is the volume of space, enclosed within the interstellar medium, formed by, and which contains, the outflowing solar wind and the Sun's magnetic field.
- The size of the heliosphere (greater than 100 AU) is determined by a balance between the dynamic pressure of the solar wind and the pressure of the interstellar medium.



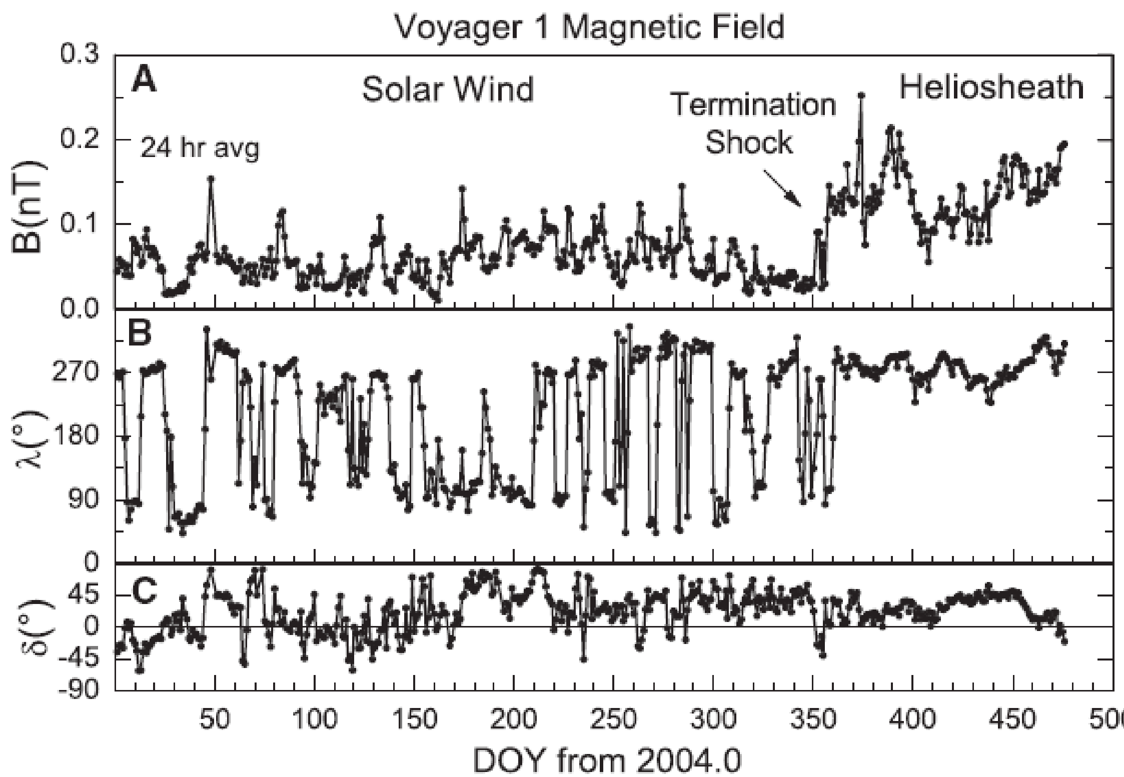
Outer boundaries of the heliosphere

- The boundary between the solar wind plasma and interstellar plasma is known as the ‘heliopause’.
- Because the solar wind flow is supersonic it cannot ‘sense’ that it is approaching the heliopause. Thus a standing shock wave, the ‘termination shock’, must form at some distance inside the heliopause so that the flow is slowed to subsonic speeds.
- The solar wind plasma can then be deflected in the region between the termination shock and the heliopause to flow down the ‘heliotail’.
- Due to the motion of the heliosphere through the interstellar medium, the interstellar plasma is deflected to flow round the outside of the heliopause.
- Depending on the speed of this motion, a bow shock may form in the interstellar medium upstream of the heliopause.



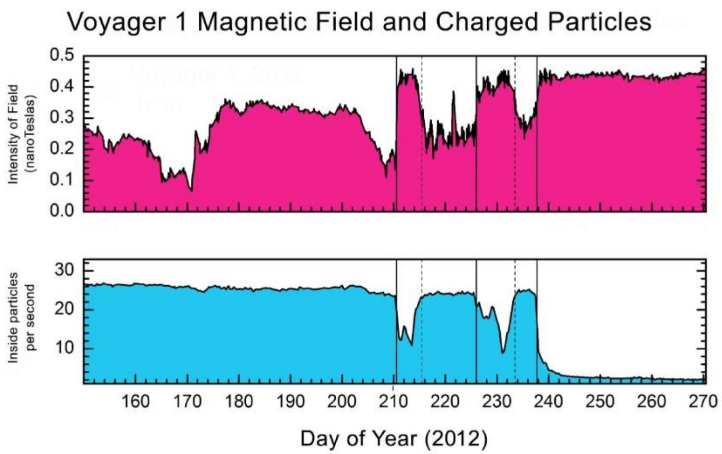
SOLAR APEX
TERMINATION SHOCK
HELIOPAUSE
INTERSTELLAR WINDS
VOYAGER 1
EARTH
SATURN
SUN
URANUS
BOW SHOCK
NEPTUNE
JUPITER
PLUTO
VOYAGER 2

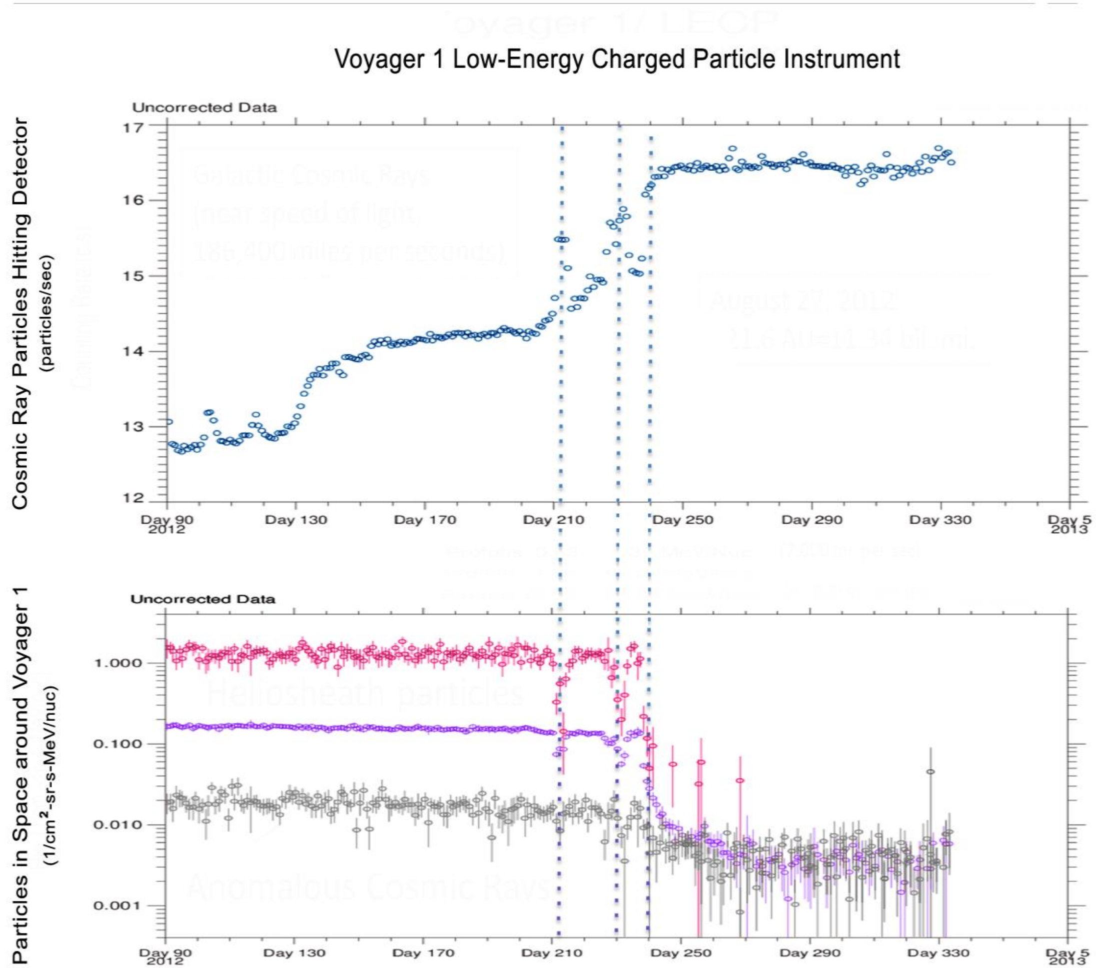
- Voyager 1 crossed the termination shock on 16 December 2004 at 94.5 AU
- Voyager 2 crossed in August 2007 at 84 AU
- Shock most visible in magnetic field magnitude increase
- However, many unexpected effects, especially in the particles



- Voyager 1 entered a new region of space on 25 August 2012 at 121.6 AU

- Strong fluxes of galactic cosmic rays suggest good connection to the interstellar medium



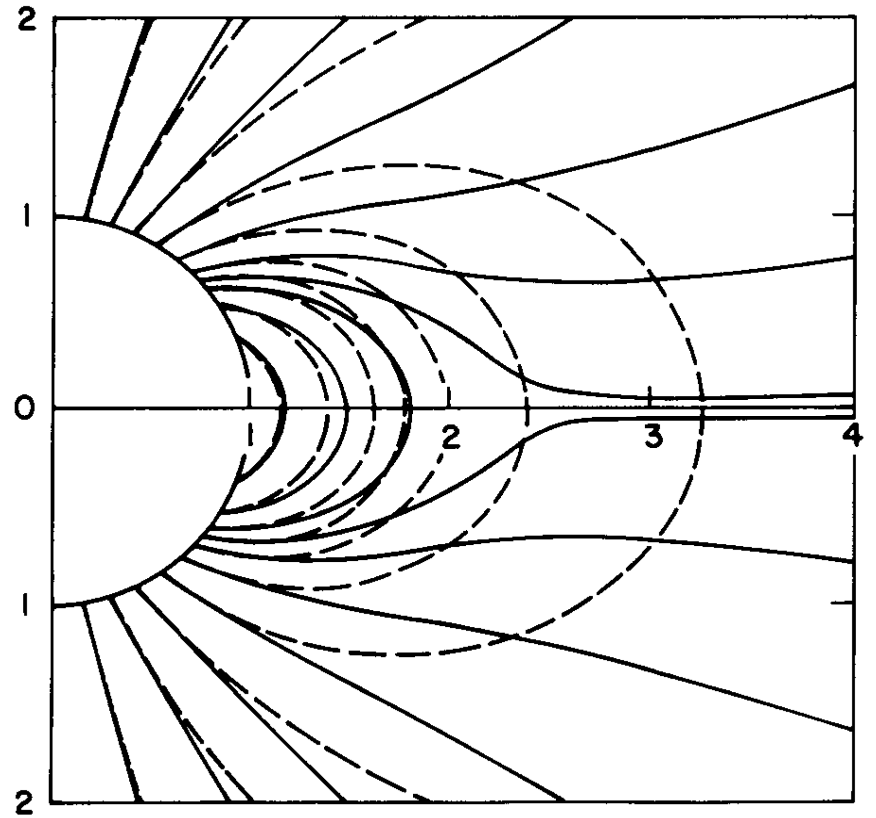


Heliospheric Spacecraft

- The first observations of the solar wind were made in the vicinity of the Earth in the early 1960s.
- Pioneer 10 and 11, launched in 1972 and 1973 were the first spacecraft to explore beyond 1 AU. Contact with these spacecraft have now been lost although Pioneer 10 was tracked to nearly 80 AU.
- Voyager 1 and 2 were launched in 1977. Both have scientific instruments still operating. Voyager 1 has now reached 140 AU and continues out into interstellar space. Voyager 2 is following behind presently at 115 AU.
- Helios 1 and 2, launched in 1974 and 1976, explored the inner heliosphere in the ecliptic plane between 0.3 and 1 AU from the Sun.
- Ulysses, launched in 1990 into a ~6 year period orbit of the Sun inclined at 80.2° to the solar equator, with perihelion at 1.3 AU and aphelion at 5.4 AU. It was thus the first spacecraft to explore the 3D structure of the heliosphere over a large latitude range. Operations ceased in 2009 after nearly 3 orbits.
- STEREO, launched in 2006, consists of two spacecraft at 1 AU separating in solar longitude ahead of and behind the Earth. They carry instrumentation aimed at obtaining stereoscopic views of the Sun and to make multi-point in-situ measurements of the solar wind.

The heliospheric magnetic field

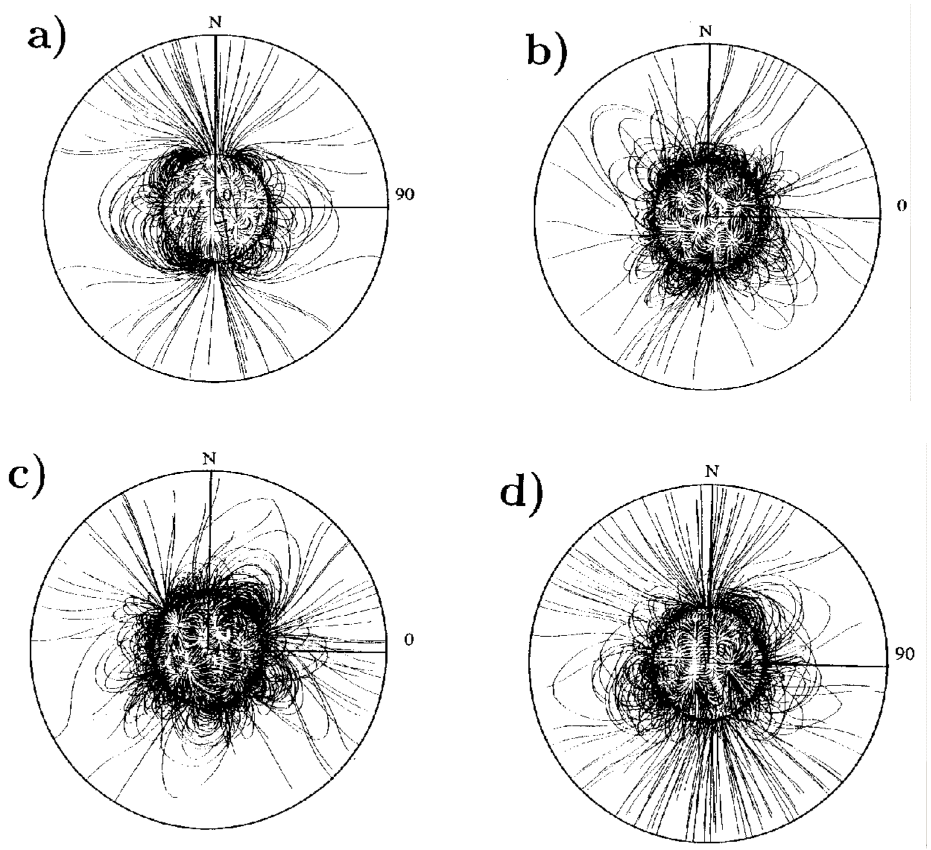
- The heliospheric magnetic field is a result of the Sun's magnetic field being carried outward, frozen in to the solar wind.
- Within the corona, the magnetic field forces dominate the plasma forces.
- As the field strength decreases with distance, beyond the Alfvén radius at a few solar radii, the plasma flow becomes dominant, and the field lines are constrained to move with the solar wind.



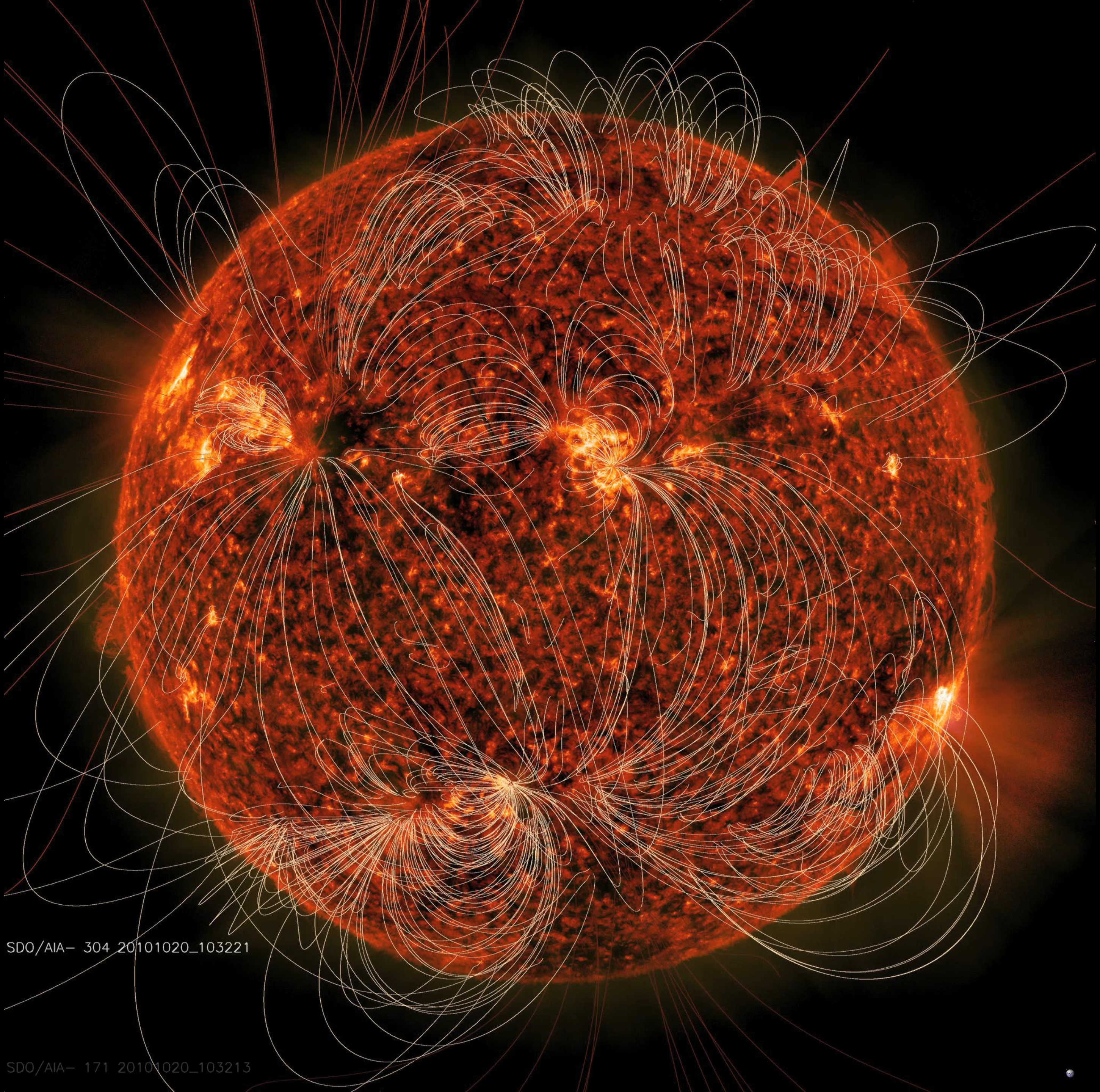
Model of Pneumann and Kopp (1971)

- For modelling purposes, a ‘source surface’ is assumed, typically ~2.5 solar radii, at which the magnetic field lines are constrained to be radial.

Examples of potential field models of the corona…



Bravo et al (1998)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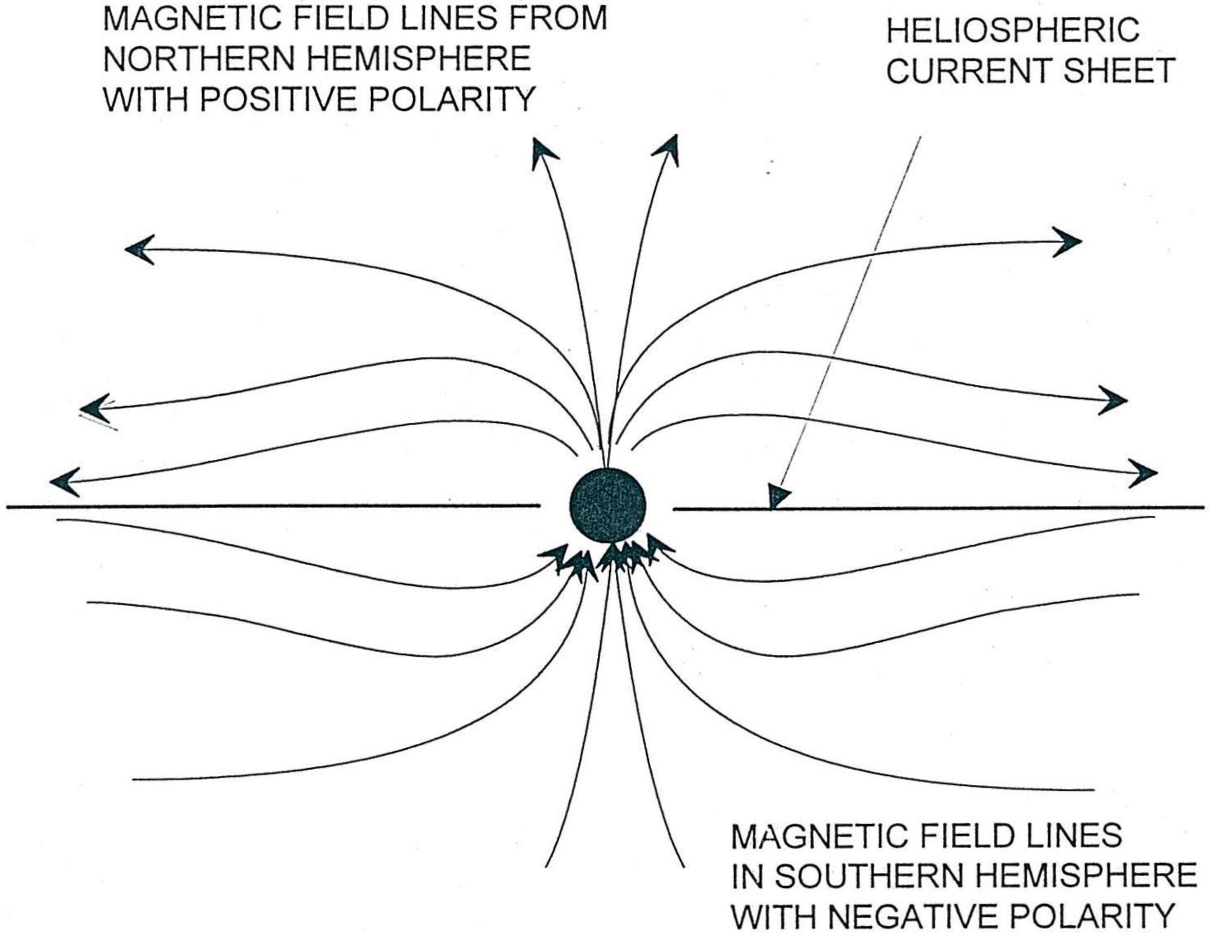
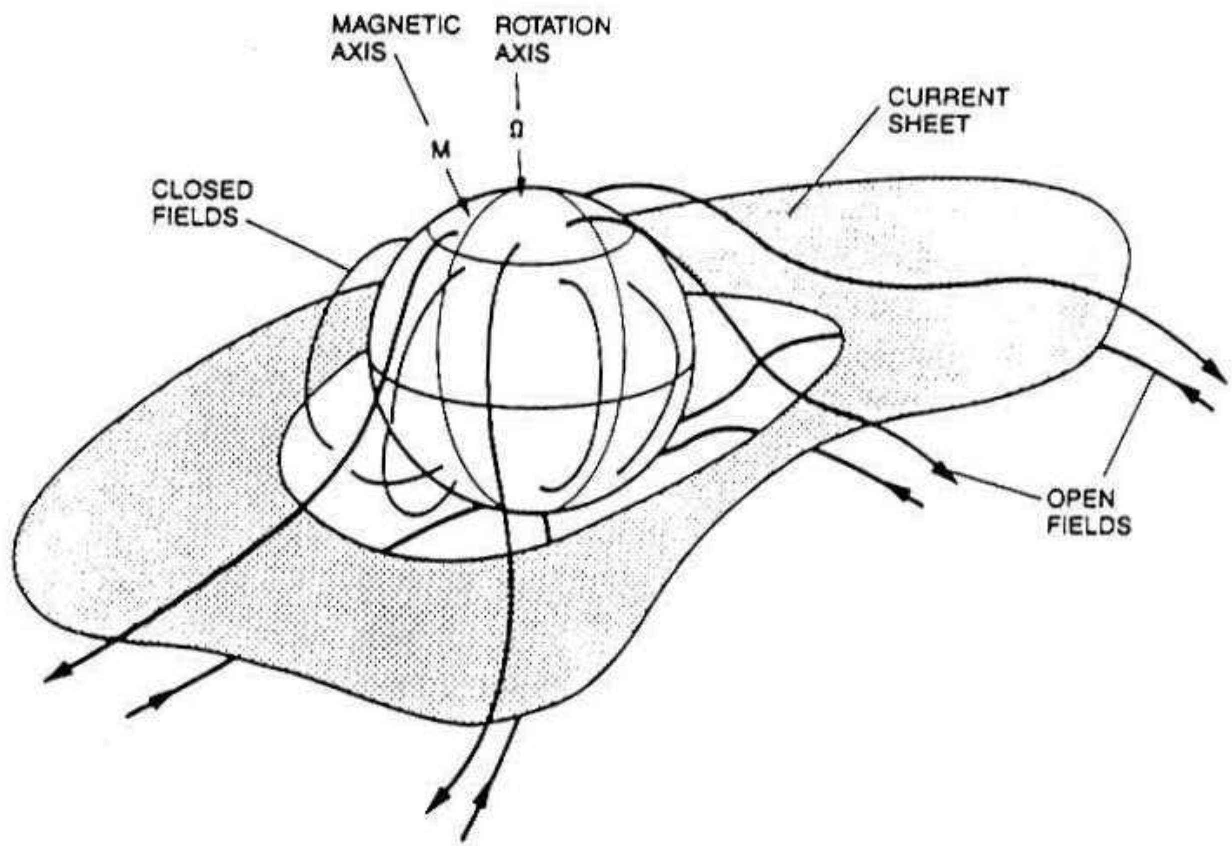
- The heliospheric current sheet forms where outward field lines from one hemisphere meet inward field lines from the other hemisphere.

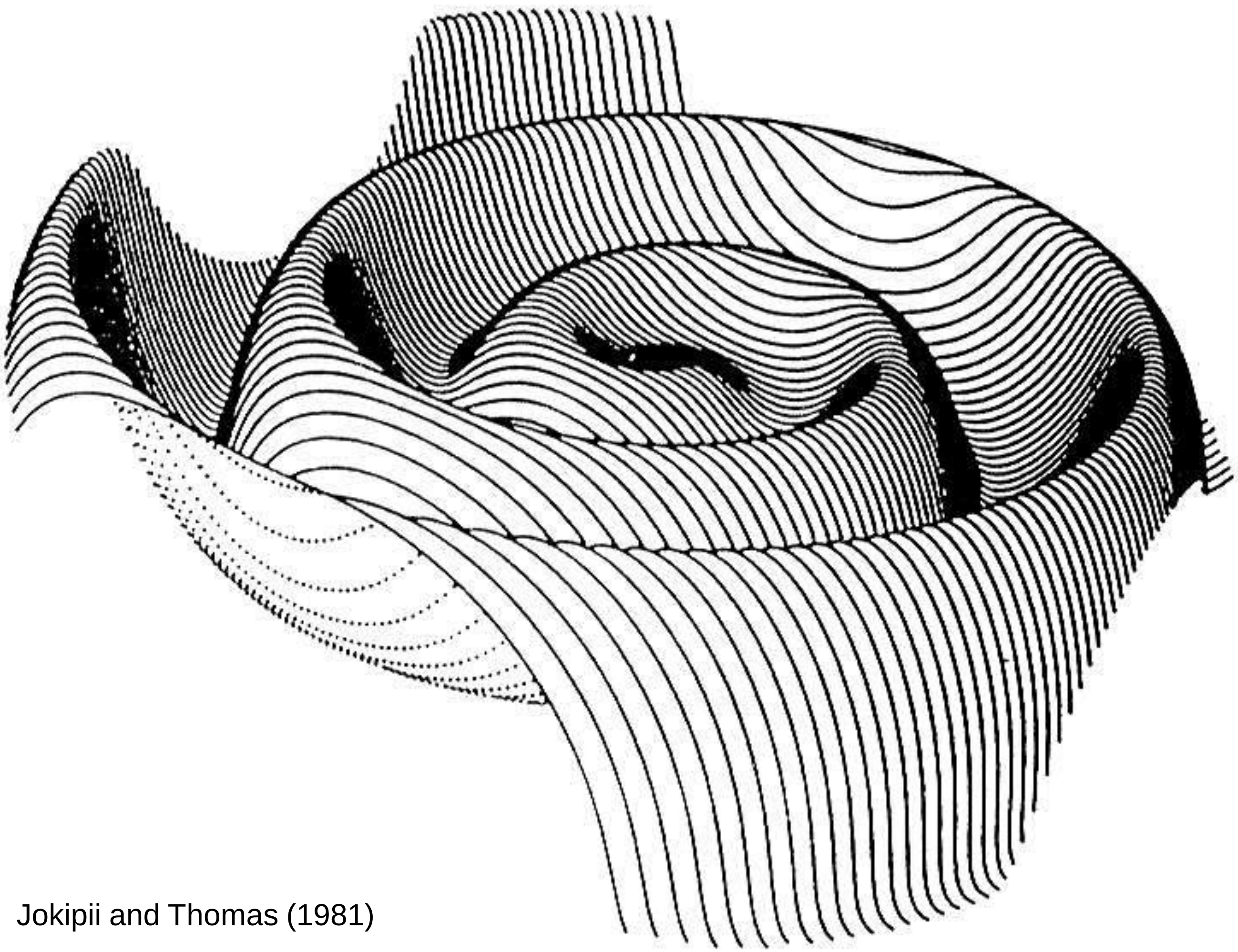


- Near solar minimum when the Sun's dipole field is dominant, the current sheet can be viewed as a plane tilted at the same angle as the dipole, embedded in the band of slow solar wind.
- Therefore interplanetary spacecraft observe current sheet crossings up to a latitude equal to the dipole tilt angle.



Smith (1997)

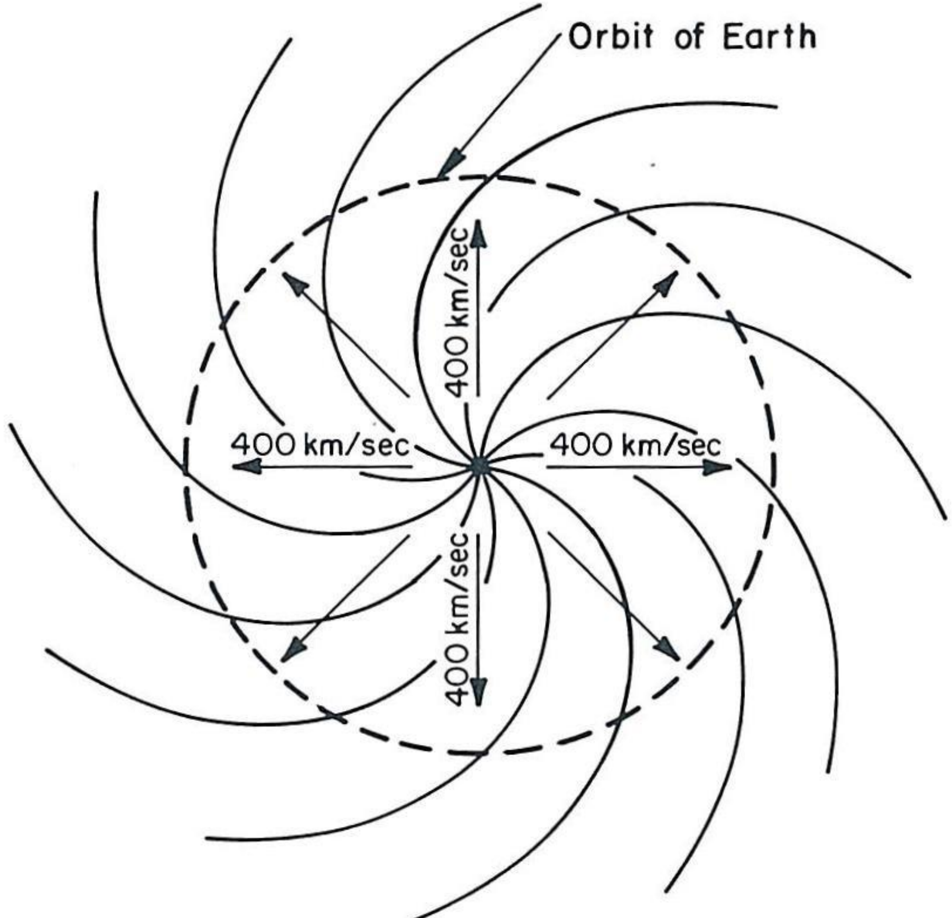
The current sheet mapped out into the heliosphere…



Jokipii and Thomas (1981)

The Parker Spiral Field

- The solar magnetic field is frozen in to the radial outflowing solar wind. Thus, due to the Sun's rotation, the magnetic field lines adopt an Archimedean spiral configuration.
- The angle to the radial direction of the magnetic field depends on distance, latitude and the local solar wind velocity.



Parker (1963)

Geometry of the Parker Field

- The radial component of the magnetic field can be shown from flux conservation to depend only on distance:

$$B_r(r,\theta,\phi) = B_r(r_0,\theta,\phi_0)(r_0/r)^2$$

- By considering the relative motion of a solar wind plasma parcel and its source point, the equation for the spiral field lines is obtained:

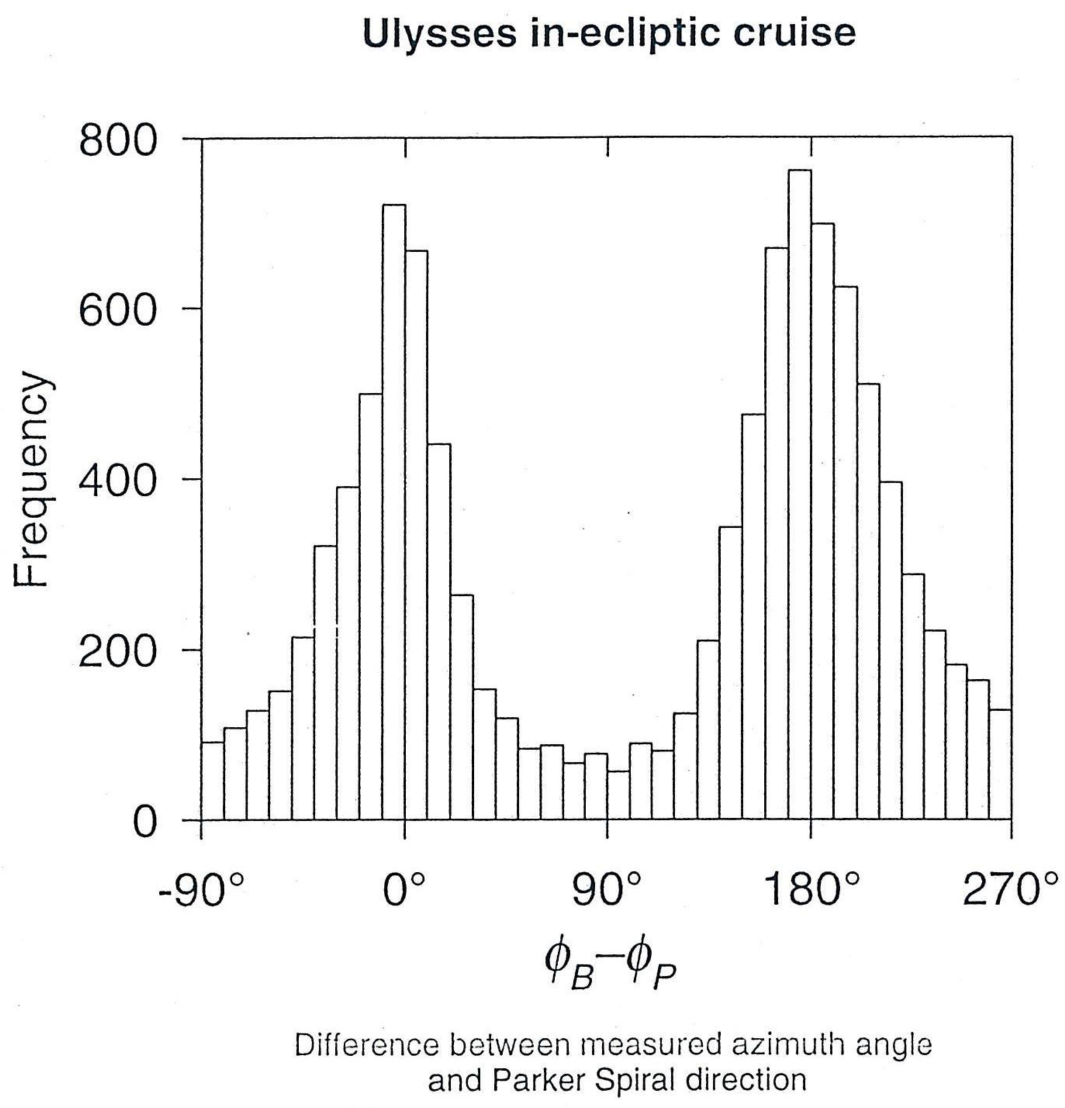
$$r - r_0 = -(\phi - \phi_0)\ V_r / \Omega\sin\theta$$

- From this it can be shown that the azimuthal component goes as 1/r:

$$B_\phi(r,\theta,\phi) = -B_r(r_0,\theta,\phi_0)\ \Omega\sin\theta\ r_0^2 / V_r r$$

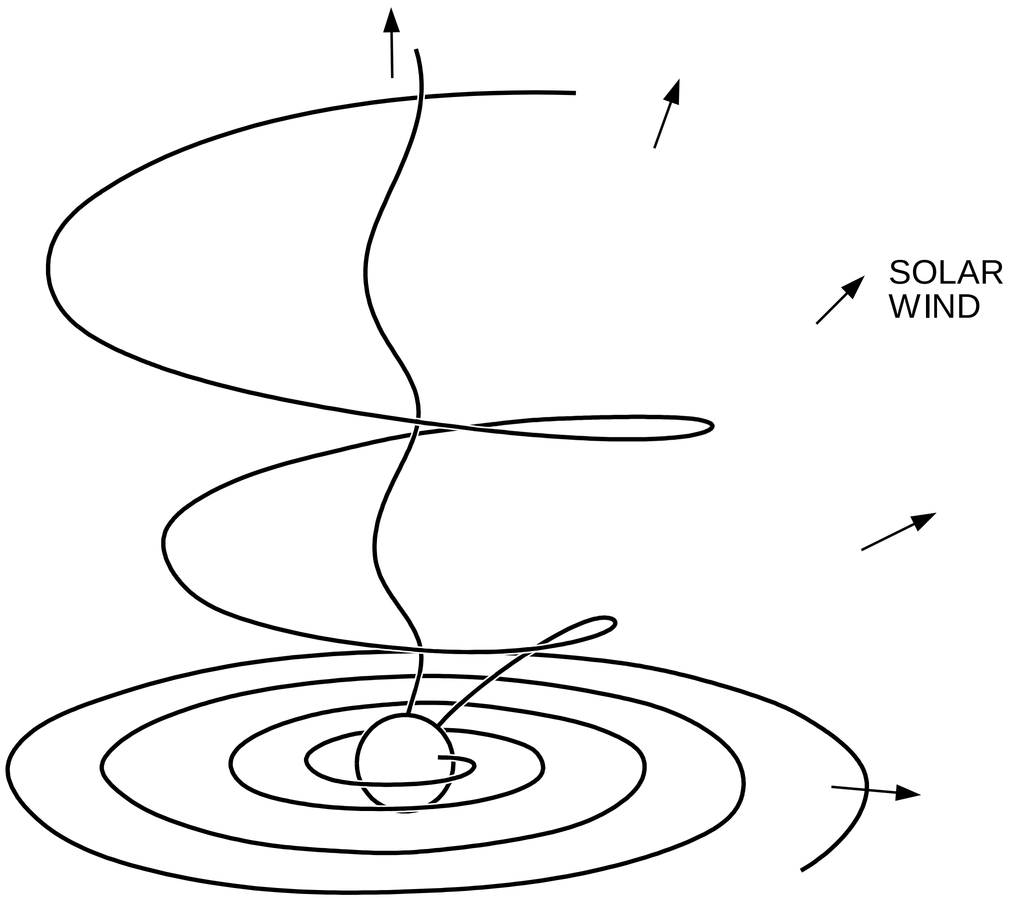
- Also $B_\theta(r,\theta,\phi) = 0$

- Measurements near the ecliptic plane are found to fit this picture to a good approximation.



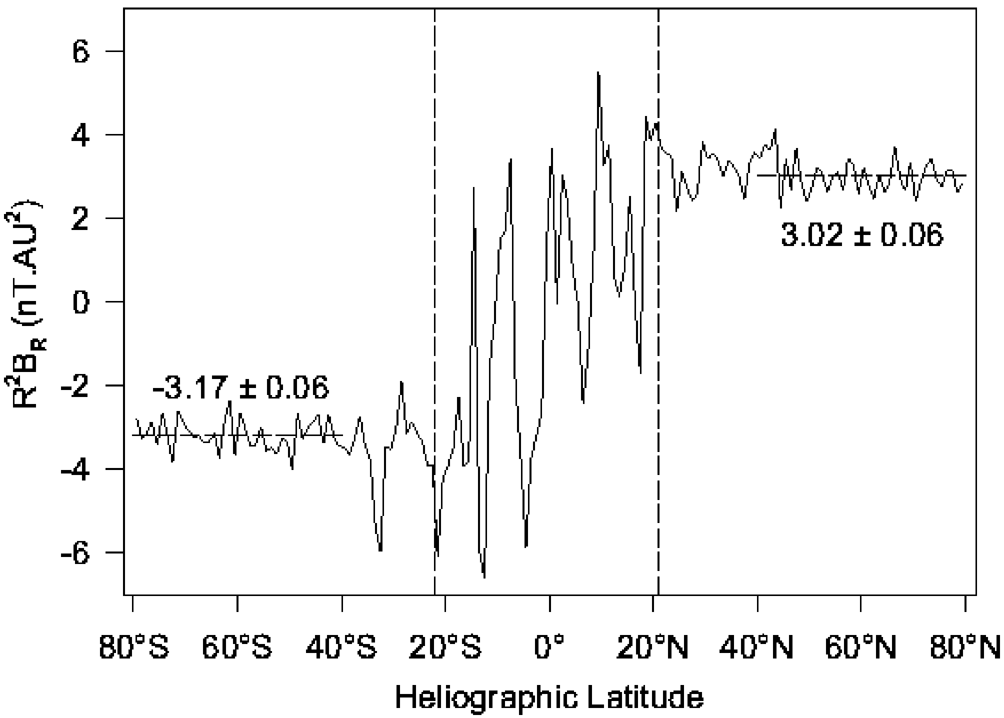
Forsyth et al (1996)

- Moving away from the equator, field lines gradually become less tightly wound with latitude until a field line originating exactly from the pole remains purely radial.
- Ulysses showed that this was followed to a good first approximation also at high latitudes.



Dependence of Field Strength on Latitude

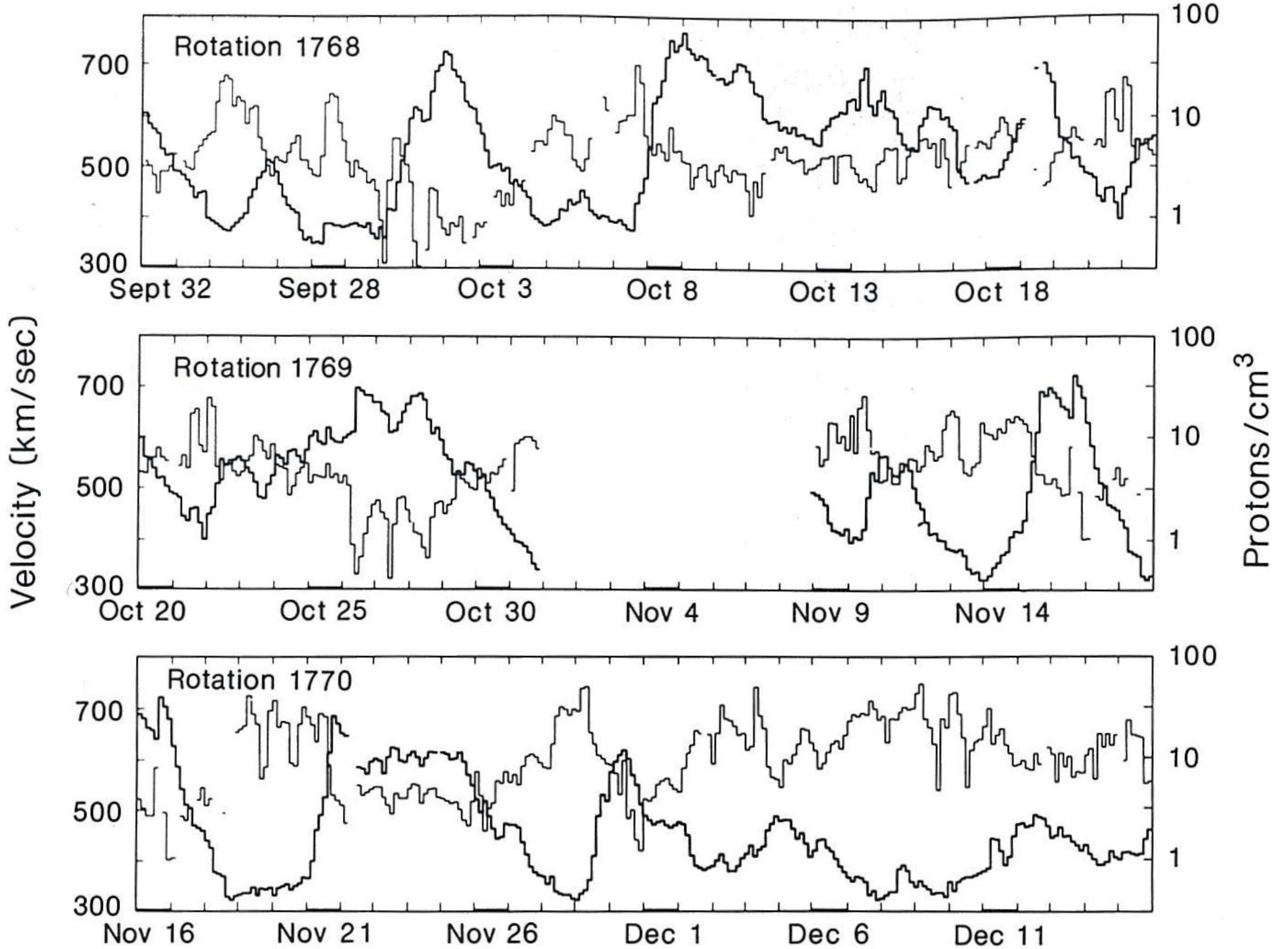
- Assuming that the magnetic field is radial at the ‘source surface’, the radial component of the magnetic field can be used to infer the field strength near the Sun since r^2B_r is a constant.
- Ulysses observations showed that r^2B_r had no dependence on latitude.
- This implies that the latitudinal magnetic pressure gradient associated with strong photospheric polar fields must have relaxed by the outer corona.



Forsyth et al (1996)

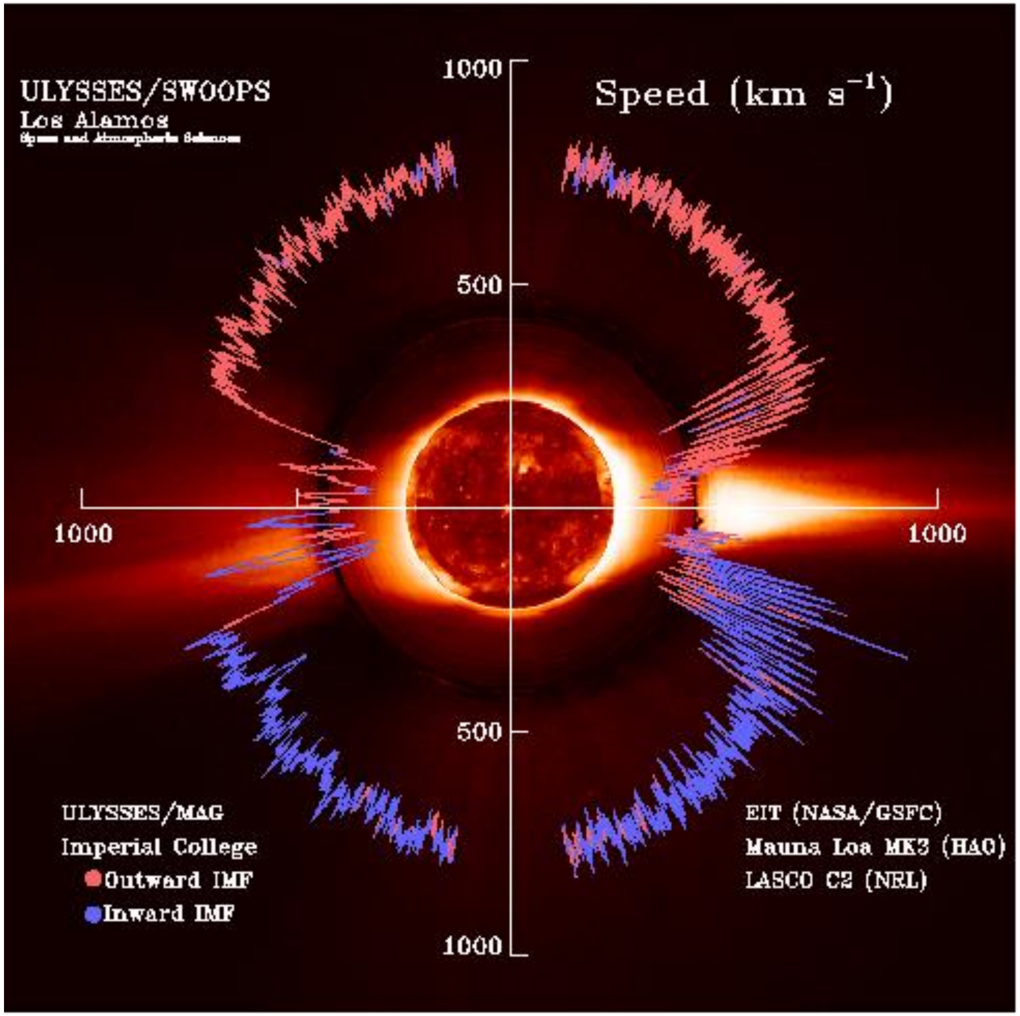
Fast and Slow Solar Wind

- Since the first spacecraft observations it was known that the solar wind was divided into streams of slow (~400 km/s) and fast (>500 km/s) wind.



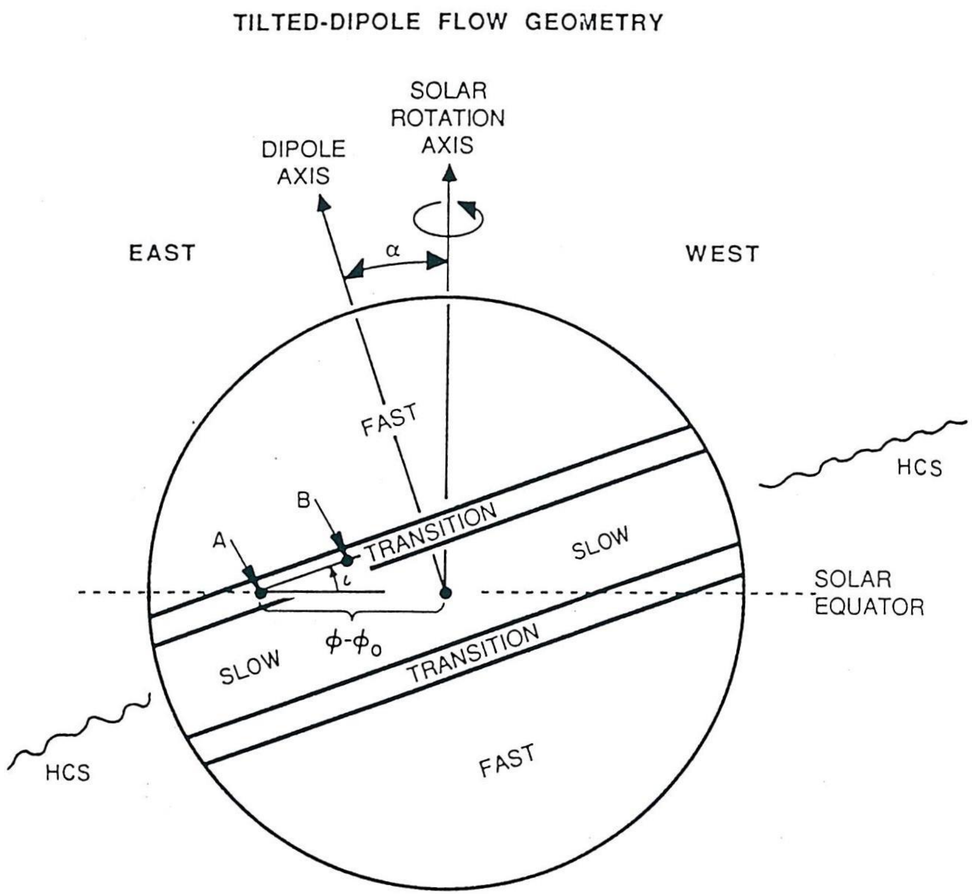
Hundhausen (1995)

- Ulysses found continuous fast solar wind (~750 km/s) at high latitudes at solar minimum in agreement with the idea that fast solar wind originated in coronal holes. This fast wind was associated with large stable polar coronal holes.
- Slow solar wind is associated with the streamers seen in coronagraph images, but its exact source is unclear.



McComas et al (1998)

- Close to solar minimum the flow pattern close to the Sun can be approximated as a band of slow wind at low latitudes, centred on the Sun's dipole equator, with fast wind at all higher latitudes.
- This pattern of fast and slow solar wind is occasionally disturbed by transient flows associated with coronal mass ejections.



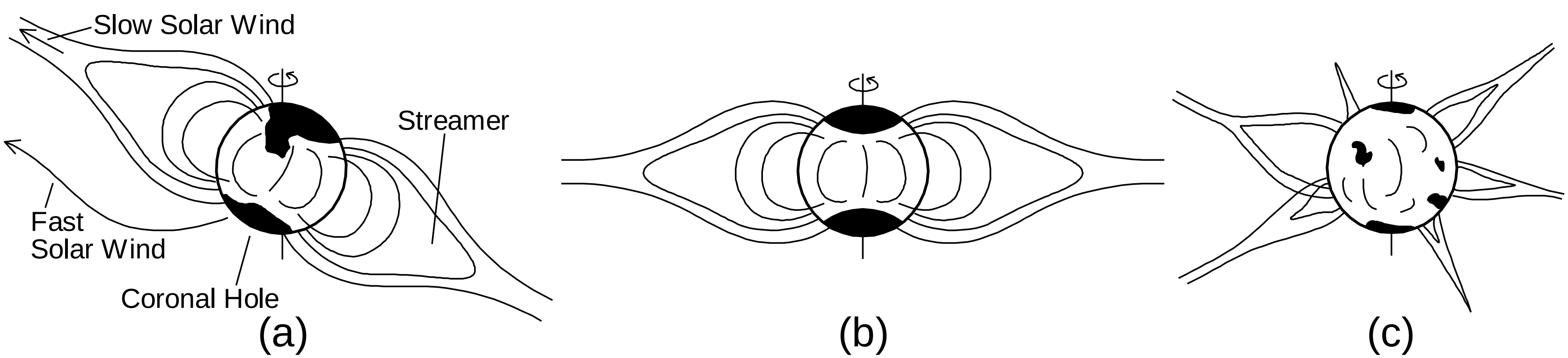
Pizzo (1991)

Characteristics of slow and fast solar wind

Property at 1 AU	Slow wind	Fast wind
Speed (v)	~400 km/s	~750 km/s
Number density (n)	~10 cm^{-3}	~3 cm^{-3}
Flux (nv)	~3×10^{8} cm^{-2} s^{-1}	~2×10^{8} cm^{-2} s^{-1}
Magnetic field (Br)	~3 nT	~3 nT
Proton temperature (Tp)	~4×10^{4} K	~2×10^{5} K
Electron temperature(Te)	~1.3×10^{5} K (>Tp)	~1×10^{5} K (<Tp)
Composition (He/H)	~1 – 30%	~5%

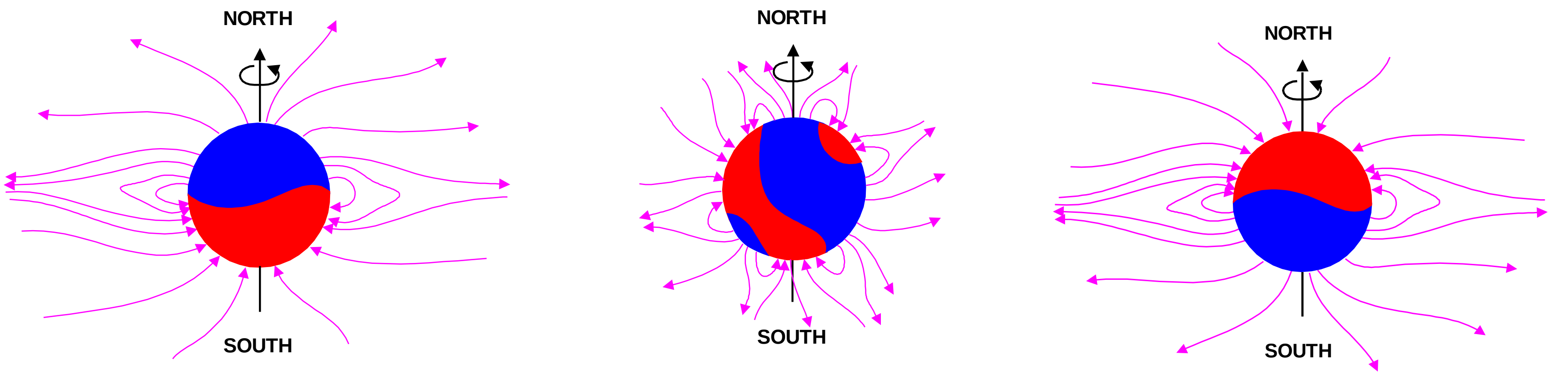
Solar cycle evolution

- The tilt of the underlying solar dipole field and hence of the heliospheric current sheet and the band of slow wind is a function of the solar cycle, with least tilt near solar minimum.
- Alternatively, the evolution of the coronal field can be viewed as the strength of the dipole component decreasing as solar activity increases so that the higher order components of the solar field have a greater effect.



Suess et al (1998)

- This evolution culminates in the reversal of the Sun's magnetic field during the solar maximum period.

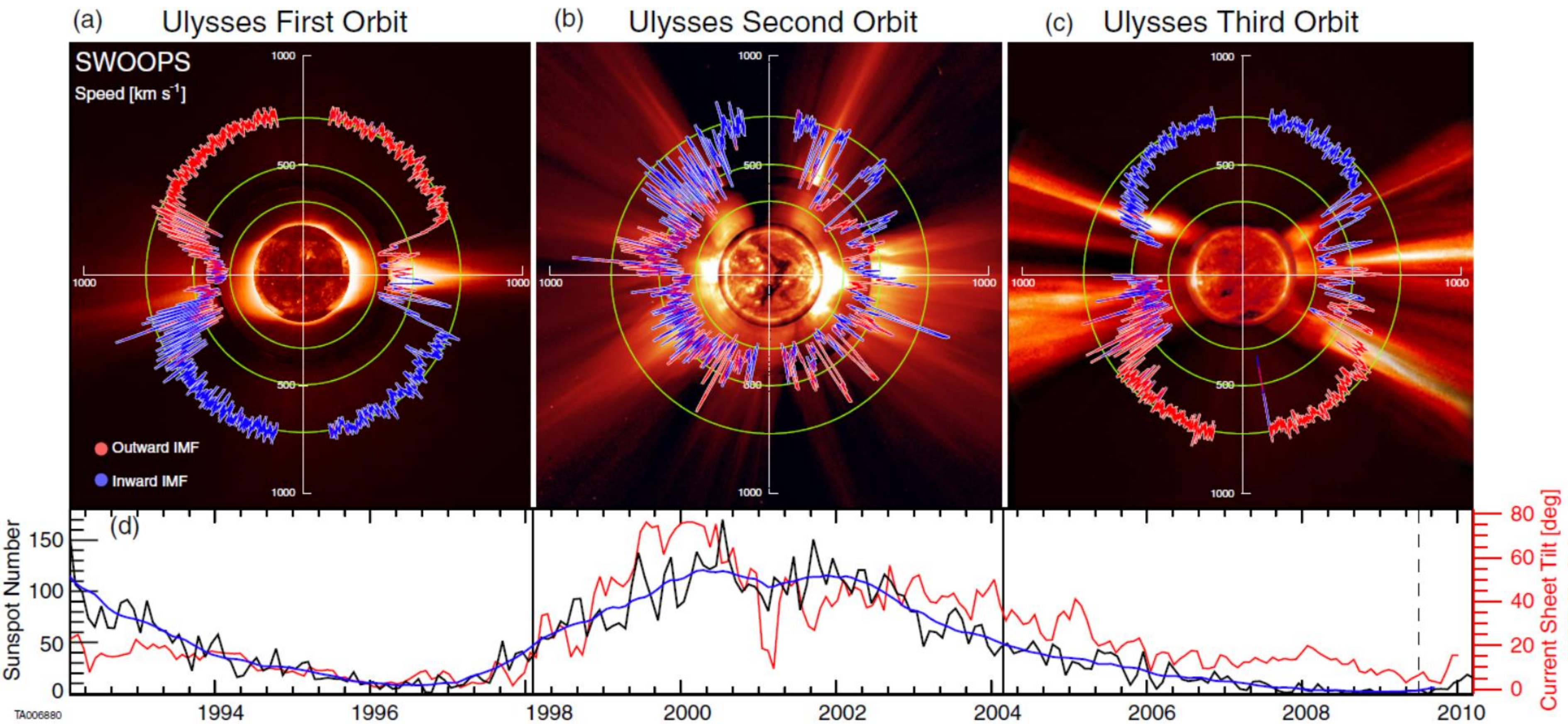


CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY

CORONAL MAGNETIC FIELD LINES AT SOLAR MAXIMUM ACTIVITY

CORONAL MAGNETIC FIELD LINES AT NEXT SOLAR MINIMUM

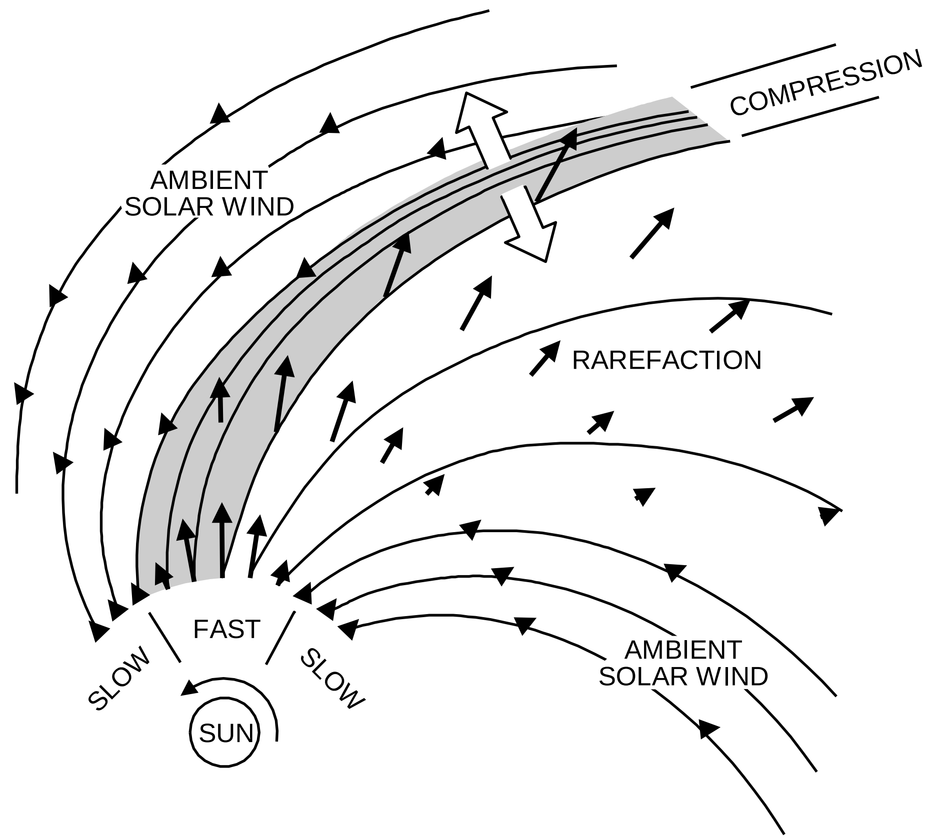
- At solar maximum the large polar coronal holes disappear and are replaced by smaller, generally short lived coronal holes at all latitudes. Ulysses observed fast and slow wind at all latitudes in the southern hemisphere.



McComas et al, (2013)

Corotating Interaction Regions

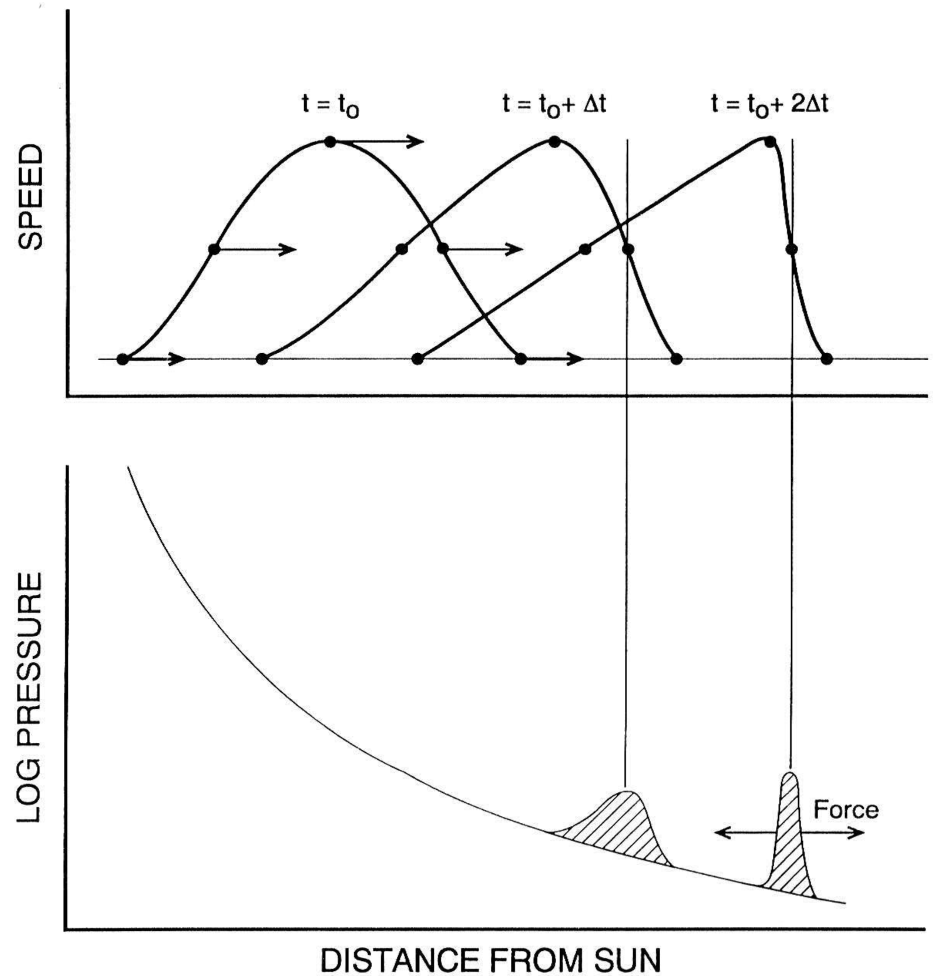
- Interaction regions form wherever fast solar wind ‘catches up’ with slower wind ahead of it.
- A compression region forms where the magnetic field lines and plasma ‘pile up’. The resulting pressure waves can steepen into shocks.
- When a fast solar wind stream originates from a stable coronal hole persisting over many solar rotations, the resulting interaction region pattern corotates with the Sun.
- Ulysses provided new results on the three dimensional geometry of Corotating Interaction regions.



Pizzo (1985)

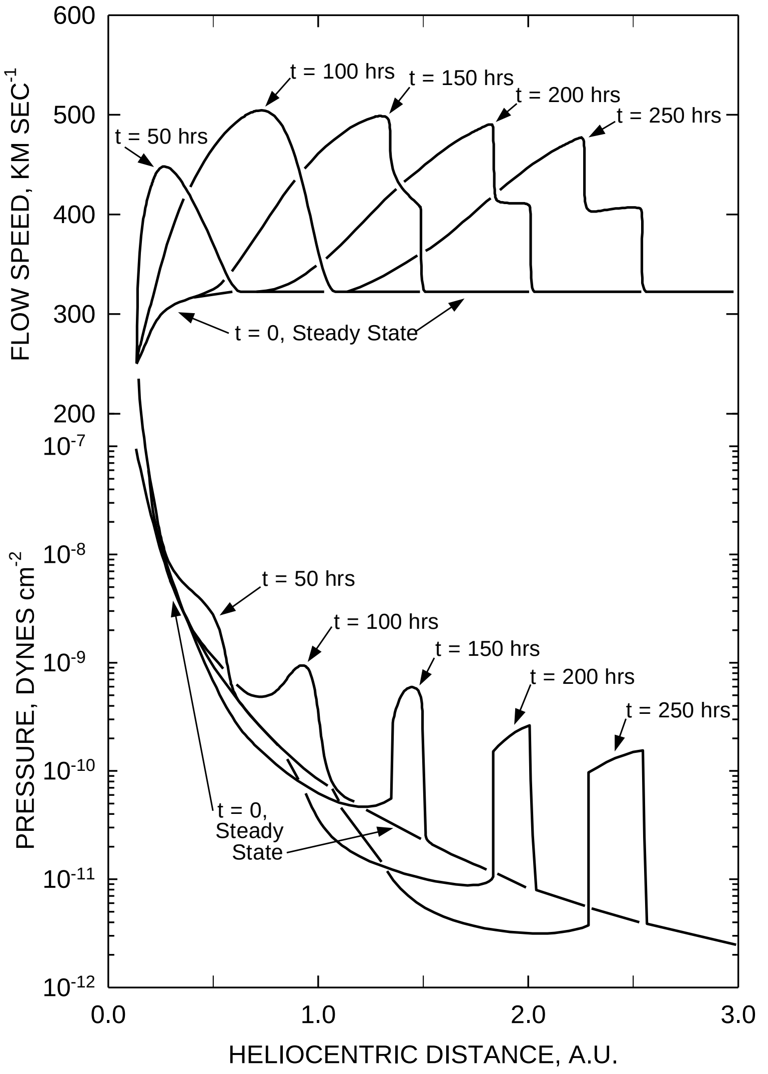
Interaction Regions in 1D

- Because of the Sun's rotation faster plasma emitted along a particular radial line, catches up with slower plasma emitted in the same direction at an earlier time.
- The plasma streams cannot interpenetrate because of the frozen in magnetic field.
- A compression region builds up leading the fast stream, while a rarefaction develops behind.
- Due to pressure gradients the compression region expands at the fast mode speed. A forward wave develops on the leading edge and a reverse wave on the trailing edge.



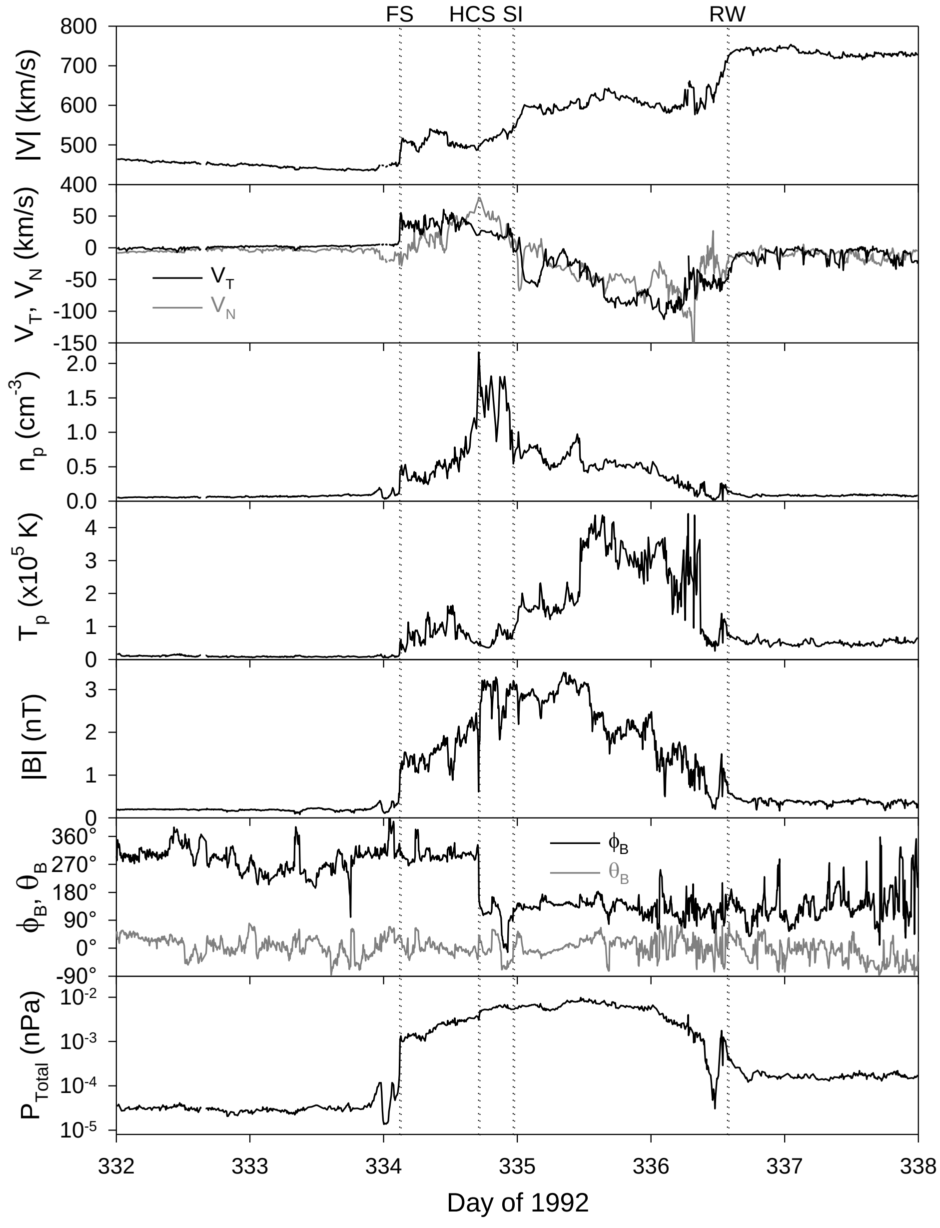
Gosling (1998)

- If the speed difference between the streams is greater than ~2 times the fast mode speed then the stream front steepens faster than the high pressure region can expand. The pressure waves then develop into shocks.
- These propagate faster than the fast mode speed allowing the compression region to expand again.
- The forward wave/shock accelerates slow plasma ahead of the interaction region.
- The reverse wave/shock decelerates fast plasma trailing the interaction region. It propagates towards the Sun in the solar wind frame but is convected outwards across a stationary observer.



Hundhausen (1973)

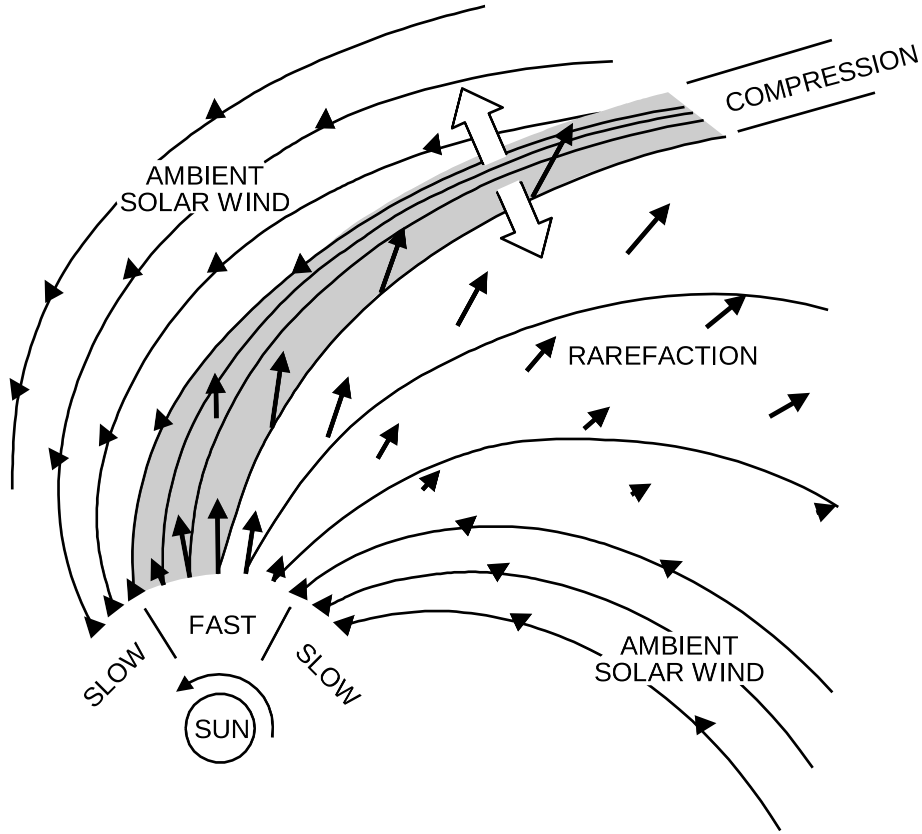
Example of a Corotating Interaction Region at 5 AU



Forsyth and Gosling (2001)

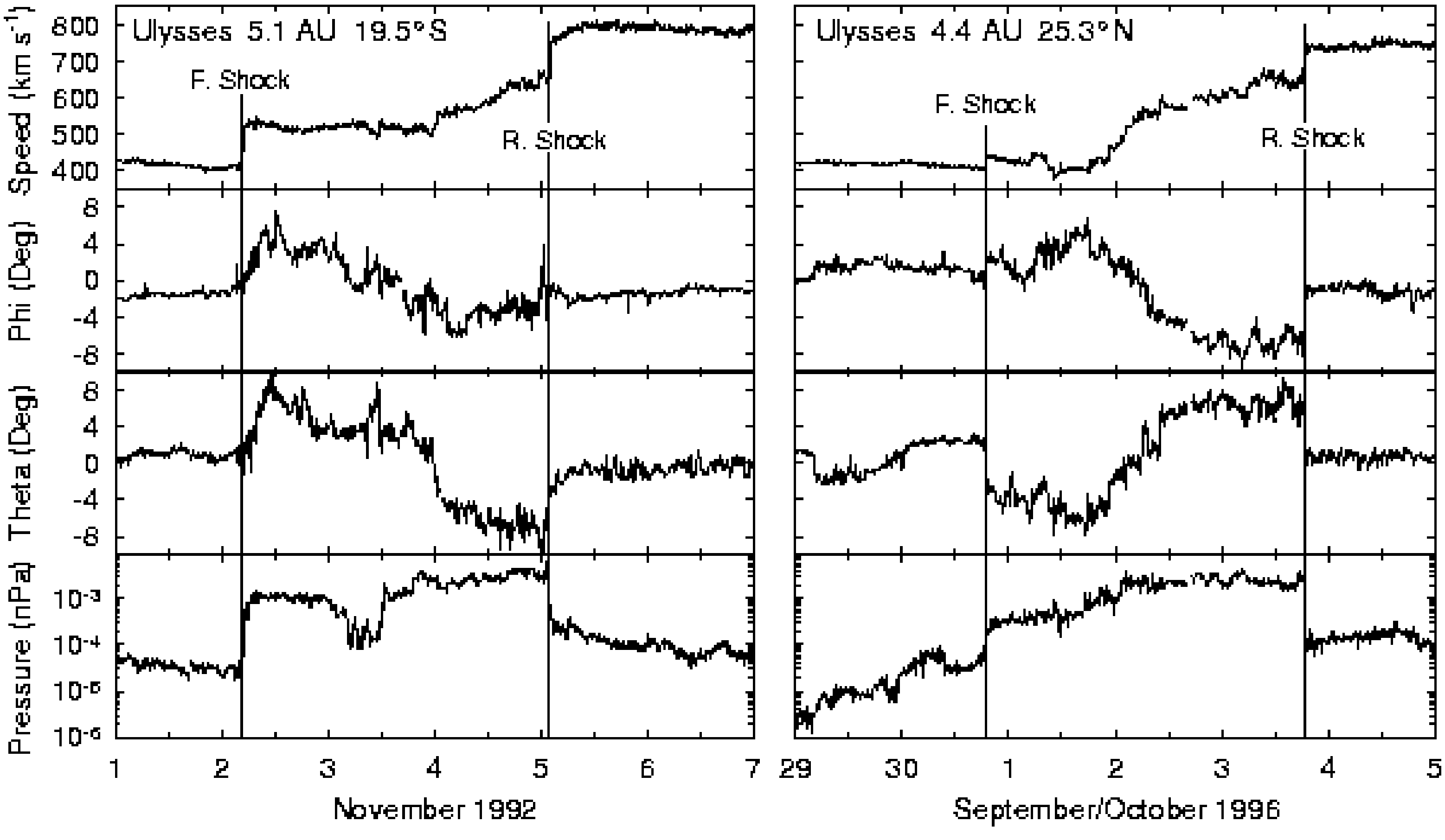
Interaction Regions in 2D and 3D

- In 2D the interaction region forms an Archimedean spiral oriented between the tighter spirals of the slow wind and the less tight spirals of the fast wind
- If the sources are quasi-stationary compared to the solar rotation period, then the entire pattern corotates with the Sun.
- Because of the spiral geometry, forward waves/shocks have a westward component of propagation. Reverse waves/shocks have an eastward component of propagation.



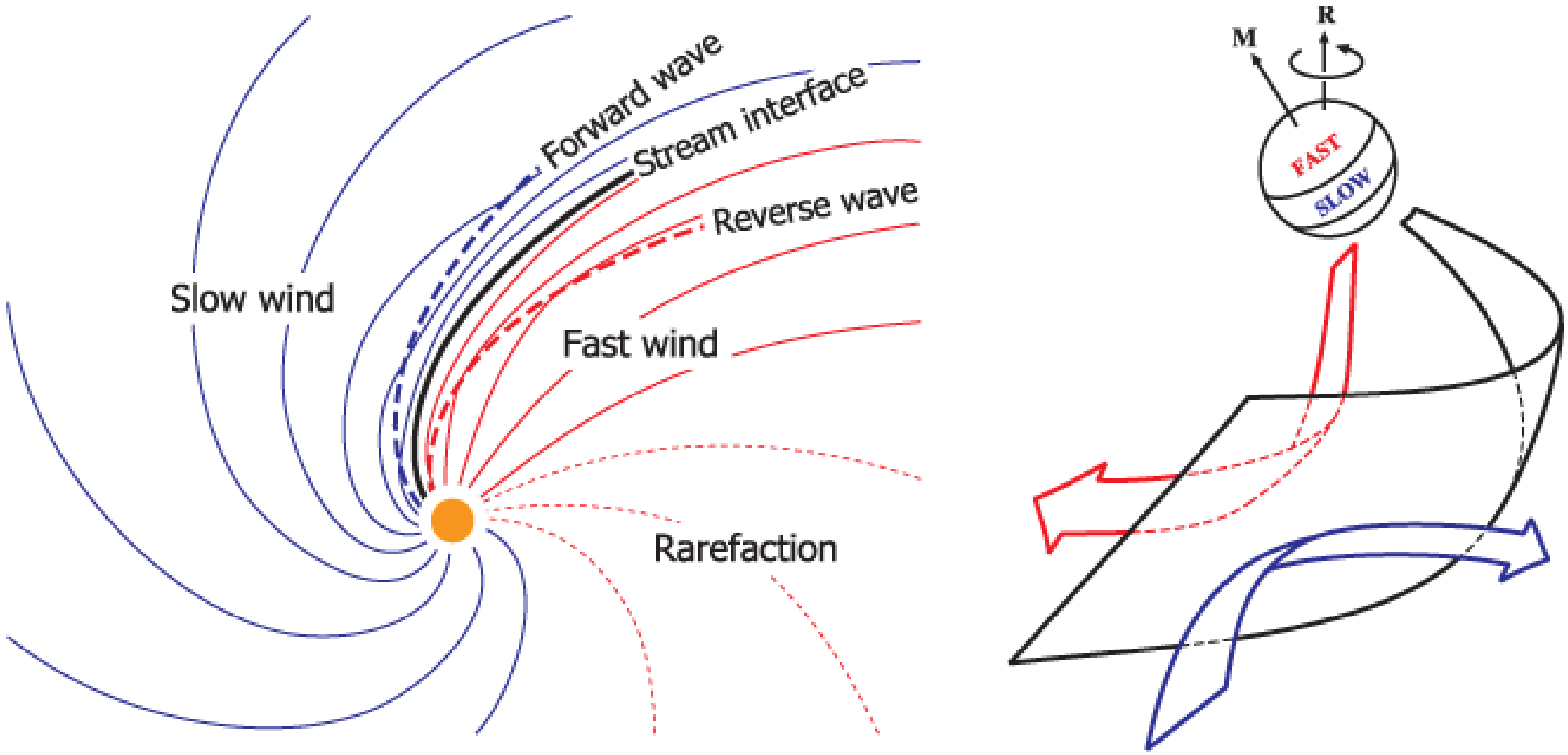
Pizzo (1985)

- Ulysses discovered north-south flow deflections associated with interaction regions implying that the forward waves/shocks propagate equatorwards while reverse waves/shocks propagate polewards.



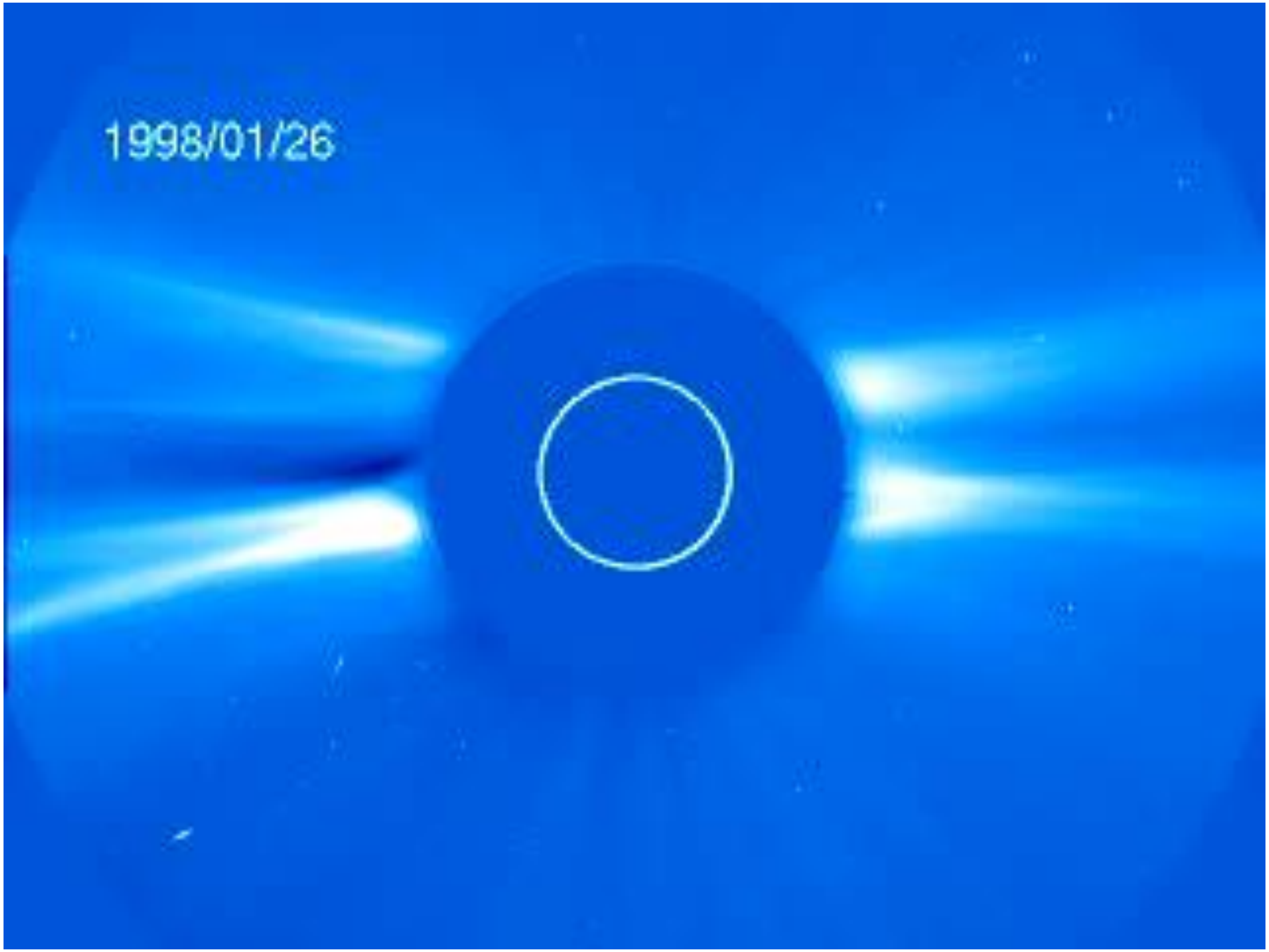
Pizzo and Gosling (1999)

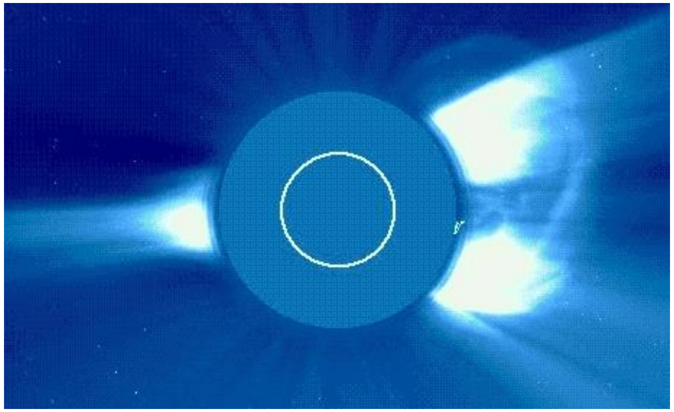
- This behaviour was shown to be consistent with the source region of slow speed solar wind forming a low latitude band symmetrical about the Sun's magnetic equator, i.e. tilted with respect the rotation axis.



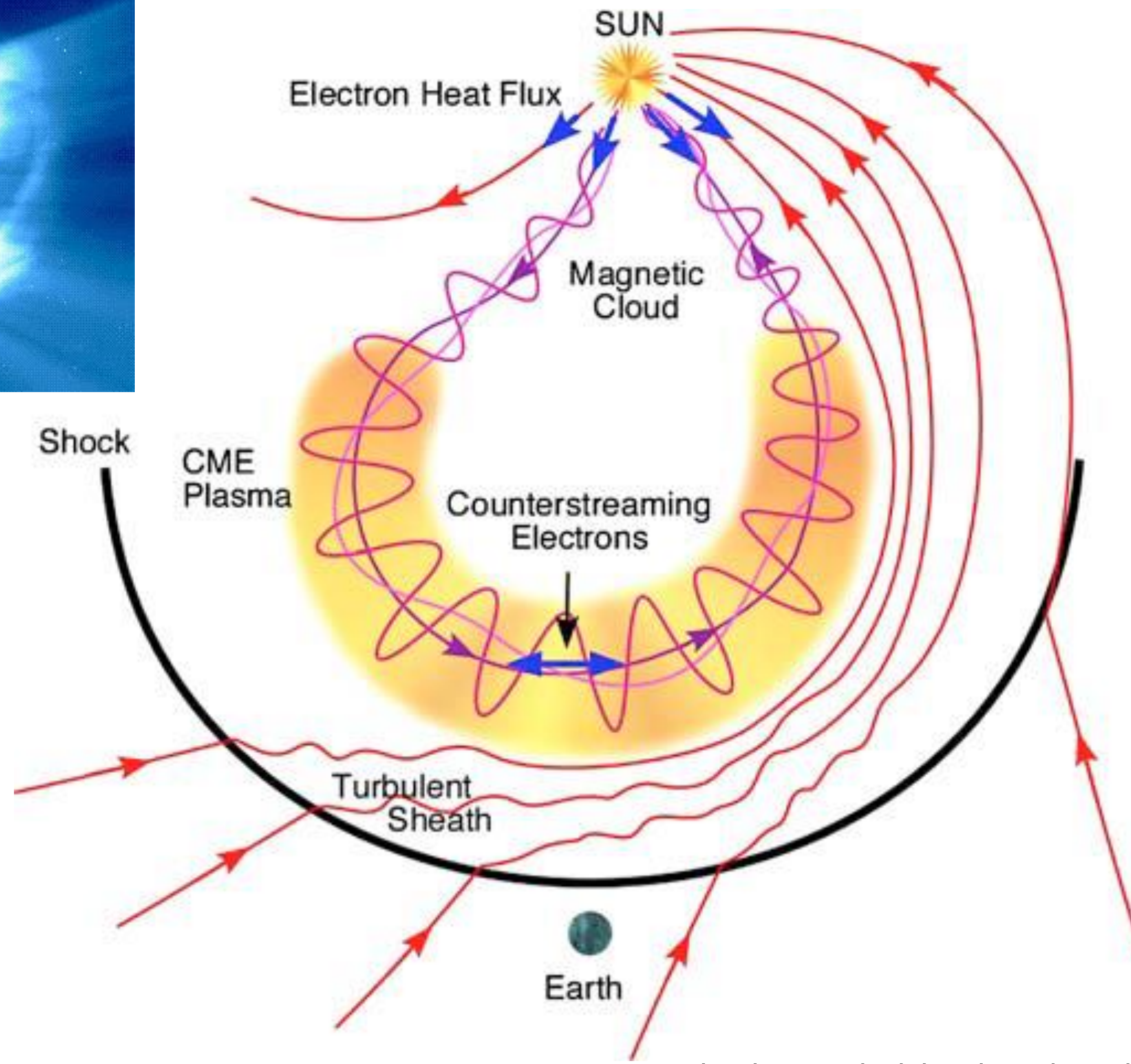
Owens and Forsyth (2013)

Coronal Mass Ejections



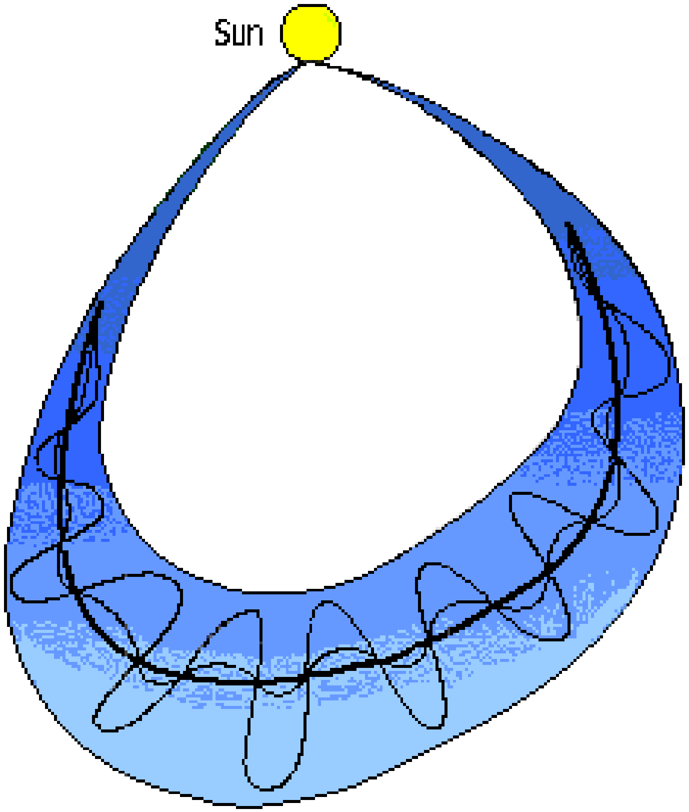


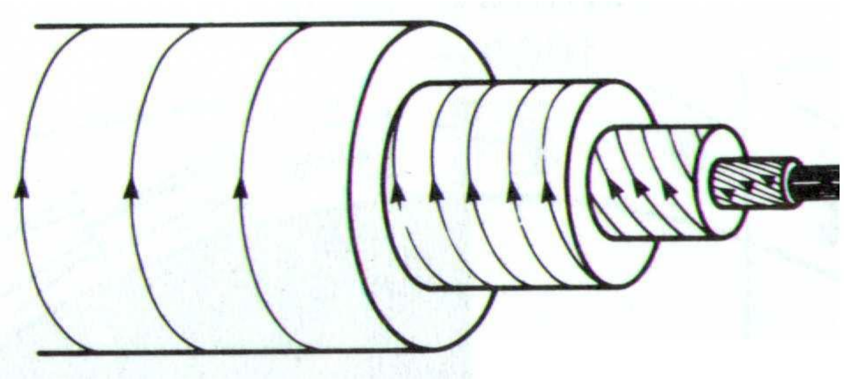
- Fast coronal mass ejections can interact with solar wind ahead of them in a similar way to high speed streams to produce compression regions and shocks.



Zurbuchen and Richardson (2006)

- Some coronal mass ejections contain a ‘magnetic cloud’ believed to represent a ‘flux-rope like’ field structure being carried out from the Sun.

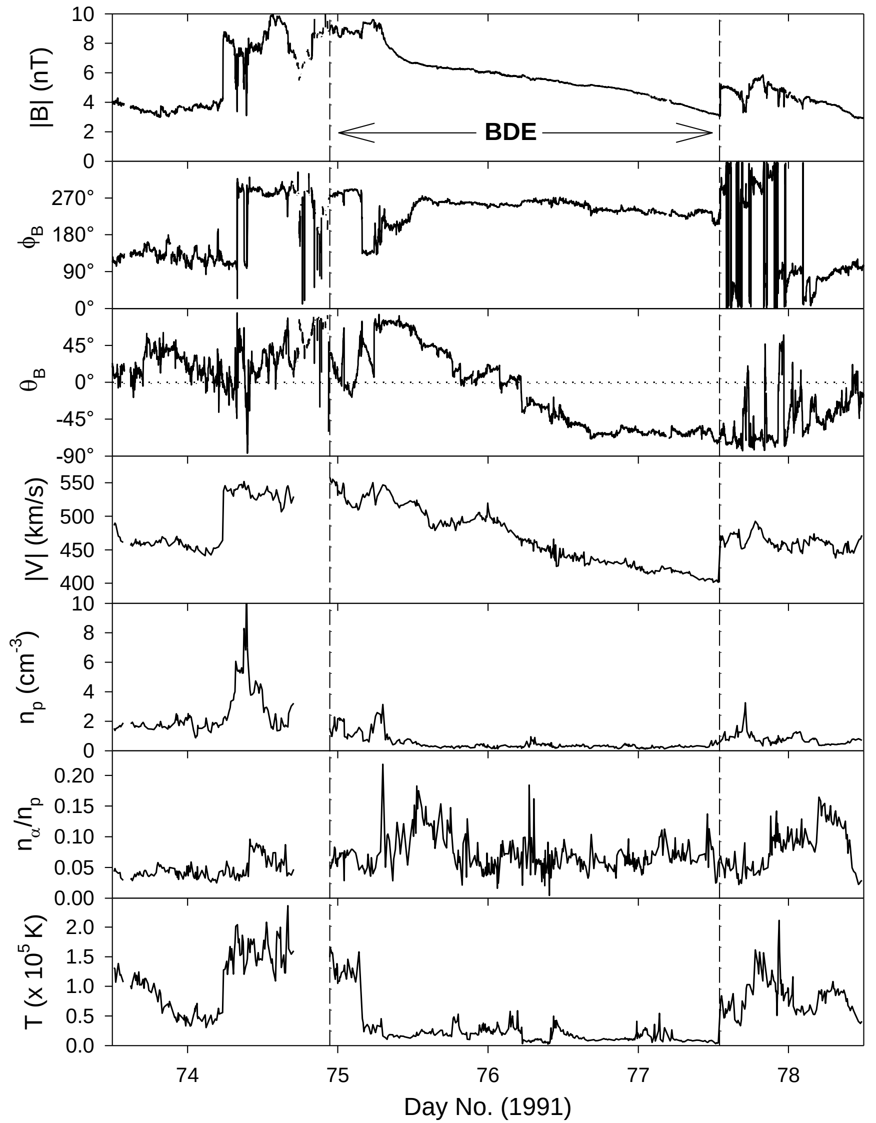




Luhmann (1995)

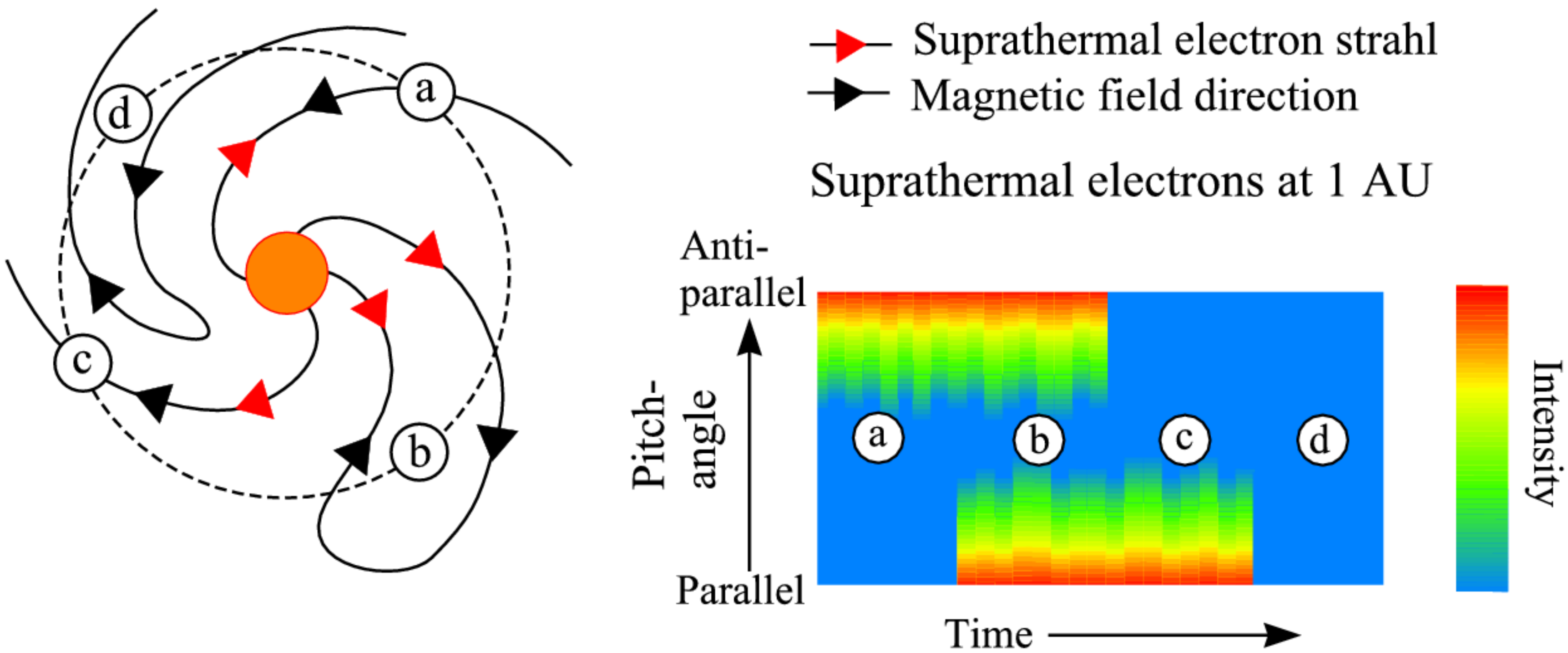
Signatures of Coronal Mass Ejections

- Counterstreaming suprathermal (>60eV) electrons
- Counterstreaming energetic protons (>~20keV)
- Helium abundance enhancements
- Ion/electron temperature depressions
- Strong magnetic fields
- Low plasma β
- Low magnetic field variance
- Characteristic field rotations consistent with flux ropes
- Different heavy ion composition from the solar wind
- Not all CMEs exhibit all of these!



Forsyth and Gosling (2001)

Origin of counterstreaming suprathermal electrons…



Owens and Forsyth (2013)

Where next?   Solar Orbiter (ESA) / Solar Probe Plus (NASA)

Solar Orbiter scientific questions

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

The outer boundaries of the helisophere

- New understanding will continue to come from the Voyager termination shock and heliopause crossings.