The Solar Wind &
Coronal Mass Ejections (CME)

STFC Summer School
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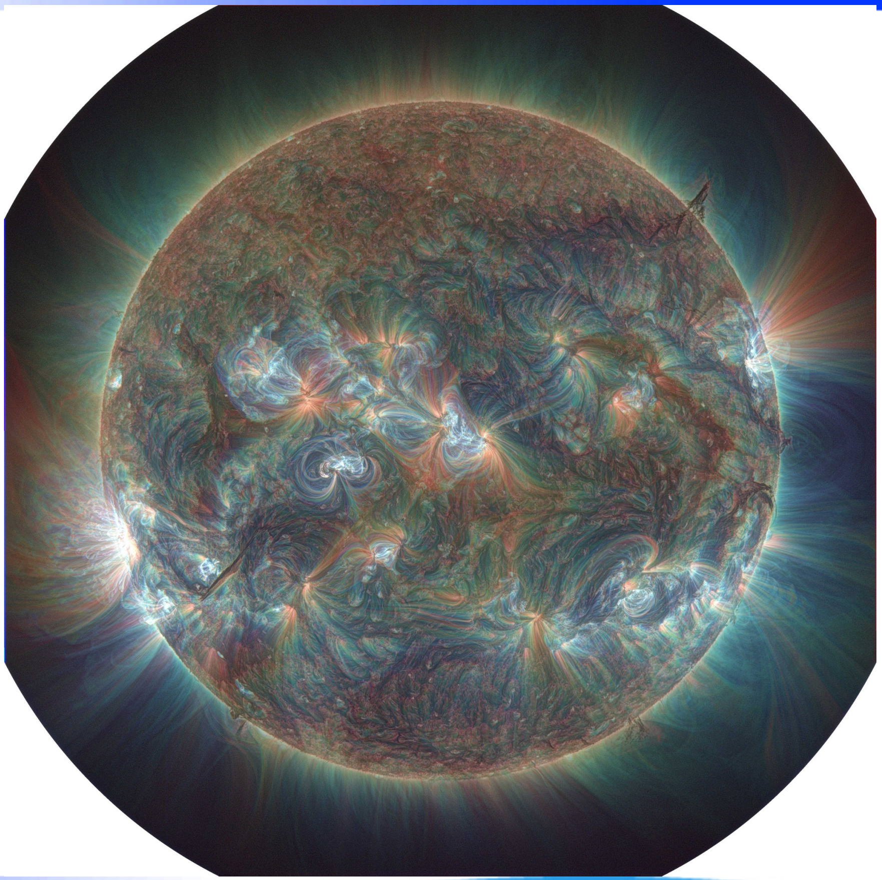
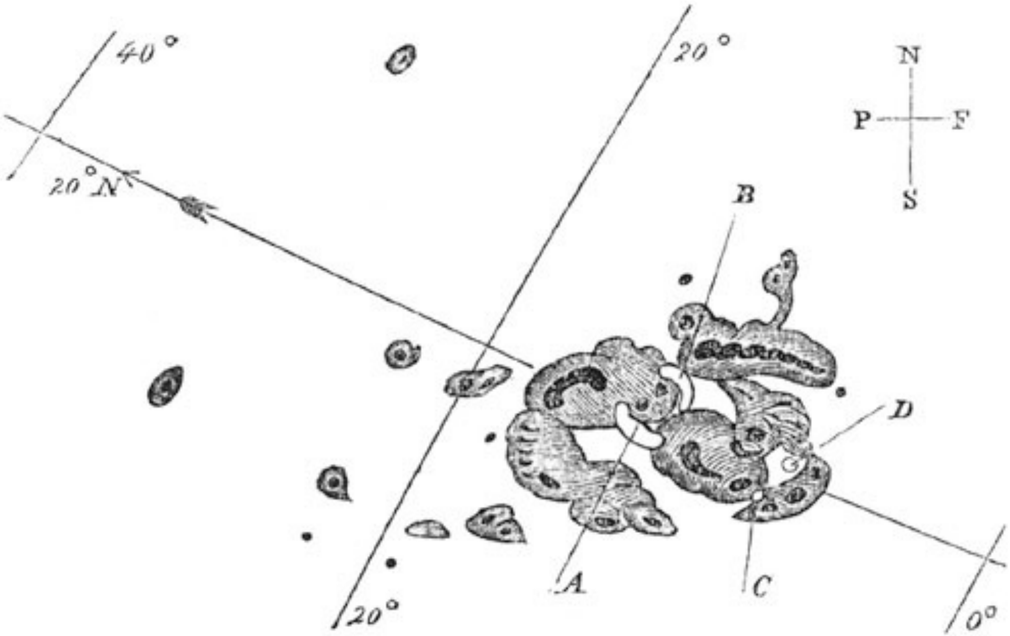


Solar System Physics
Ffiseg Cysawd yr Haul

- **Solar Wind**
  - Historical
  - Parker model
  - Large-scale coronal structure
    - Magnetic
    - Plasma
  - Expansion of corona into space & SIRs
  - Where does the slow solar wind come from?
- **CMEs**
  - Overview & historical
  - CME initiation & models
  - Importance of studying CMEs
  - Categorization of CMEs
  - Observational challenges & the near future

Early evidence for a solar wind: The Carrington Event, 1859

- Astronomers Carrington & Hodgson made first observations of a solar flare
- Balfour Stewart measures geomagnetic storm the following day. One of largest storms on record.
- Aurorae seen down to equatorial regions. Bright enough to read newspaper at night!



Carrington presents this event to the Royal Society as evidence of a solar-terrestial connection.

Many prominent scientists of the time reject his proposition. How can there be a physical connection between the Sun and Earth? Space is empty…

Recommended reading: The Sun Kings, Stuart Clark

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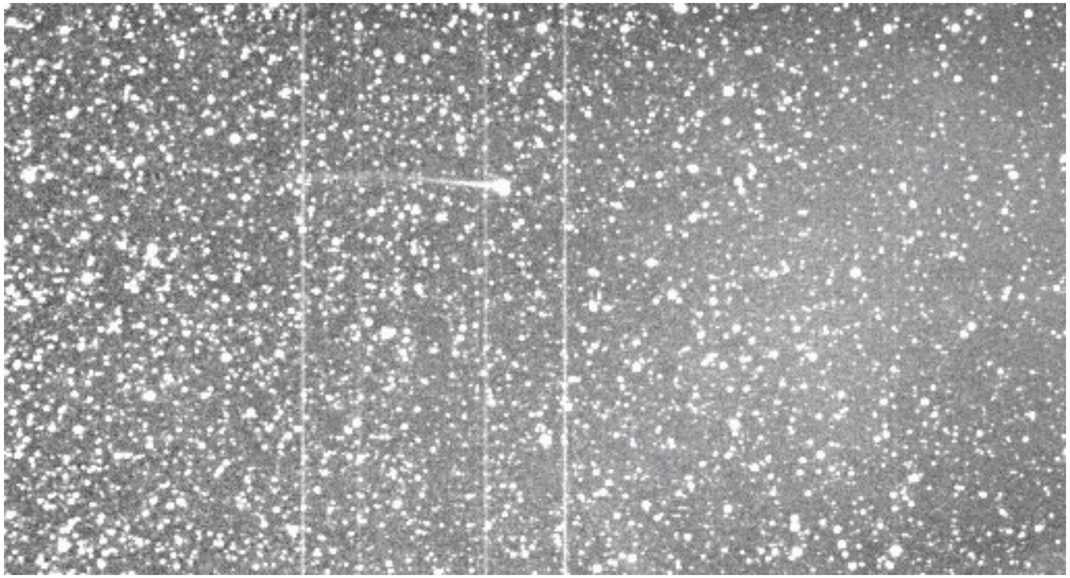
Early evidence for a solar wind: **Comet tails**

- Comet Morehouse, observed in 1908, had a highly variable tail (splitting up, detaching). What could cause this variation?
- Eddington suggested the existence of a stream of electrons/ions flowing through interplanetary space
- Comet ion tails point away from the Sun. Still occasionally used in solar wind studies

Comet Encke, April 2007 (STEREO HI)

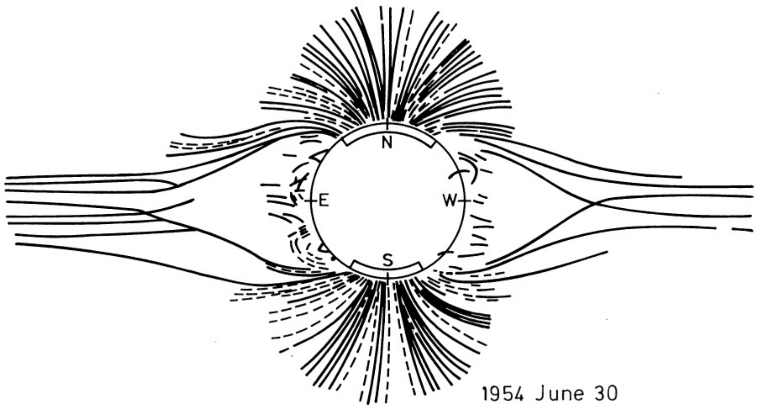


https://en.wikipedia.org/wiki/File:Encke_tail_rip_off.ogg

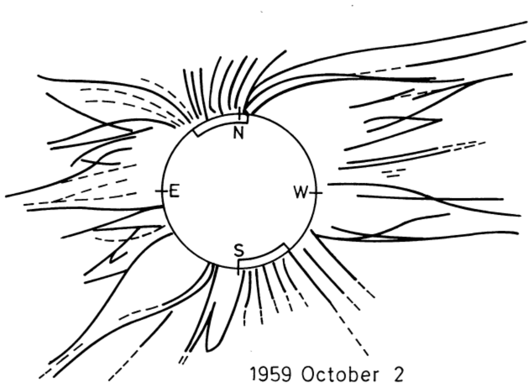
Early evidence for a solar wind: **Aurorae**

- Birkeland observed almost constant auroral activity, and predicted the source of the aurora as the solar wind
- Birkeland (1913): *"…the whole of space is filled with electrons and flying electric ions of all kinds. We have assumed that each stellar system in evolutions throws off electric corpuscles into space. …the greater part of the material masses in the universe is found, not in the solar systems or nebulae, but in 'empty' space."*
- Birkeland (1916): *"From a physical point of view it is most probable that solar rays are neither exclusively negative nor positive rays, but of both kinds"*

Solar eclipses: Early photography & the solar cycle



1954 June 30
(ϕ=0.04 ; R_Z=2.5)



1959 October 2
(ϕ=−0.74; R_Z=128)

- Before photography uncertainty as to nature of corona. Scattering by Earth's atmosphere? A lunar phenomenon? Astronomers mostly concerned with timings & locations of eclipses.

- Advent of photography during eclipses shows corona is Sun's atmosphere

- Studies of corona during eclipses begin in earnest

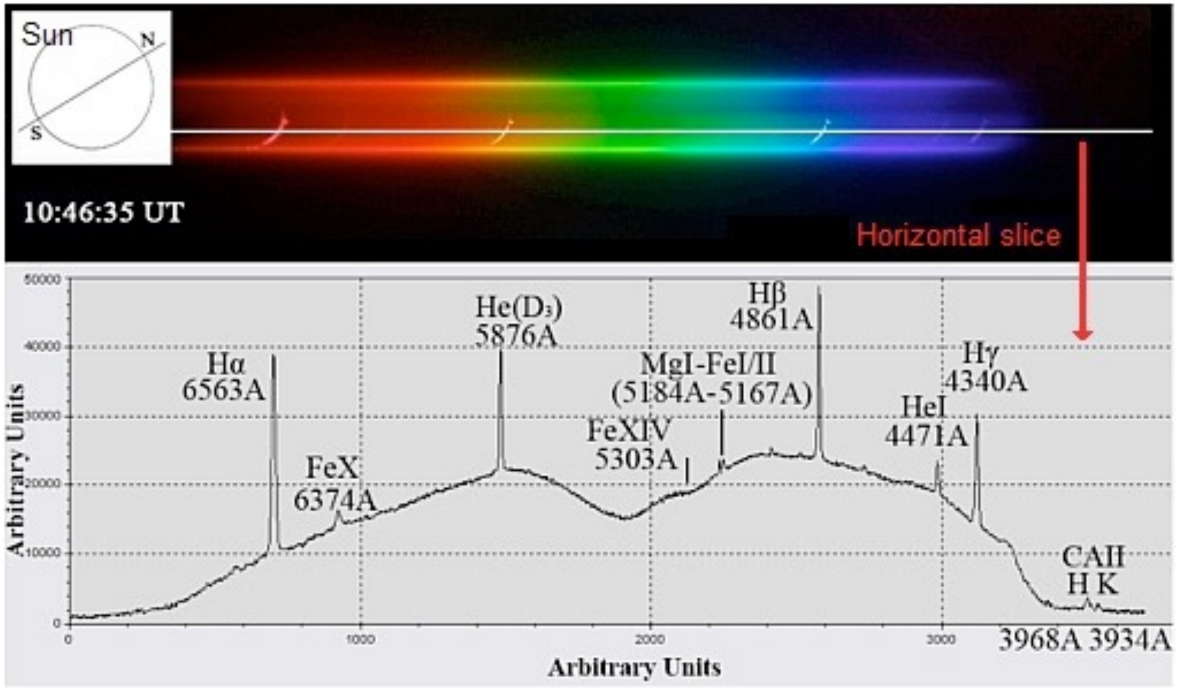
- Apparent solar cycle dependence

- Large extent of corona = Hot corona? Outflow?

Loucif & Koutchmy, Astron. & Astroph. Supp. (1980)

Solar eclipses: Spectroscopy & Coronium

- Modern example of 'flash' spectrum, best taken during total eclipses
- Similar spectra in late 19th Century showed weak unidentified line near 530nm
- New element, lighter than Hydrogen: *Coronium,* or *Newtonium*



http://kho.unis.no/Eclipse/index_Cor.html

- Lyot used his newly invented coronagraph in 1931 to more accurately measure the line outside of an eclipse
- Grotrian & Edlen finally showed the 530.3nm line to be from highly-ionized iron (Fe XIV line, from Fe^{13+} ions.
- Evidence of very hot corona, >1MK

More details: http://laserstars.org/spectra/Coronium.html

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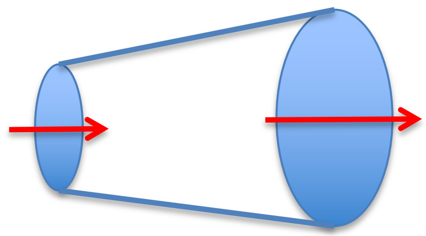
Parker model: first complete theoretical basis for solar wind

- Parker – first to use term "solar wind".
- 1958 paper rejected by ApJ referees! Decision overturned by editor (Chandrasekhar)

Parker Model – isothermal, steady state, spherically symmetric

Mass flux conservation

$r^2 \rho u = constant$



Momentum conservation

$$\rho u \frac{du}{dr} = -\frac{dp}{dr} - \rho \frac{G M_\odot}{r^2},$$

Pressure gradient force

Gravitational force

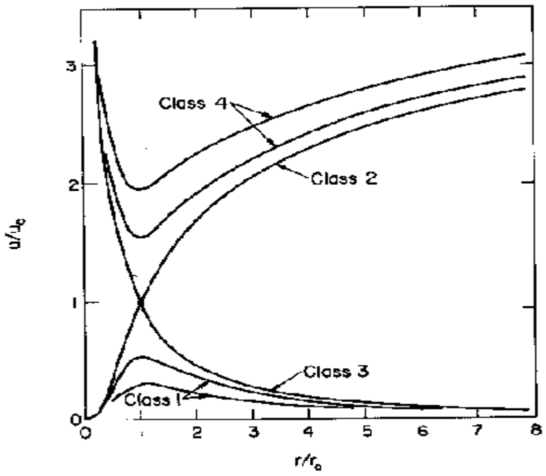
Pressure related to density (isothermal corona)

$$p = \frac{2 \rho T}{m_p},$$

$$\frac{1}{u}\frac{du}{dr}\left(u^2 - \frac{2T}{m_p}\right) = \frac{4T}{m_p r} - \frac{G M_\odot}{r^2}.$$

Parker model: first complete theoretical basis for solar wind

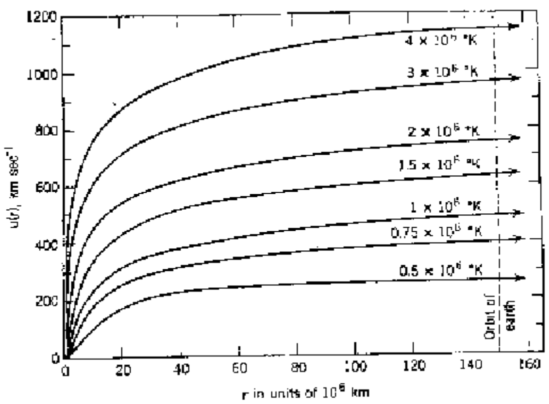
4 main classes of possible solutions, each for a different set of boundary conditions



Class 3, 4 =>supersonic at coronal base) ✖

Class 1 => Decreasing outflow, finite pressure at large *r* ✖

Class 2 => Pressure goes to zero at large *r* ✓



For coronal temperature ~1MK:

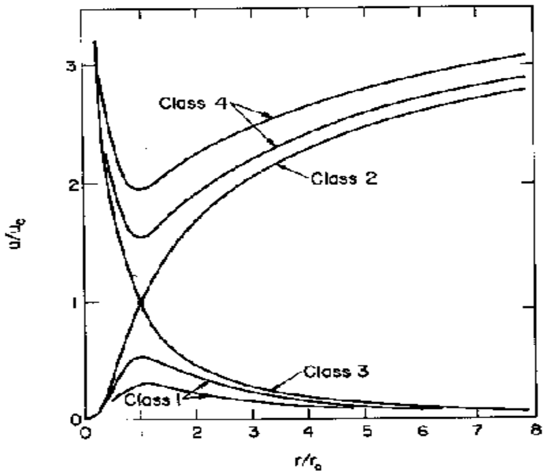
- Outflow speeds several 100km/s at 1AU
- Critical radius (subsonic->supersonic) few solar radii

However:

- Density at 1AU too high compared with observation
- *Why?*

Parker model: first complete theoretical basis for solar wind

4 main classes of possible solutions, each for a different set of boundary conditions



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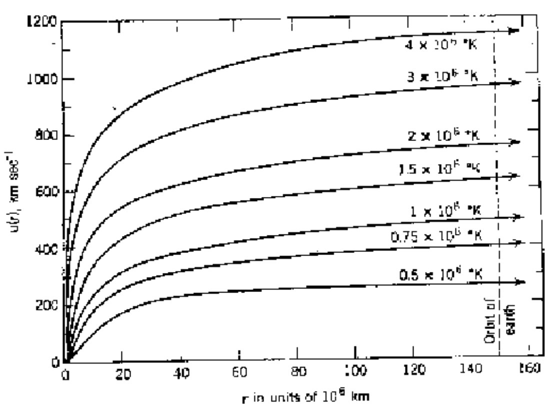


For coronal temperature ~1MK:

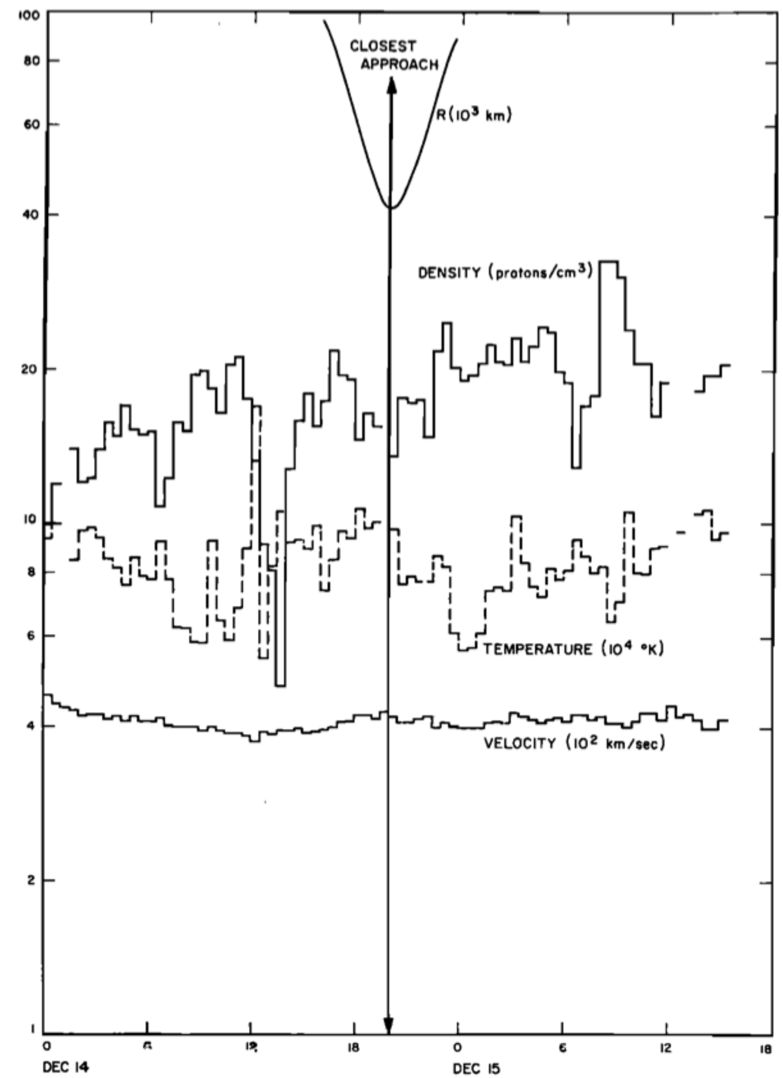
- Outflow speeds several 100km/s at 1AU
- Critical radius (subsonic->supersonic) few solar radii

However:

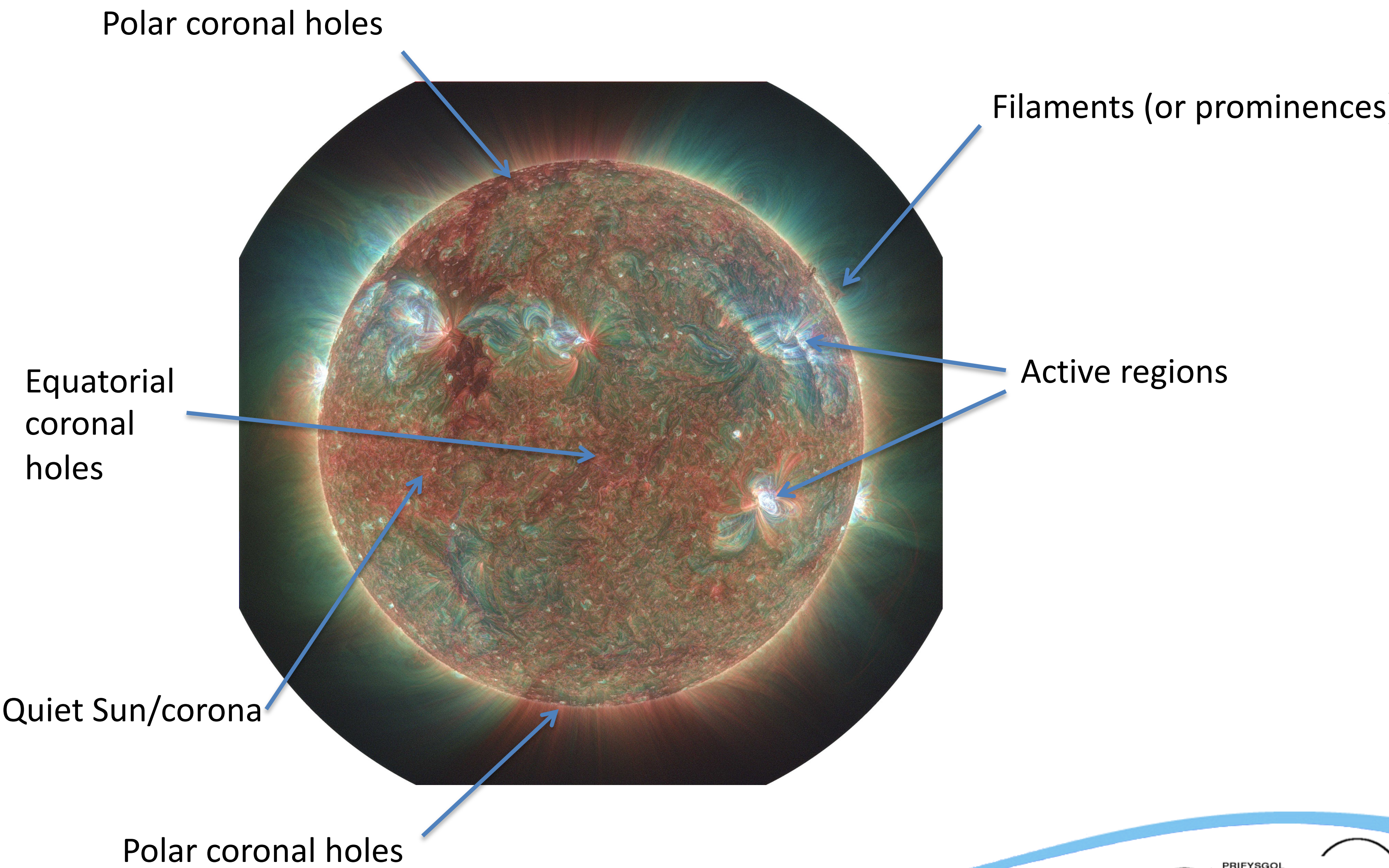
- Density at 1AU too high compared with observation
- *Corona not isothermal*
- *Plasma not composed of one fluid*

First direct measurement of solar wind, 1959

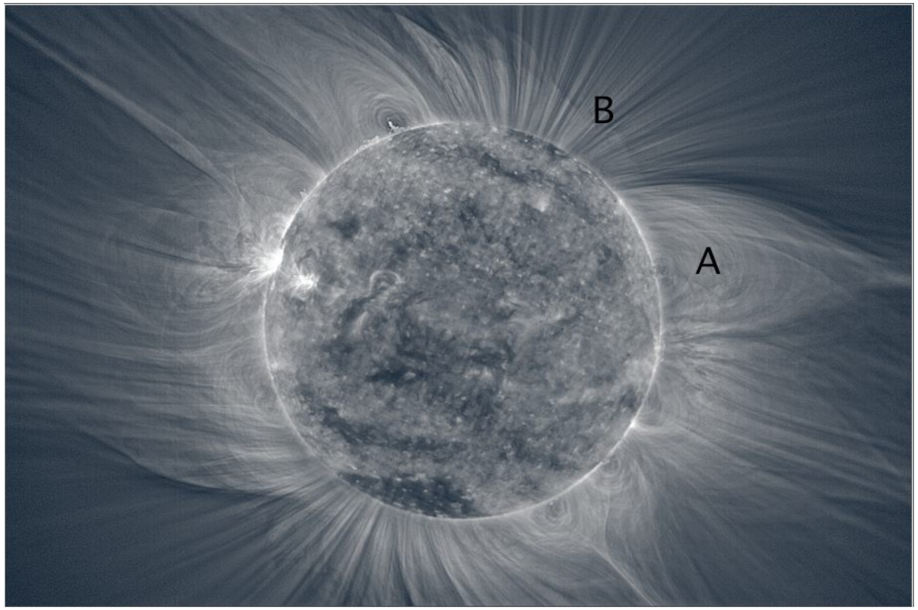
- Soviet spacecraft (LUNA 1), Konstantin Gringauz
- Neugebauer & Snyder (1962), Mariner 2 spacecraft
- Confirmation of Parker and others' work
- Heralds new era in solar system physics



Large-scale low coronal structures (EUV images)



Large-scale low coronal structures



Beta = plasma pressure/magnetic pressure

$$\beta = \frac{P_{gas}}{P_{mag}}$$

In the inner solar corona, the magnetic pressure dominates (plasma Beta<1)

Sun's magnetic field imposes structure on the corona

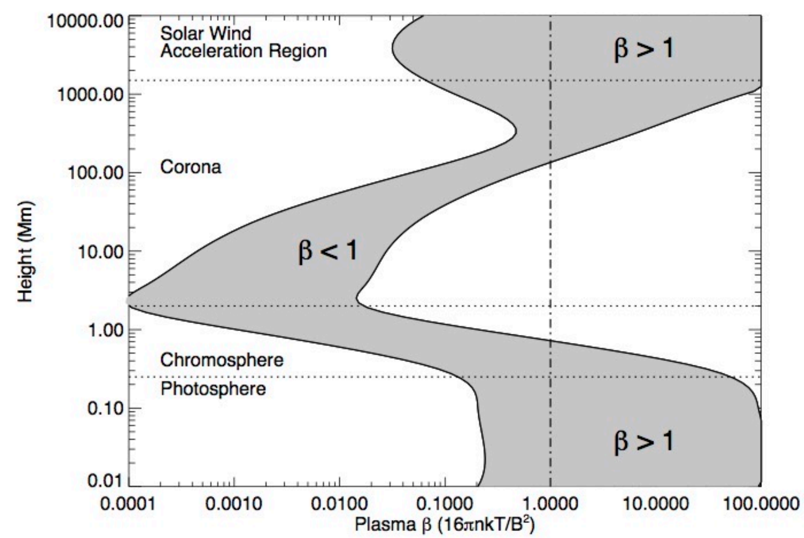


Figure 1.22: Plasma β in the solar atmosphere for two assumed field strengths, 100 G and 2500 G. In the inner corona ($R \lesssim 0.2R_\odot$), magnetic pressure generally dominates static gas pressure. As with all plots of physical quantities against height, a broad spatial and temporal average is implied (Gary, 2001).

Discussion – plasma beta sandwich

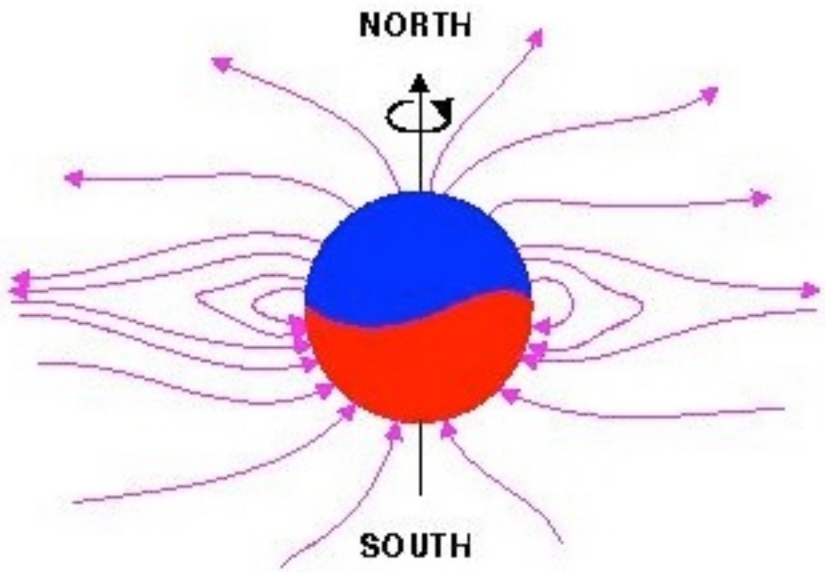
Photosphere/chromosphere: plasma dominates

Inner corona: magnetic field dominates

Extended corona: plasma dominates

Implications in terms of structure/bulk movement?

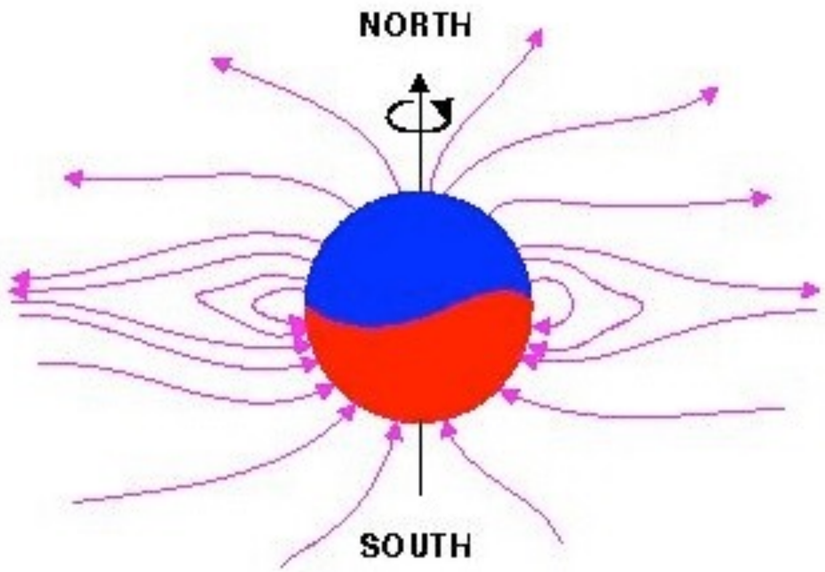
Large-scale coronal magnetic field: dipole model



CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY

- This schematic shows an over-simplified model of the coronal magnetic field at low heights (axisymmetric)
- Most suitable for solar minimum conditions
- Averaged over large spatial regions, photospheric field is generally negative/positive in north/south hemispheres
- Dipole field a good approximation at large distances from Sun at solar minimum

Large-scale coronal magnetic field: dipole model



CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY

Discussion:

The photospheric field is never this simple

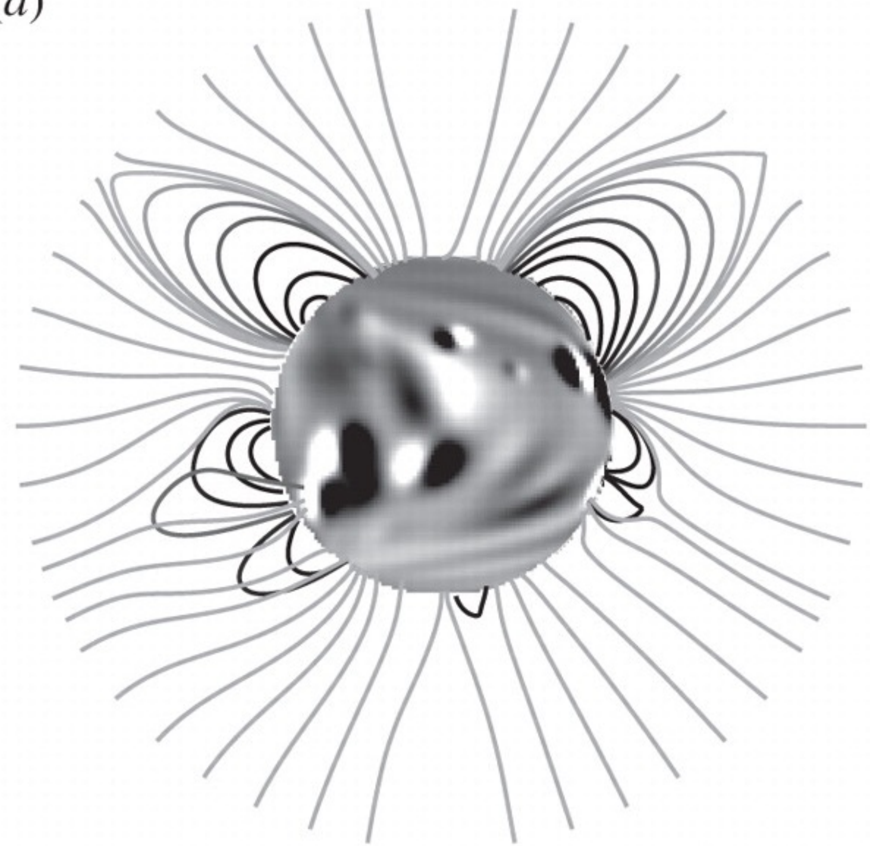
Mix of negative and positive polarities everywhere, even at solar minimum

How would you draw a more complex magnetic field suitable for such a mix of polarities?

How is the simple dipole configuration for solar minimum possible with such a complex photospheric field?

Magnetic field models: potential field (force-free)

(a)

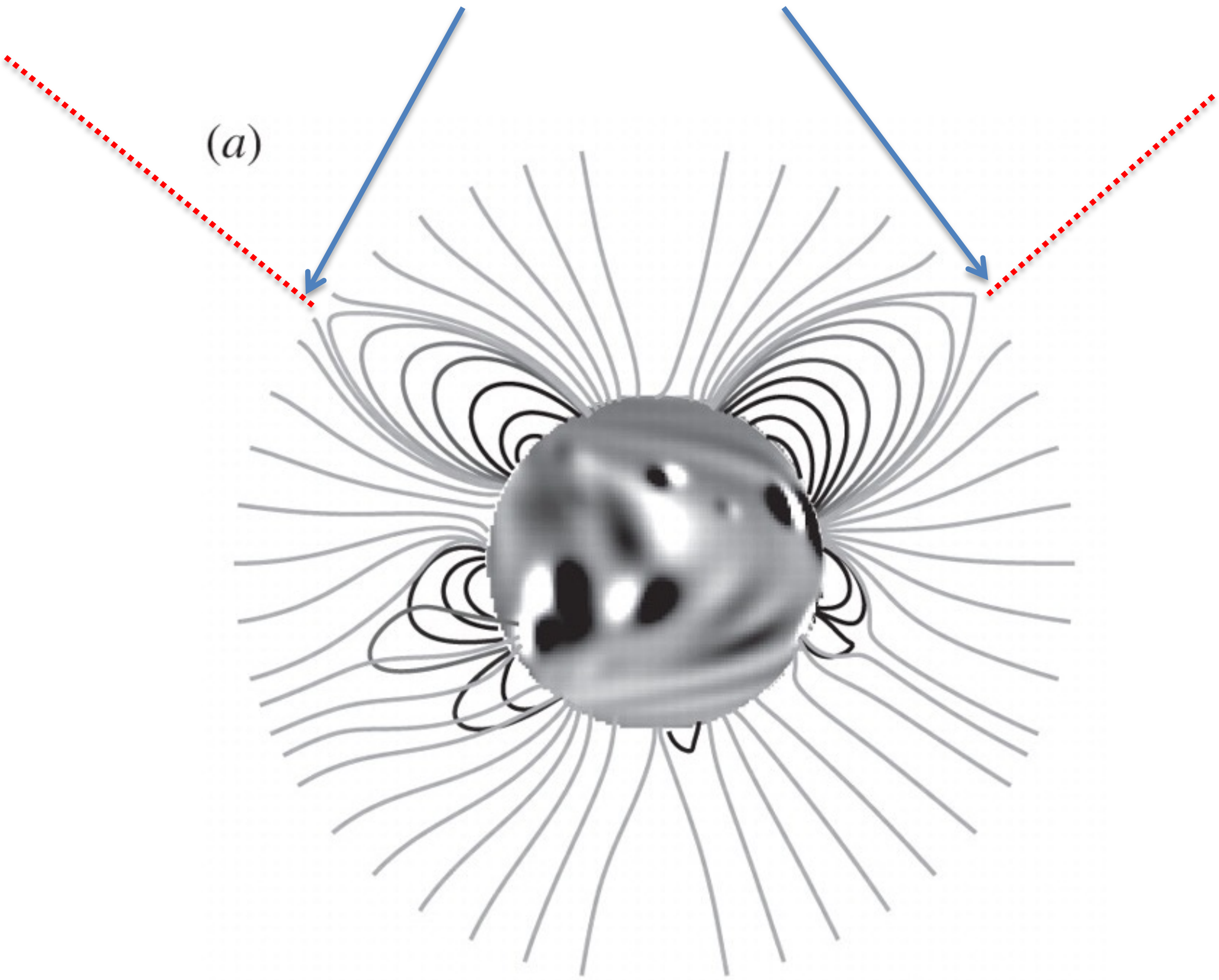


- Smoothed photospheric field
- Fit to spherical harmonics (lower boundary condition)
- Assume coronal ‘source surface’ at ~2Rs (purely radial field)
- Provides unique solution to magnetic field
- Force-free assumption
- Potential field source surface (PFSS) models very widely used

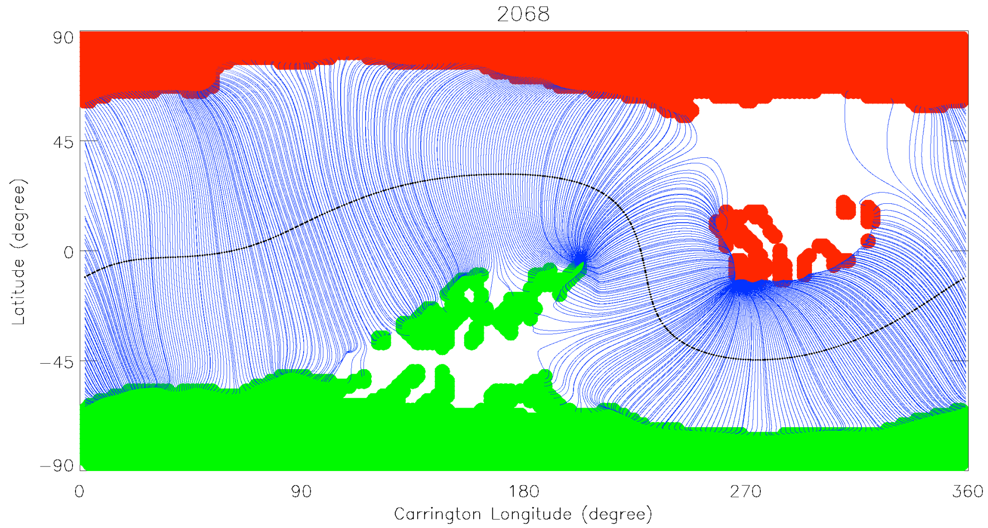
What are the strengths and weaknesses of PFSS models?

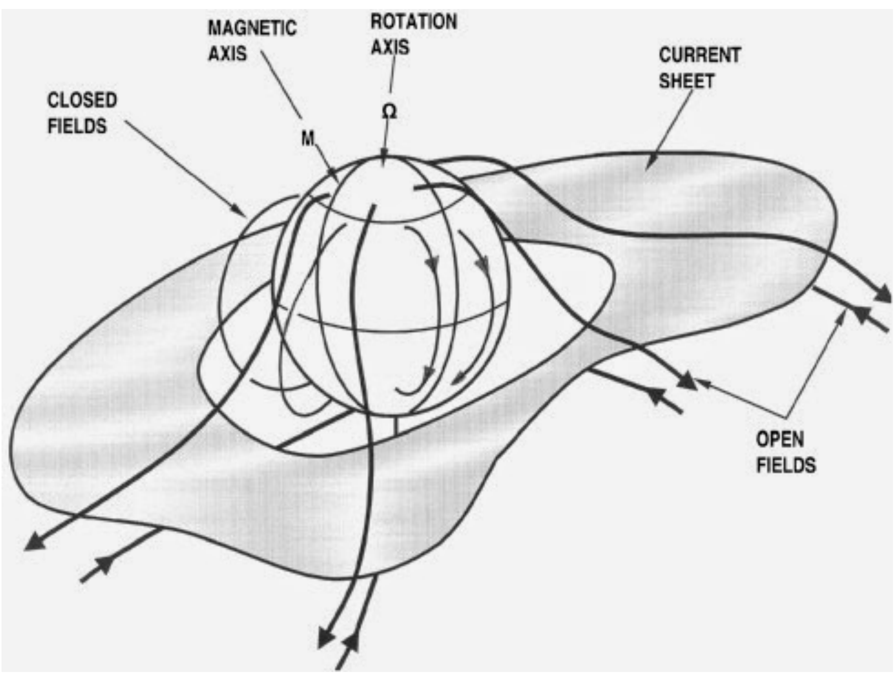
Magnetic field models: potential field (force-free)

Why are these regions special?



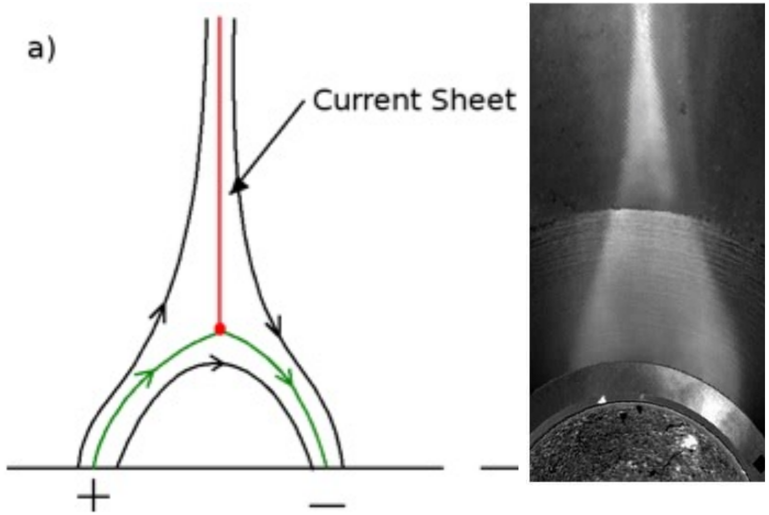
Coronal magnetic field & neutral sheet/current sheet



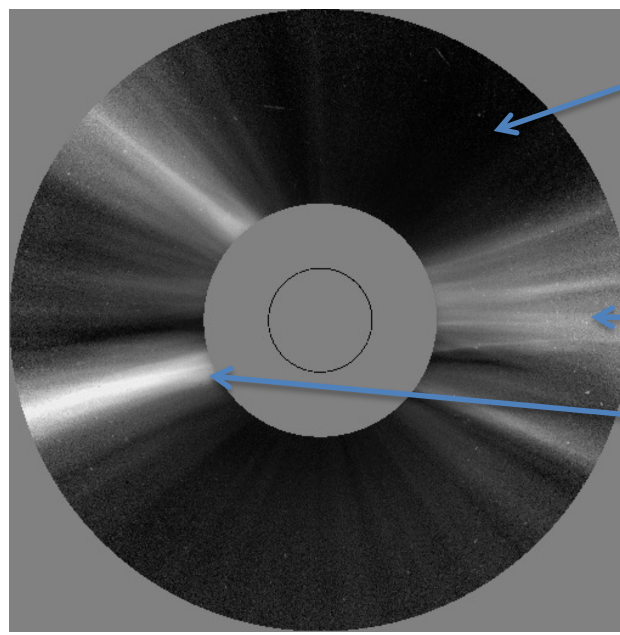


- Line on source surface separating field lines of opposite polarity
- In 3D, a sheet or 'ballerina's skirt'
- Lies at apex of large-scale closed field regions

Coronal streamers / helmet streamers



- Current sheets associated with bright, radial structures in coronagraph images called ‘streamers’ or ‘helmet streamers’
- Current sheet also called ‘streamer belt’
- Dense, slow wind



Pseudostreamers

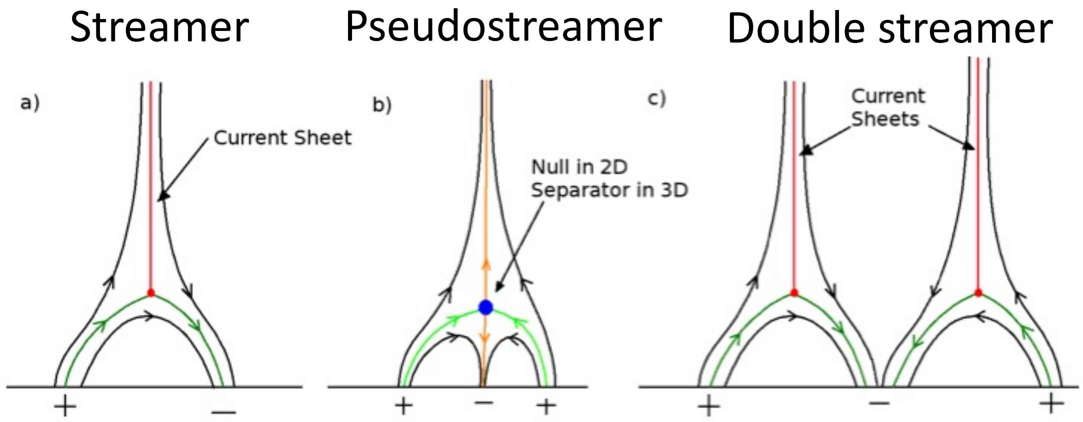


Figure 9. Sketch of the cross section of a streamer (a), a pseudostreamer (b) and a double streamer (c).

From Edwards, Yeates, Bocquet, Mackay et al (2015)

- Streamers have a single current sheet, separating opposite magnetic polarities. Open magnetic field lines arise from widely-separated regions on the Sun. They bridge over large-scale closed-field regions.
- Pseudostreamers have no current sheet, field lines are the same polarity. Open magnetic field lines arise from widely-separated regions on the Sun. They bridge over large-scale closed-field regions.
- (Double streamers – multiple current sheets)

Streamers = Highest density, slow outflow, highly variable outflow (blobs)

Pseudostreamers = Lower density (yet higher than ‘background’ coronal holes), slow outflow, less variation (no blobs)

Magnetic vs. Plasma structure: 'Q' factor, or 'squashing' factor, or 'convergence' factor

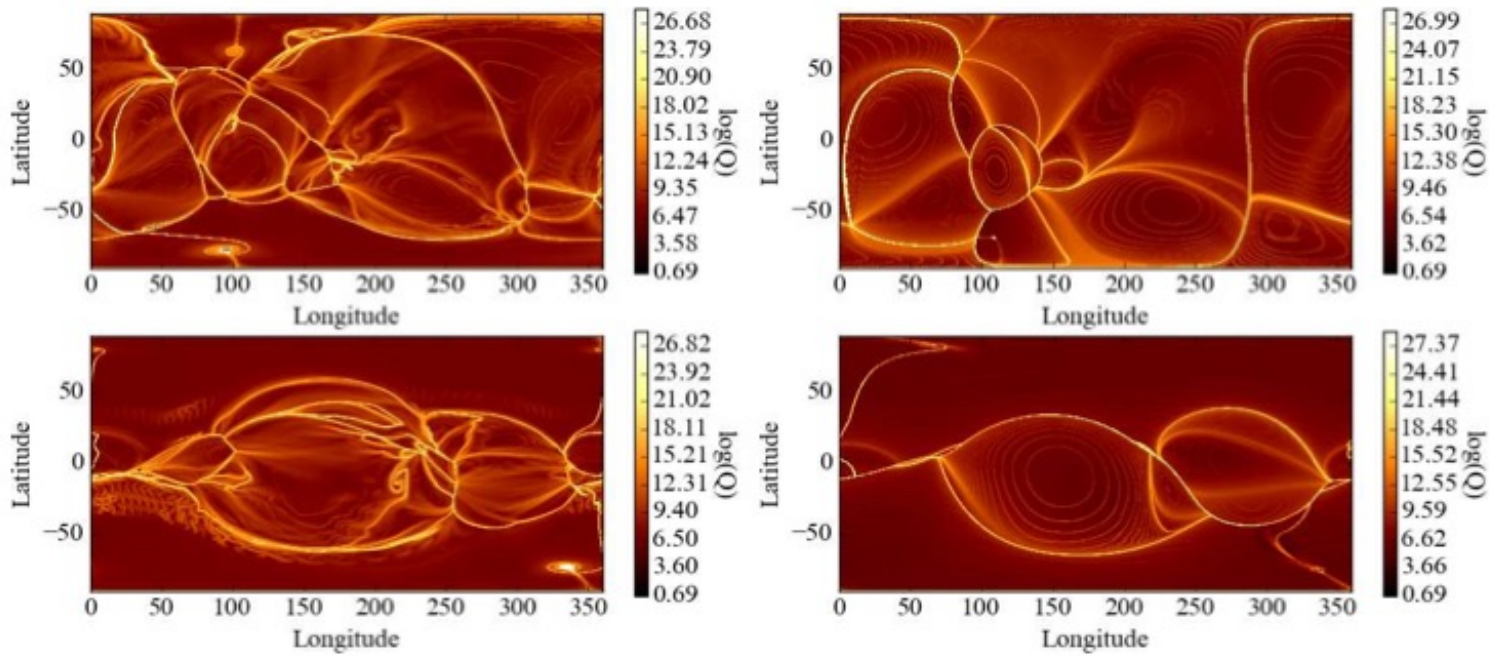


Figure 10. Squashing factor [Q] calculated at 21.5 $R_\odot$ boundary for 4 April 2000 (top row) and 30 April 2013 (bottom row) for the NP (left column) and PFSS (right column) models.

From Edwards, Yeates, Bocquet, Mackay et al (2015)

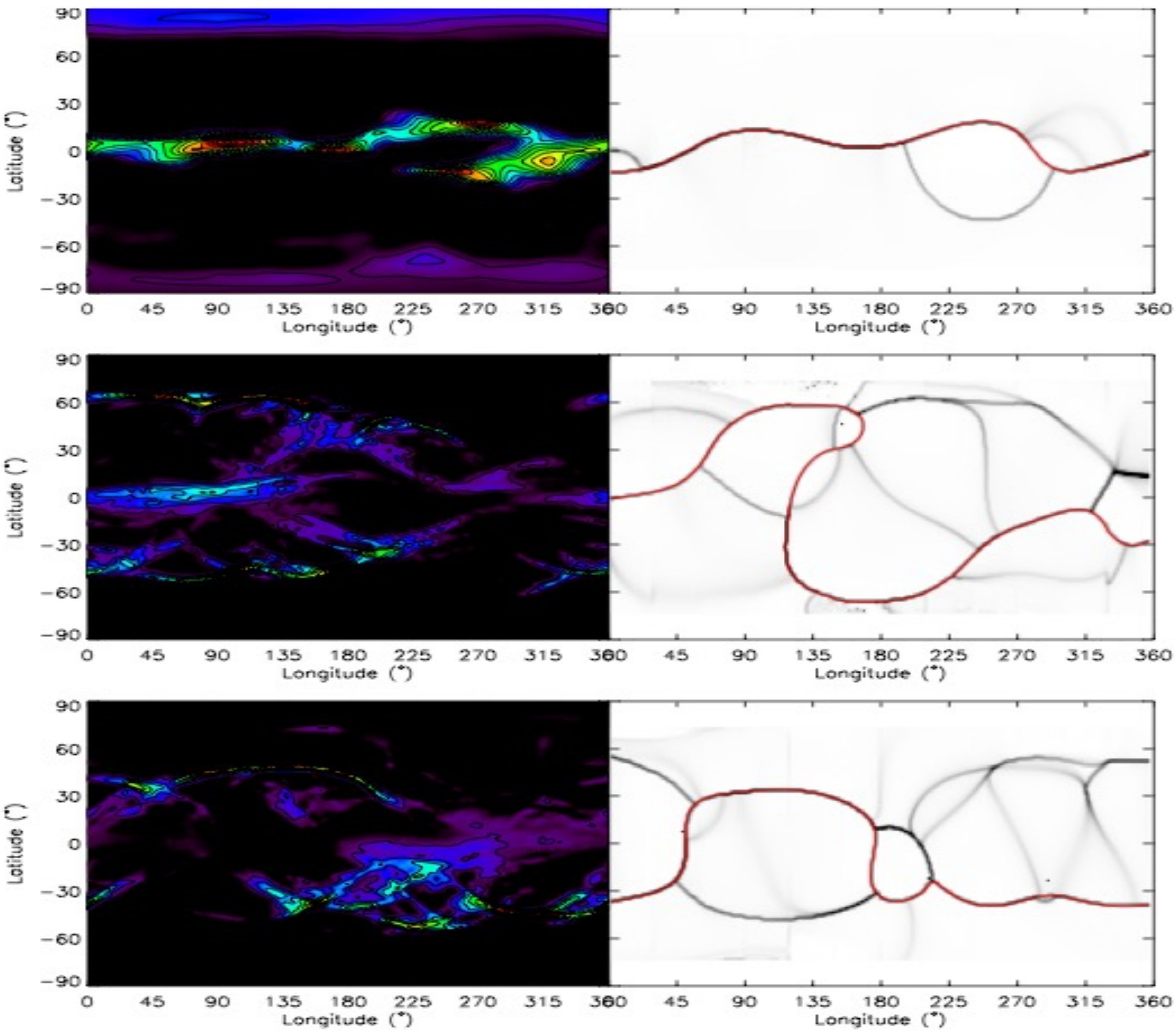
- At source surface, local measure of separation of field line footpoints at the Sun
- Regions containing field lines arising from widely-separated sources -> high Q factor
- Contains both streamers (current sheet) and pseudostreamers
- Should relate to density structure

Magnetic structure vs. Plasma structure

Density structure | Magnetic structure

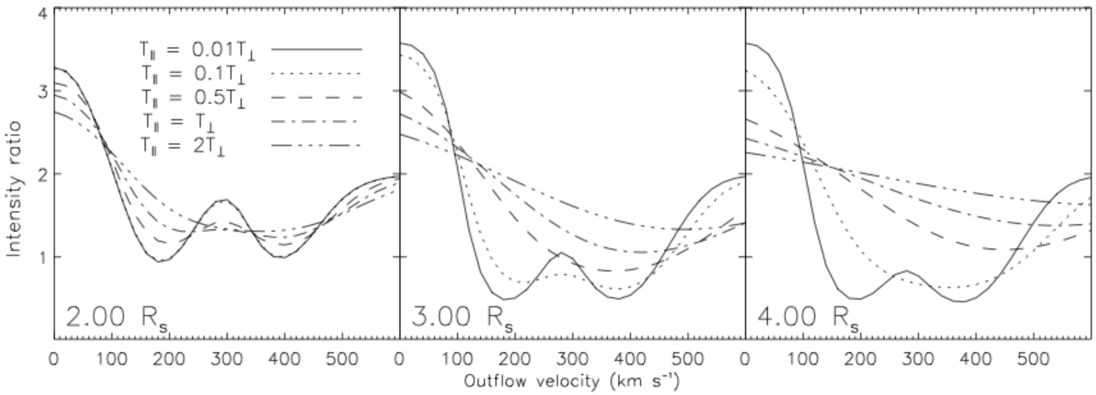
Solar min (1996)

Solar max (1999)

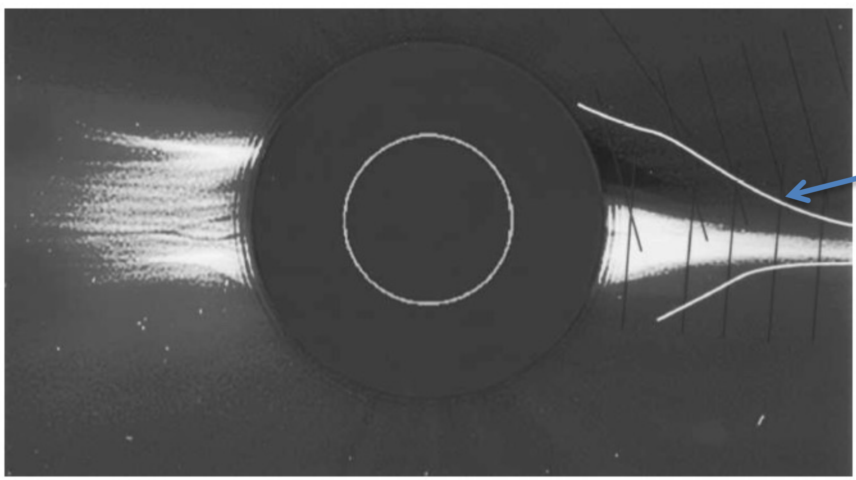


- Magnetic maps from PFSS
- Density maps from tomography of LASCO coronagraph data
- Current sheet = red
- Pseudostreamers = black

The UltraViolet Coronagraph Spectrometer: UVCS/SOHO



Intensity ratio of O VI doublet provides constraint on the ion outflow velocity and ion temperature

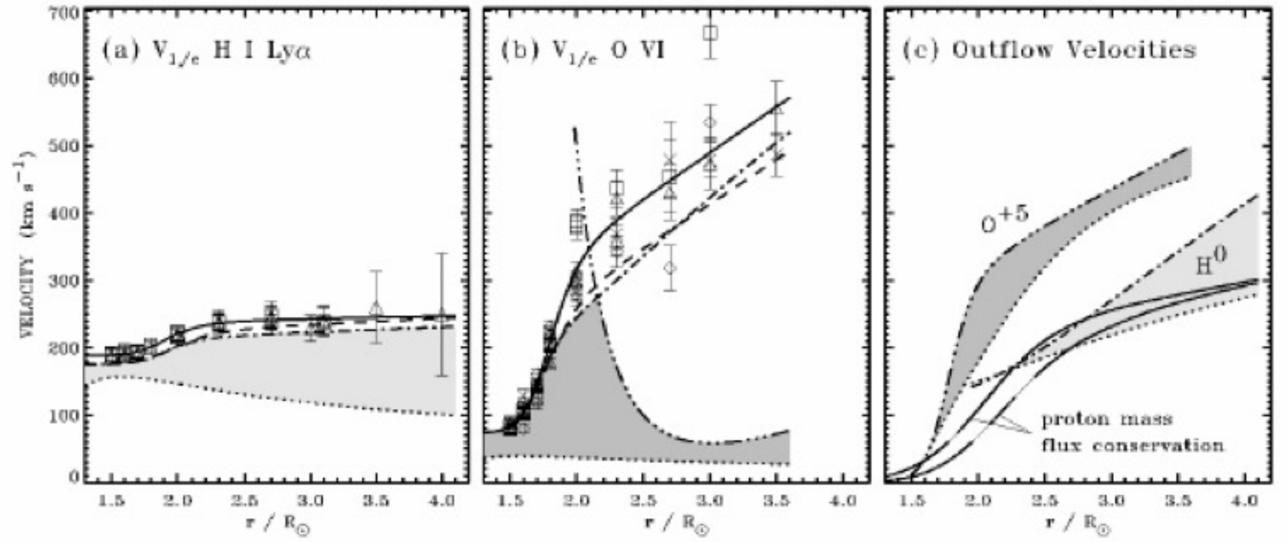


Contour indicates measured line ratio corresponding to ~100km/s

First direct evidence of solar wind speeds close to the Sun

Streamers = slow
Coronal holes = fast

The UltraViolet Coronagraph Spectrometer: UVCS/SOHO



Results for large polar coronal hole

For open field regions:

- Preferential heating & acceleration of heavy ions, at low heights
- Temperature anisotropy (T_{perp}>>T_{par})
- Very high linewidths (Effective temperature = thermal + wave motions)
- Constraints on solar wind heating/acceleration models/theories.
  Ion cyclotron resonance with Alfven waves?

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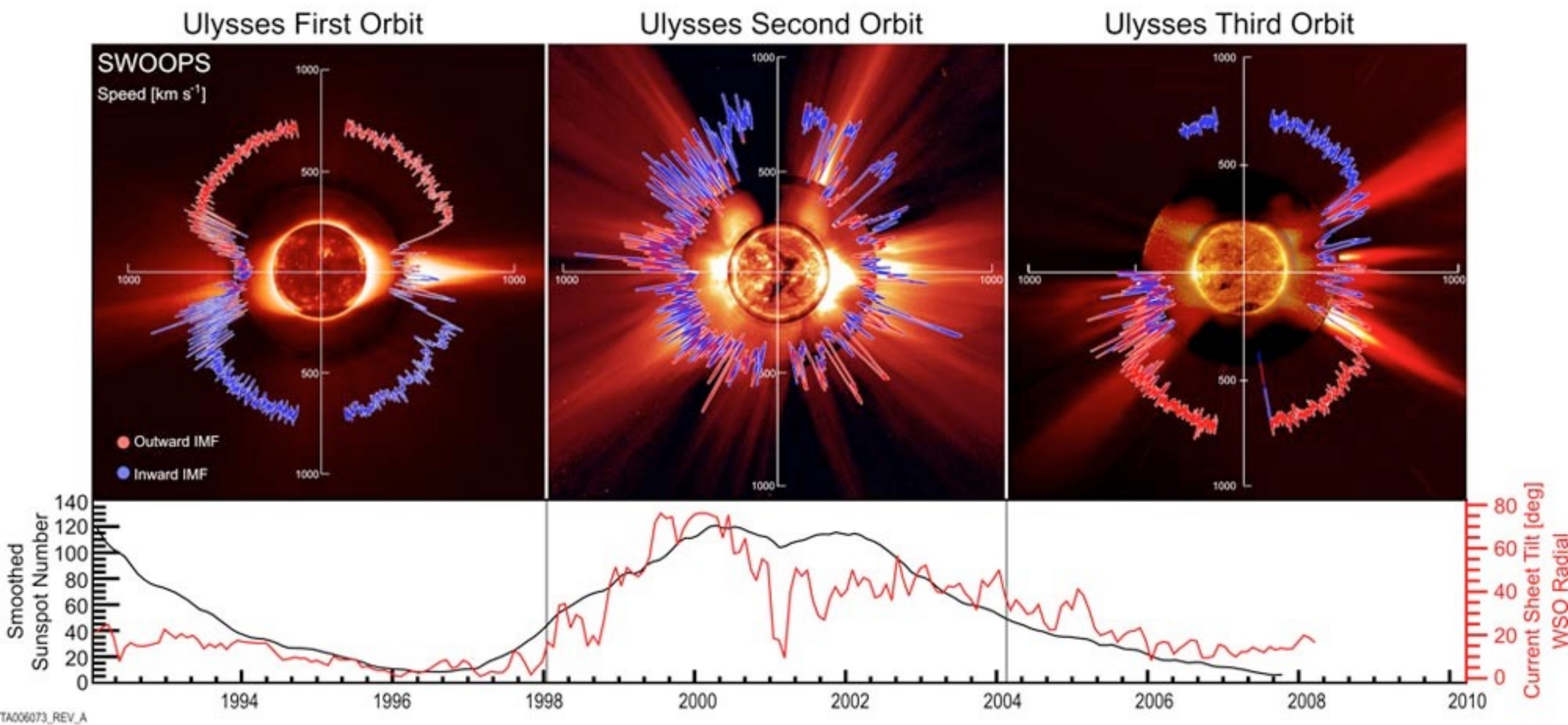
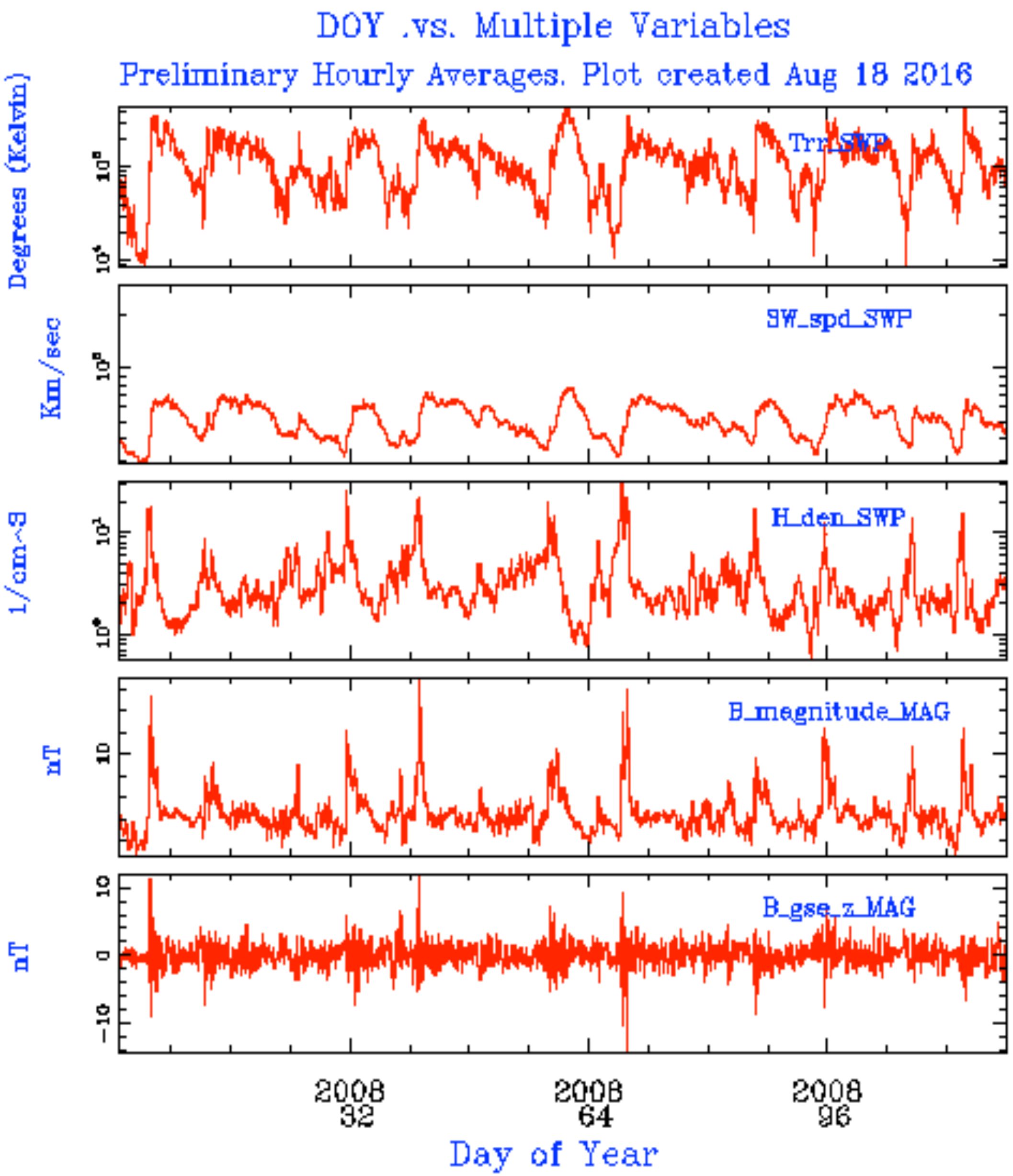
Ulysses mission –out-of-equatorial orbit



Fast, low-density wind, low-variability associated with coronal holes

Slow, high-density wind, high-variability associated with streamer belt

In situ measurements of the solar wind (typically 1AU)



- Several spacecraft dedicated to measuring solar wind near Earth orbit (ACE, WIND, STEREO)
- Package of instruments measuring magnetic field components, electrons (energy distributions, direction), protons (speed, density, distribution), Helium, other minor ions.

Discussion: *This plot shows ~120 days from 2008, measured by ACE. Any noteworthy features?*

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Parker spiral

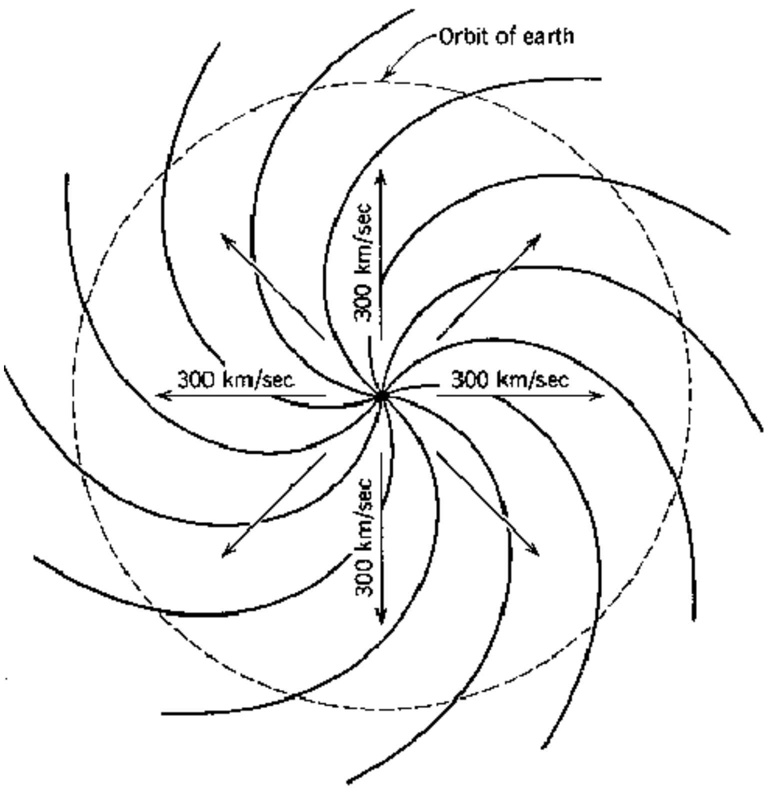


Figure 5.4: *The interplanetary magnetic field.*

- Plasma flows ~radially out from the Sun
- Sun rotates at ~27 day period (synodic)
- Magnetic field 'frozen in' to outflowing plasma
- Describes spiral pattern
- ~45 deg inclined to Earth orbit tangent

Parker spiral

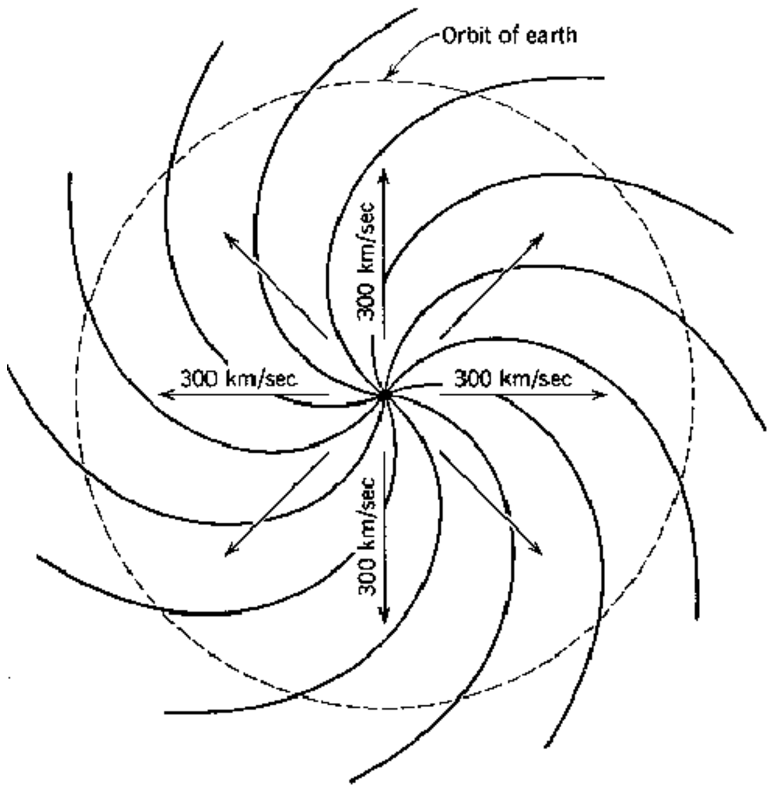


Figure 5.4: *The interplanetary magnetic field.*

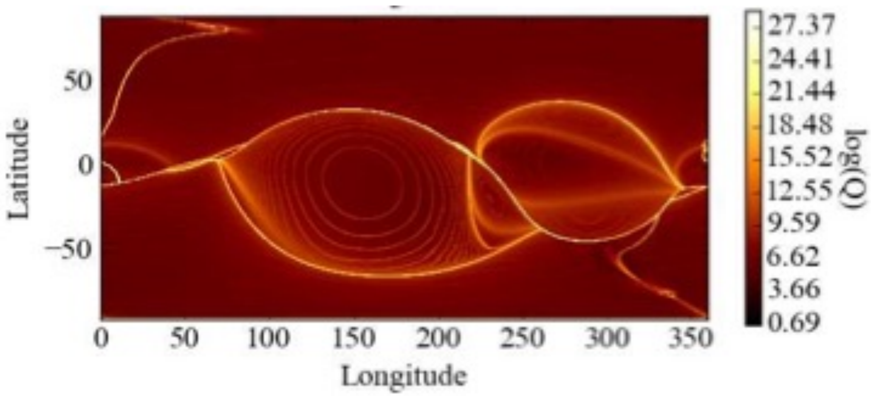
Even in the equatorial plane, large, long-lived coronal holes can exist (=fast wind ~700km/s).

Even in the absence of equatorial coronal holes (solar minimum), current sheet is not exactly aligned with equatorial plane of Sun.

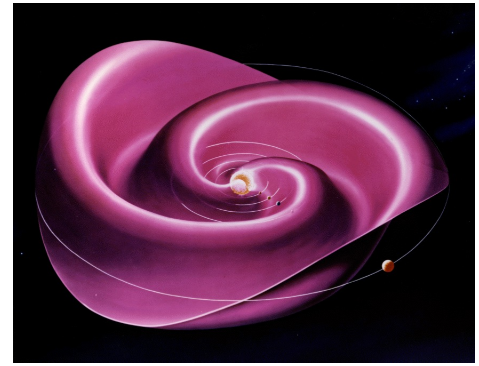
What happens to the Parker spiral pattern in the case of streams of different outflow speed?

Stream interaction regions

Density/magnetic structure near Sun

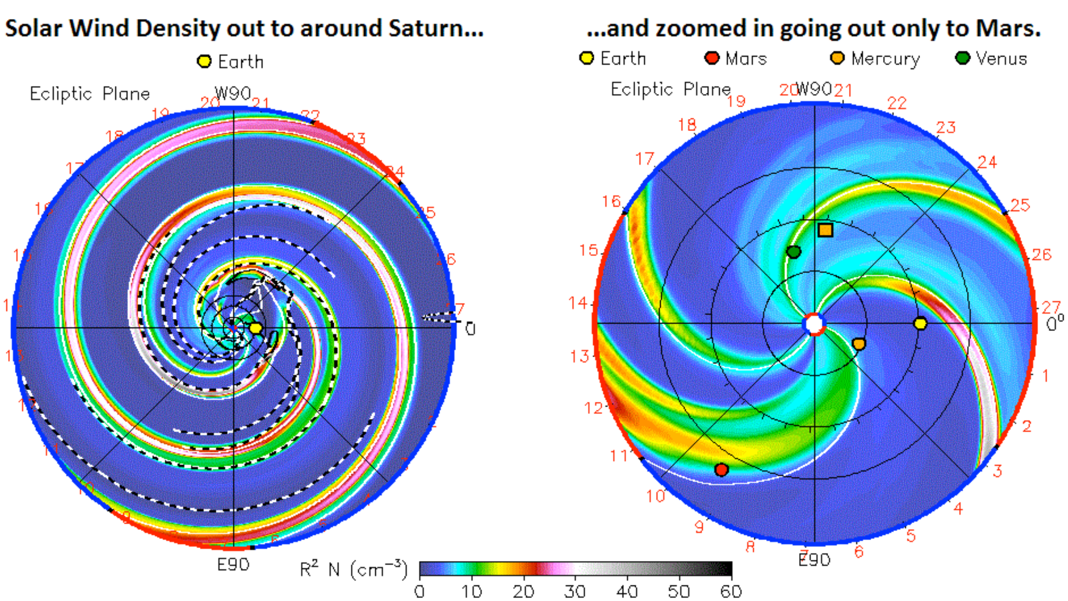


Ballistic extrapolation into heliosphere



“Ballerina’s skirt”

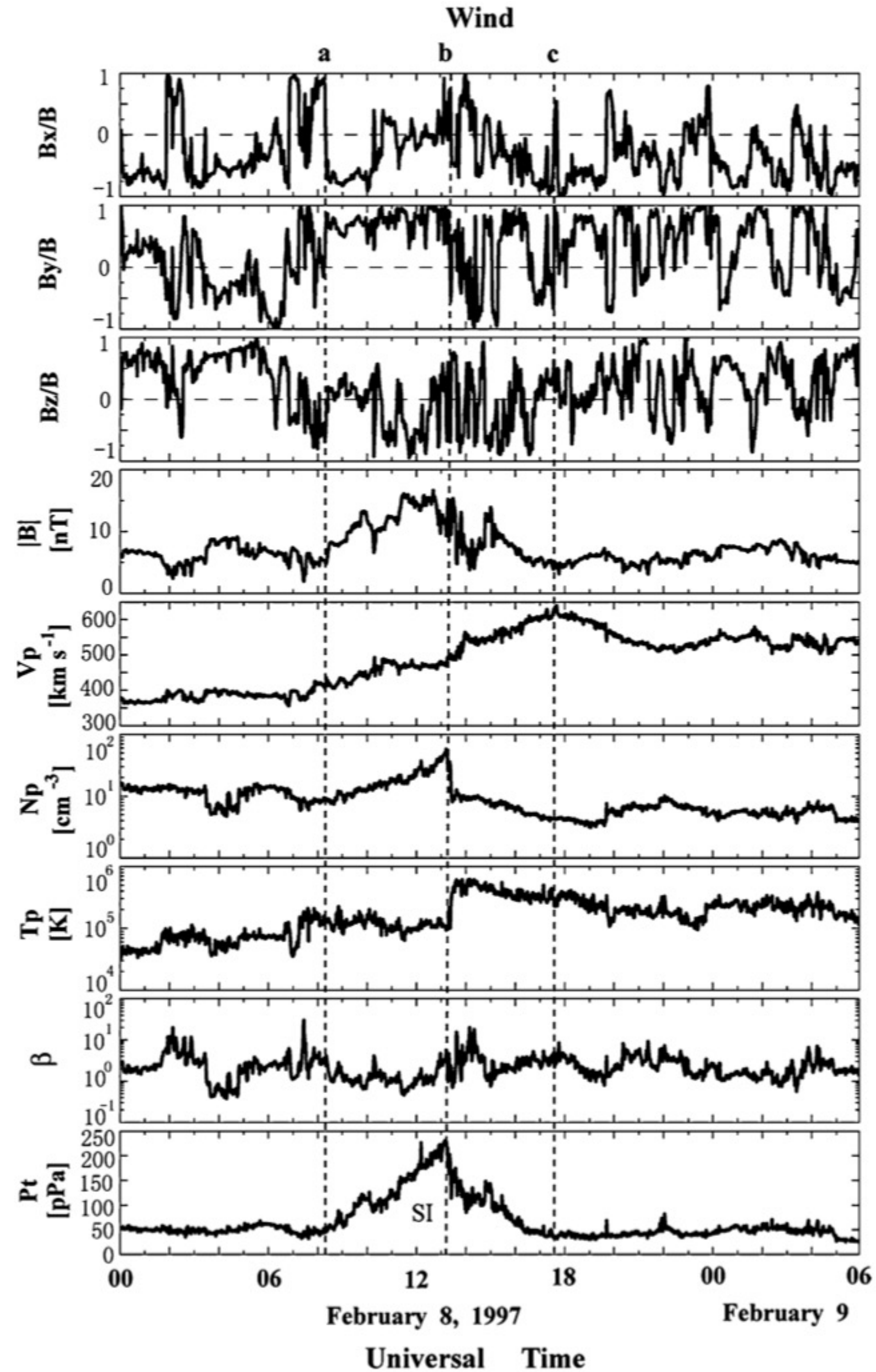
In-situ spacecraft in the ecliptic plane measure recurrent patterns of slow/fast wind



- Bands of slow/fast wind.
- Different outflow speed, different spiral ‘winding’
- Stream Interaction regions (SIR), or Corotating Interaction regions (CIR)

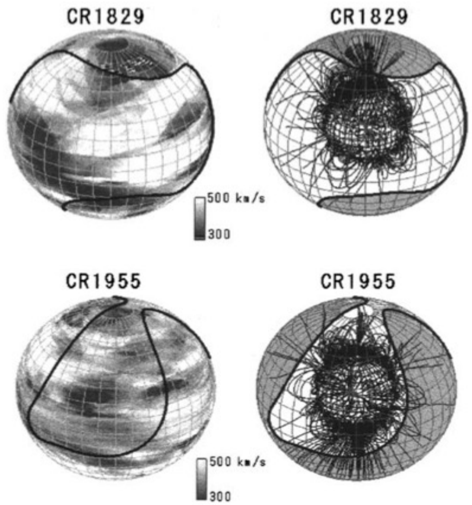
The Solar Wind – stream interaction regions (SIR)

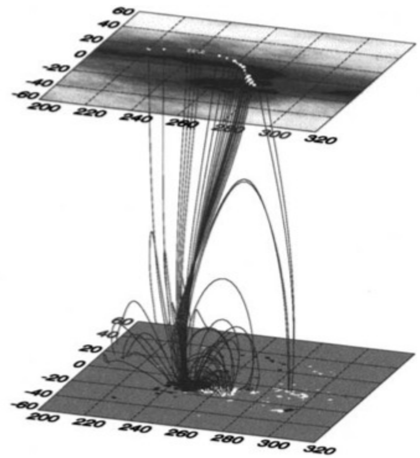
- Stream Interaction Region: fast wind interacting with preceding slow wind
- Corotating Interaction Region is an SIR that persists over several solar rotations (~27 days synodic)
- SIR last ~36 hours on average
- Large fluctuations in B-field
- SIRs evolve with increasing distance from Sun
- Often accompanied by forward/reverse shocks
- If shocks not present – evolve further than 1AU
- Often associated with sector boundaries (magnetic polarity reversal)



Source of the slow solar wind

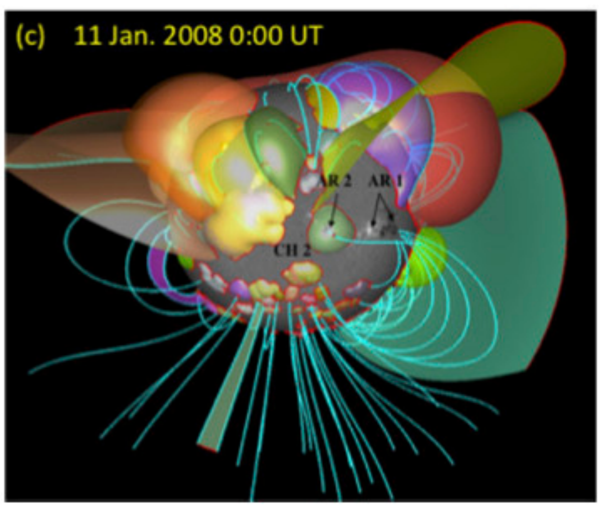
An outstanding problem in solar/heliophysics – what are the sources of the slow solar wind at the Sun?

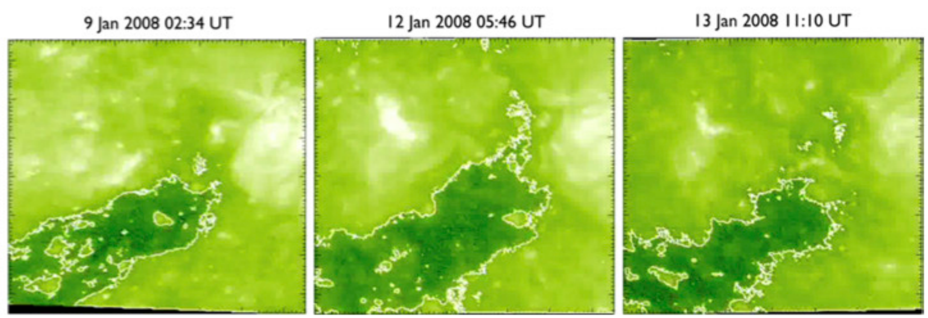


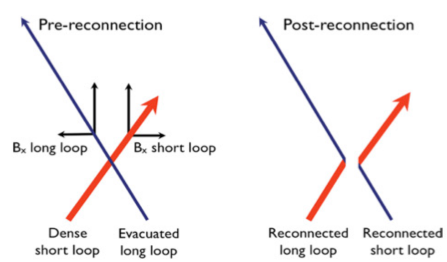


From Ohmi *et al* 2013

- Map *in situ* measured slow flows ballistically back to ~3Rs (source surface)
- Use PFSS models to map back to photosphere
- Sources near boundary of active region
- But this result will *always* be the case for PFSS models!
- NOT a robust conclusion







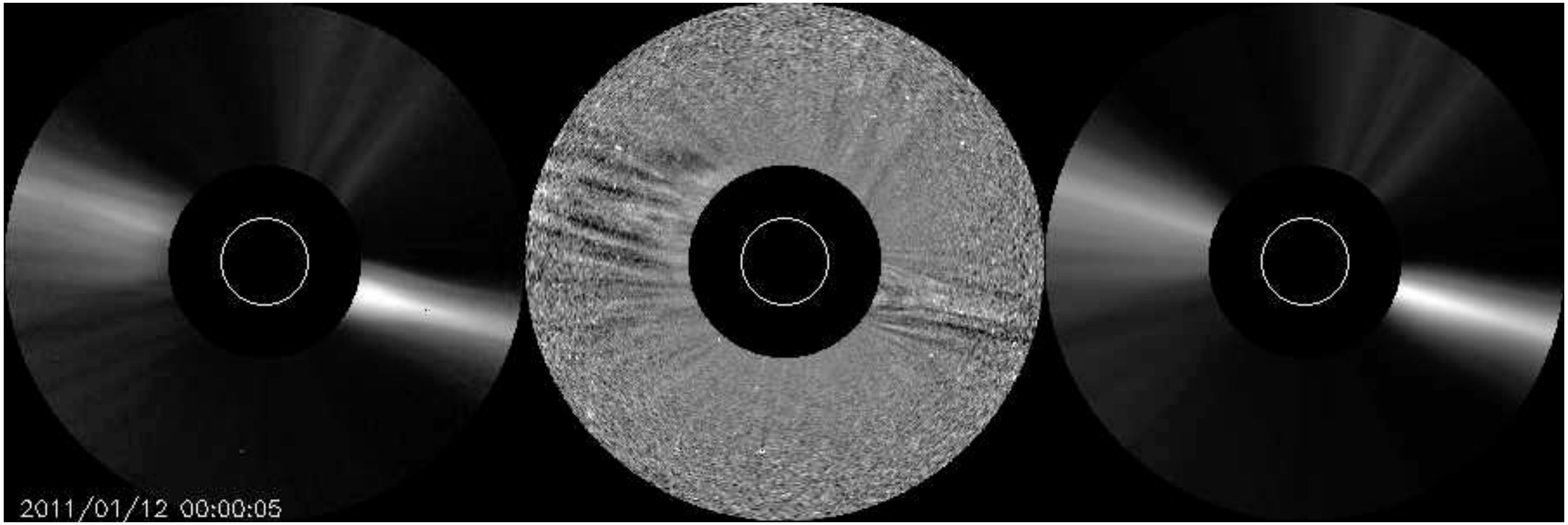
From van Driel-Gesztelyi et al (2012)

- Increasingly sophisticated models for low corona
- Invokes exchange reconnection at boundaries between active regions and neighboring coronal holes

Some stuff I've neglected

- Details of in situ measurements (proton velocity distributions, ion composition, waves, electron measurements)
- Models (large-scale MHD models)
- Turbulence
- Shocks
- Solar wind at large distances beyond Earth
- Interaction with planetary magnetospheres/atmospheres
- Details of heating & acceleration mechanisms

Coronal Mass Ejections: CMEs



- Large eruptions of magnetised plasma
- Solar cycle dependence on CME frequency. Several large CMEs per day @solar max
- Wide distribution of speeds (~100-1000km/s)
- Wide distribution of mass (~10^{14}-10^{16}g, or several Snowdons)
- Larger CMEs associated with closed-field regions at Sun, so latitudinal dependence
- Larger CMEs are structured as *magnetic flux tubes*, with footpoints embedded in photosphere. Croissant-shaped.
- Associated with filament eruptions, flares, jets

Solar eclipses: Hand drawings & First record of a CME, 1860

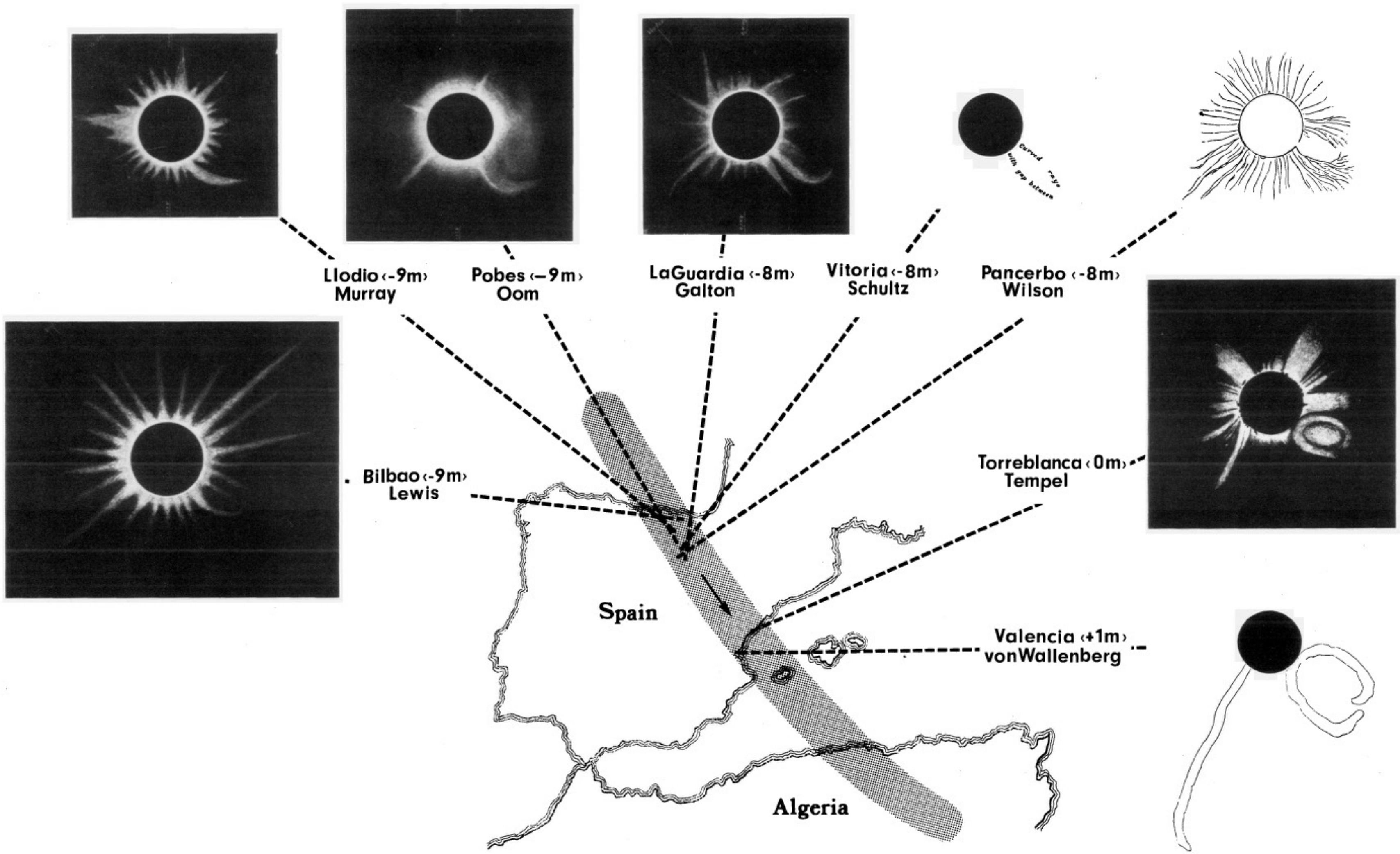
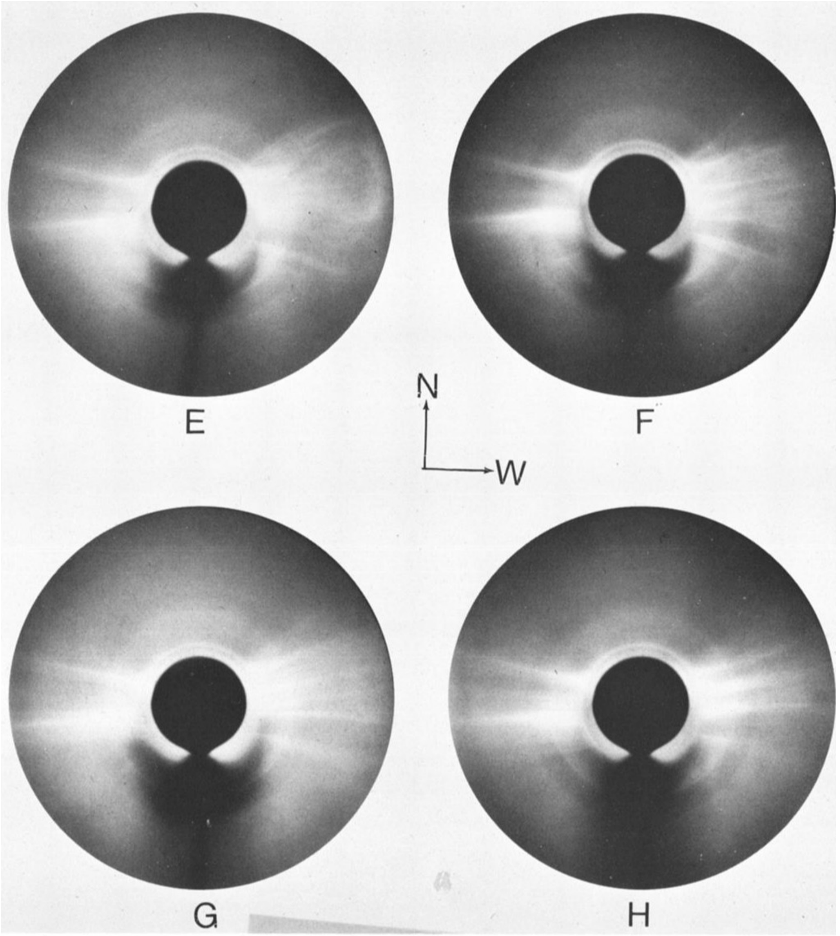


Fig. 4. Selected drawings of the corona (from Ranyard, 1879), made by different observers along the path of totality in Spain during the 1860 eclipse. Times are relative to mid-totality at Tempel's station at Torreblanca

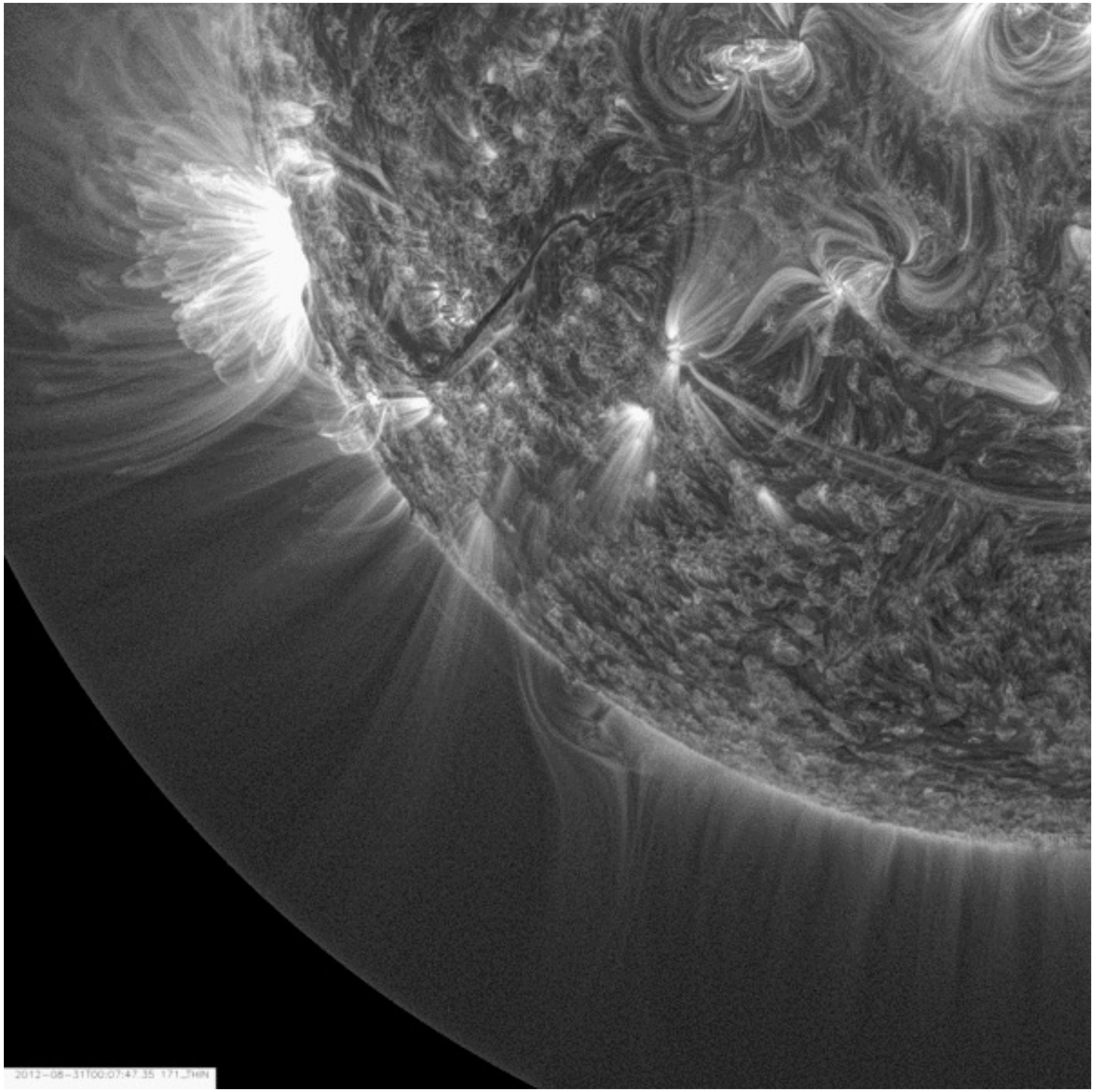
Eddy, Proc. Conf. Ancient Sun (1980)

First modern observations of CMEs

- Gosling (JGR, 1974)
- Skylab coronagraph
- Reported >30 instances of ‘sudden mass ejections from the sun’
- Large magnetic loops rooted at the Sun, expanding outwards at ~400km/s
- 18 associated with prominence eruptions, 3 with flares



Models of CME initiation



Magnetic field footpoints moved by photospheric motions

↓

Build-up of magnetic energy in overlying corona.

↓

System is unstable - prone to catastrophic (rapid) change

↓

Small trigger causes eruption

↓

Release of magnetic energy, return to lower-energy state

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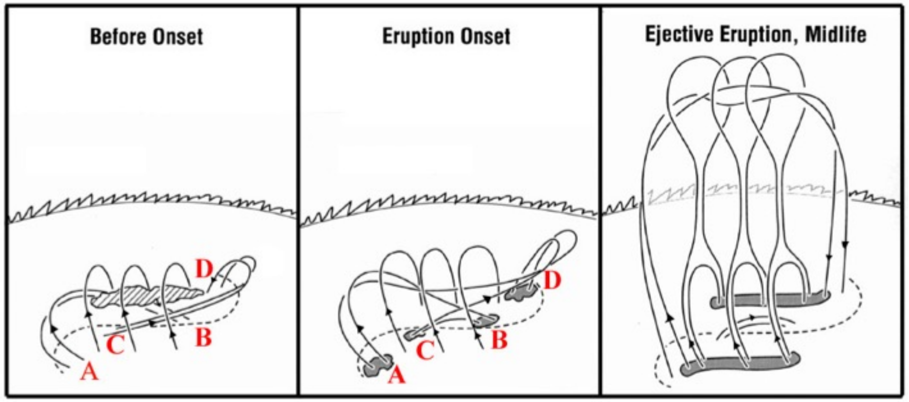
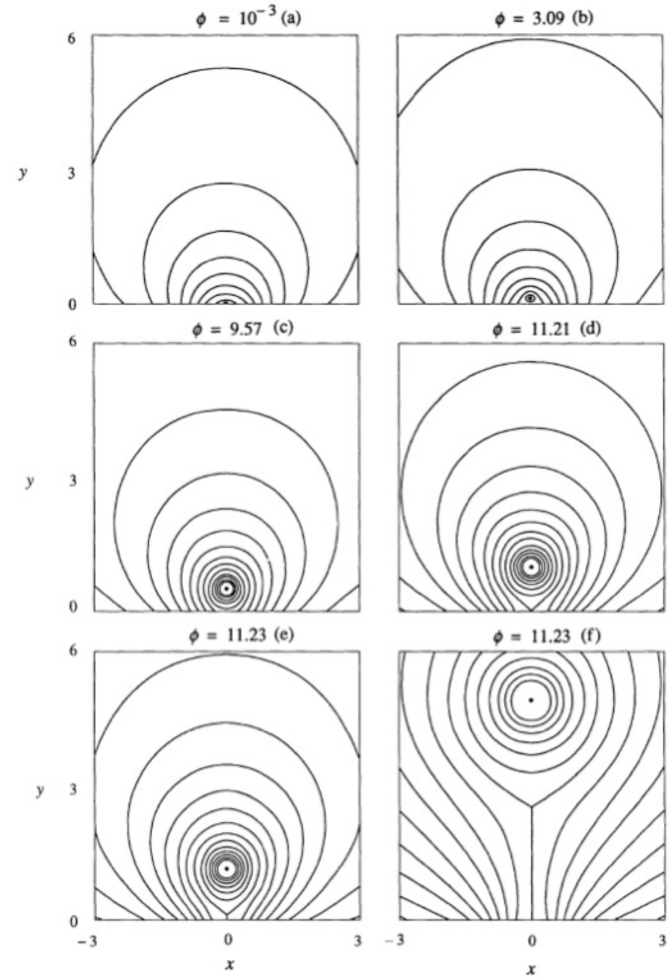
Generic model of CME initiation

Moore *et al* (2001)



Forbes & Isenberg (1991)



- Flux rope formed in low corona (see models of filament formation for more detail)
- Equilibrium: magnetic tension vs. buoyancy of plasma
- Some process causes magnetic field to weaken/become unstable (reconnection/twist)
- Flux rope rises and overcomes magnetic confinement, accelerates outwards, expands

CME initiation/triggering mechanisms – tether-cutting

Tether-cutting / shearing motions:

- Strong magnetic shear at base of filament/flux tube
- Reconnection occurs at base
- Flux tube is free to rise

- But what causes the reconnection?
  - Photospheric motions – gradual reconnection/flux cancellation (shearing motions)
  - More rapid process – genuine tether-cutting, more impulsive event

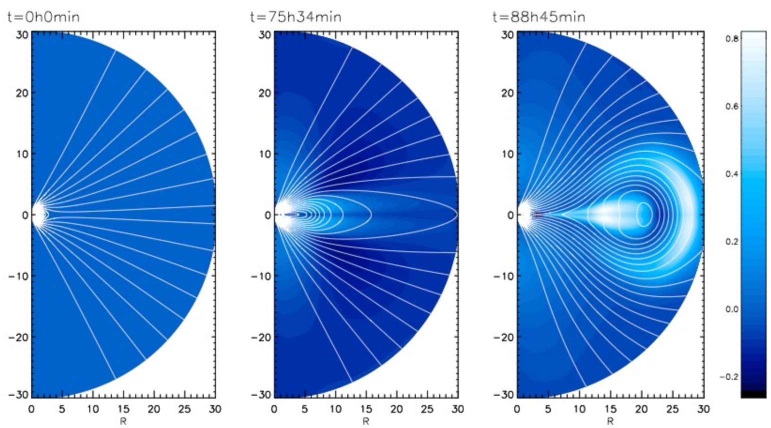


Fig. 2. Three snapshots of the simulation on wind model 1 and $v_{\varphi}^{max} = 6\ \mathrm{km\,s^{-1}}$, showing the relative density (colour scale) and the magnetic field lines (white). *On the left*: the stationary wind, *in the middle*: just before the flux rope is formed, *right*: propagation of the flux rope.

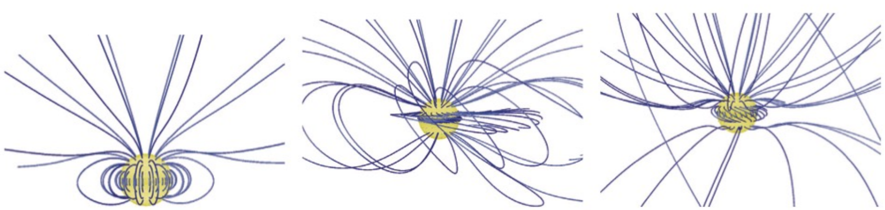


Fig. 3. Representation of the 3D configuration of the magnetic field for the same simulation as in Fig. 2. The snapshots are taken after respectively 0 h, 75 h 34 min and 88 h 45 min.

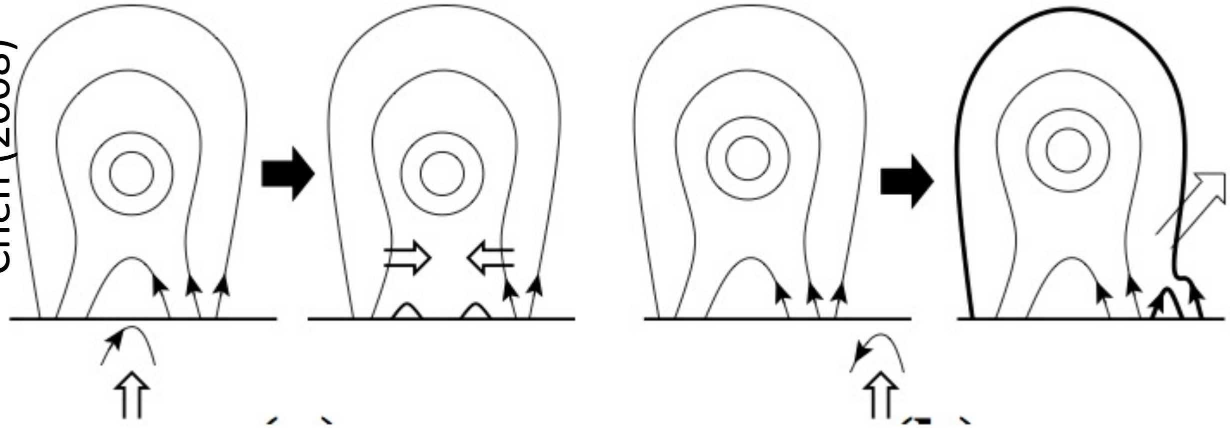
Jacobs *et al* (2006)

In response to the imposed shearing of the magnetic foot points the helmet streamer starts rising into the corona and also starts to swell. The shearing increases the outward pointing magnetic pressure force, such that this force is no longer in balance with the inward pointing magnetic tension force and, as a result, an outward expansion can occur. Hence, this process brings

CME initiation/triggering mechanisms – flux emergence

Instability in overlying flux tube caused by new flux emergence in the photosphere

Chen (2008)



Opposing flux directly under flux tube triggers reconnection, weakening field between legs of flux tube

Opposing flux at one footpoint of overlying arcade. Weakens overlying field, allows flux tube to rise

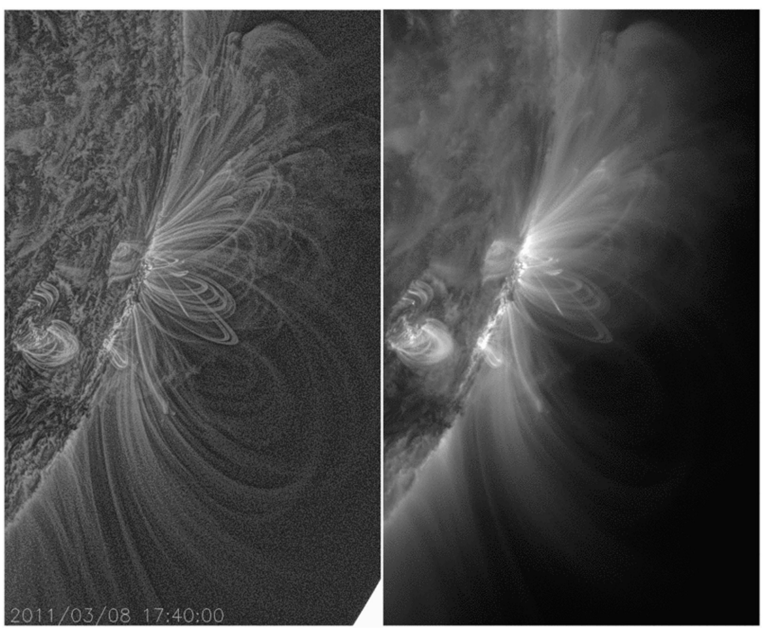


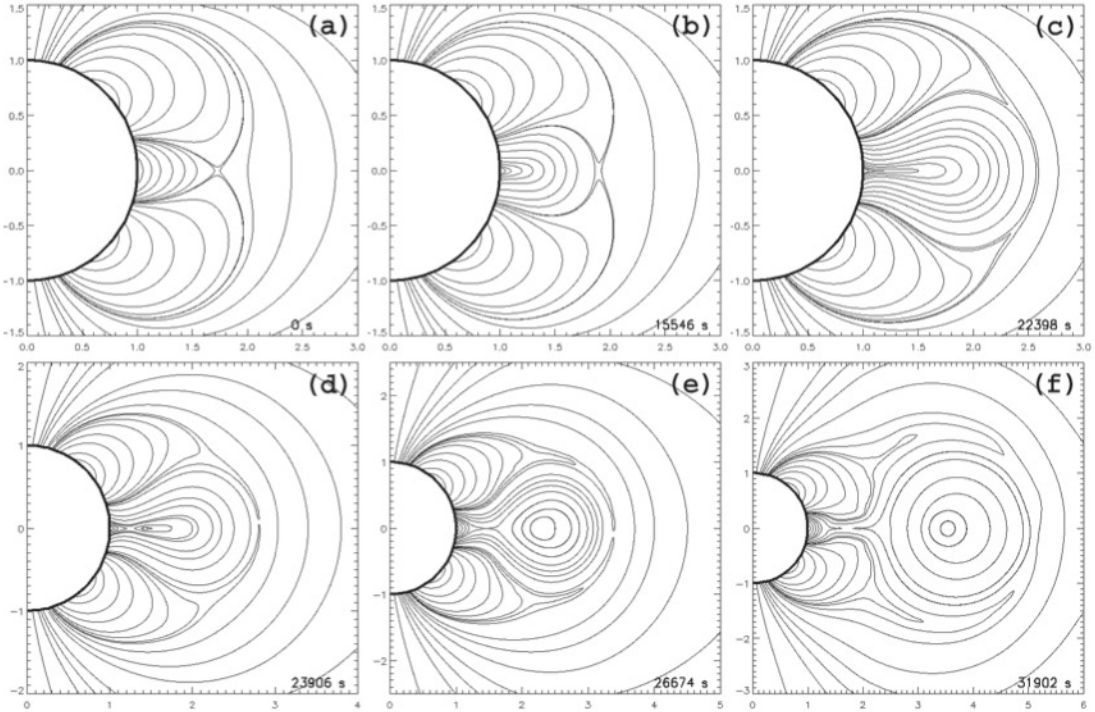
Image processing shows flux emergence in active region leading to large eruption

From Byrne *et al* (2013)

CME initiation/triggering mechanisms – breakout

Reconnection *above* the erupting structure – weakening of overlying field and release of flux tube. Note more complex initial structure (quadrapolar in this case)

Lynch *et al* (2004)

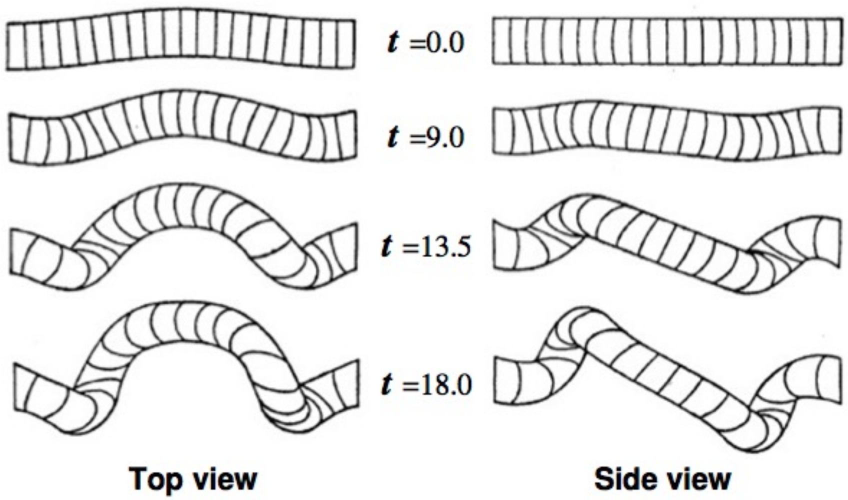


- X-point (null-point) above central structure
- Some process forces small expansion of central structure (shear motions, flux emergence)
- X-point is squeezed, invokes reconnection
- Overlying field weakens, allows further expansion of central structure
- Feedback -> fast reconnection
- Eruption guaranteed

CME initiation/triggering mechanisms – Kink & Torus instabilities

Twisting of flux tube by photospheric motions/reconnection, reaches critical twist and erupts.

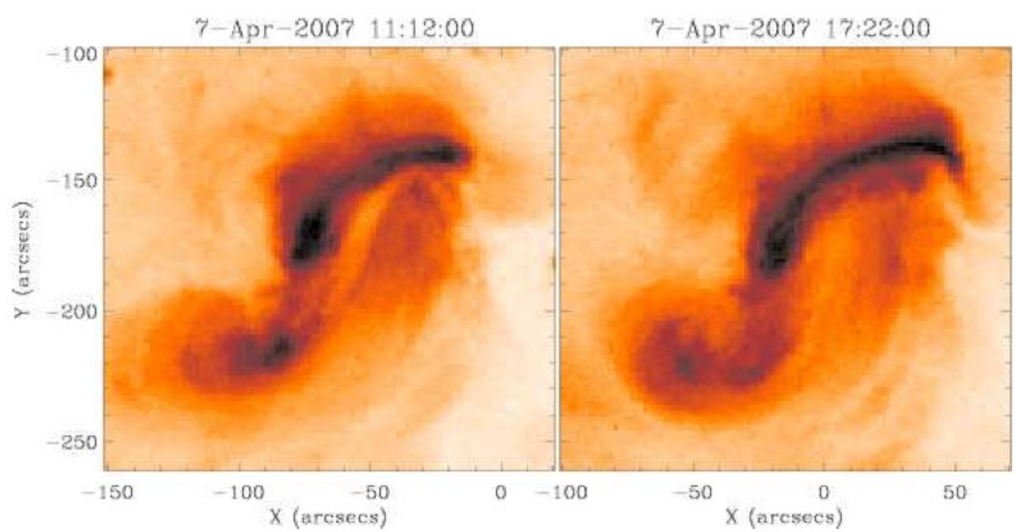
Sakurai (1976)



- 1-3 twists is critical?
- Length/curvature/diameter of flux tube important
- Surrounding magnetic environment important
- Flux tube may become unstable and erupt below critical twist if there is steep decline in surrounding field (torus instability)

- *Sigmoids* are often observed in active region filaments prior to eruption. Signature of kink instability?

Tripathi *et al* (2014)



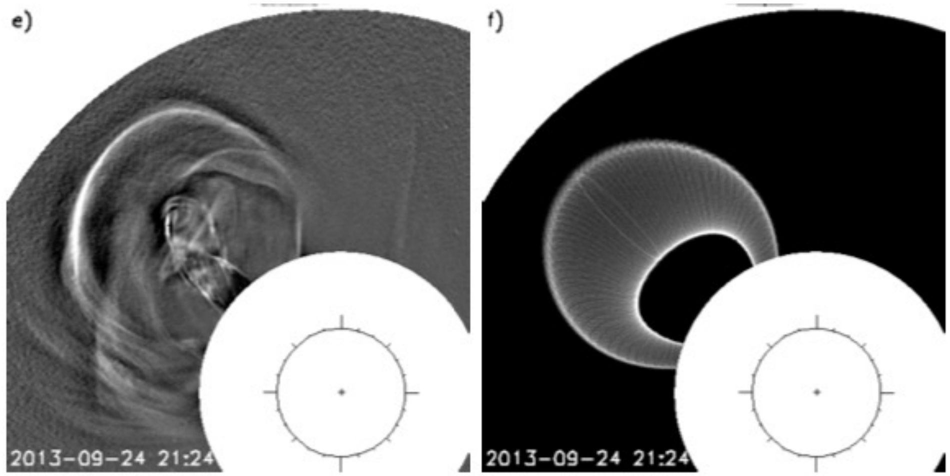
Why is studying/understanding CMEs important?

A family of CMEs – large 3-part CMEs

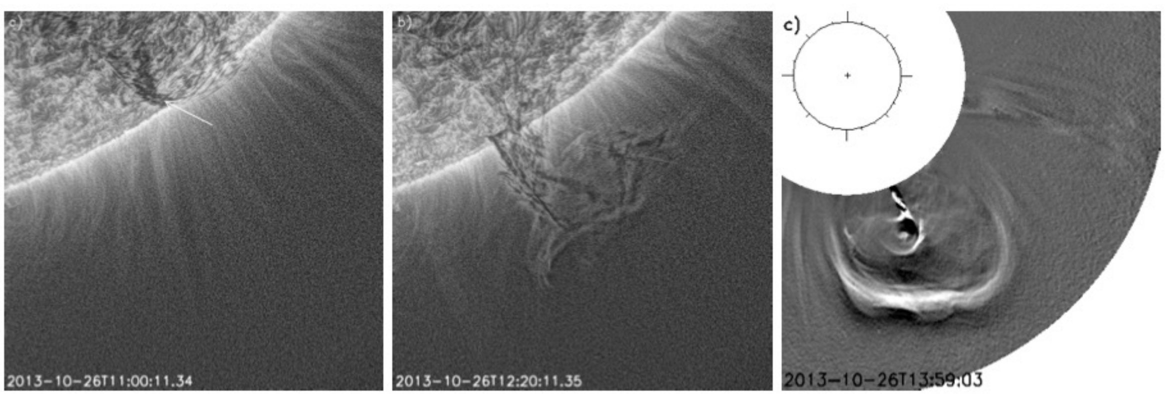
Large 3-part structure CMEs

- Bright front edge
- Depleted center
- Bright, dense core

Large flux tubes ('Croissant' model) with prominence (cool, dense) material forming core



Closely linked to eruption of large filament/cavity systems.
Cavity forms large-scale flux tube, prominence material collects at bottom of tube. This structure is maintained during eruption to form 3-part CMEs



A family of CMEs – large unstructured CMEs

Large, high-mass

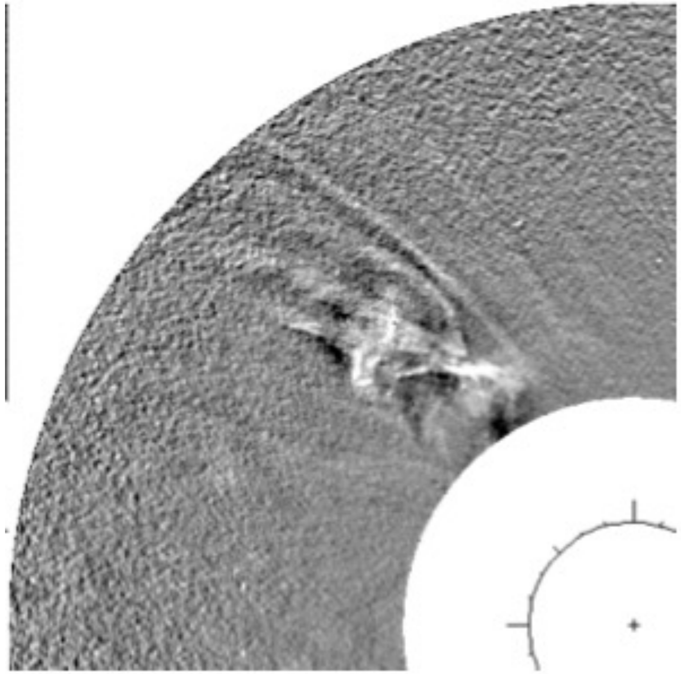
No clear 3-part structure

Closely linked to eruption of large filaments *without* cavity systems.

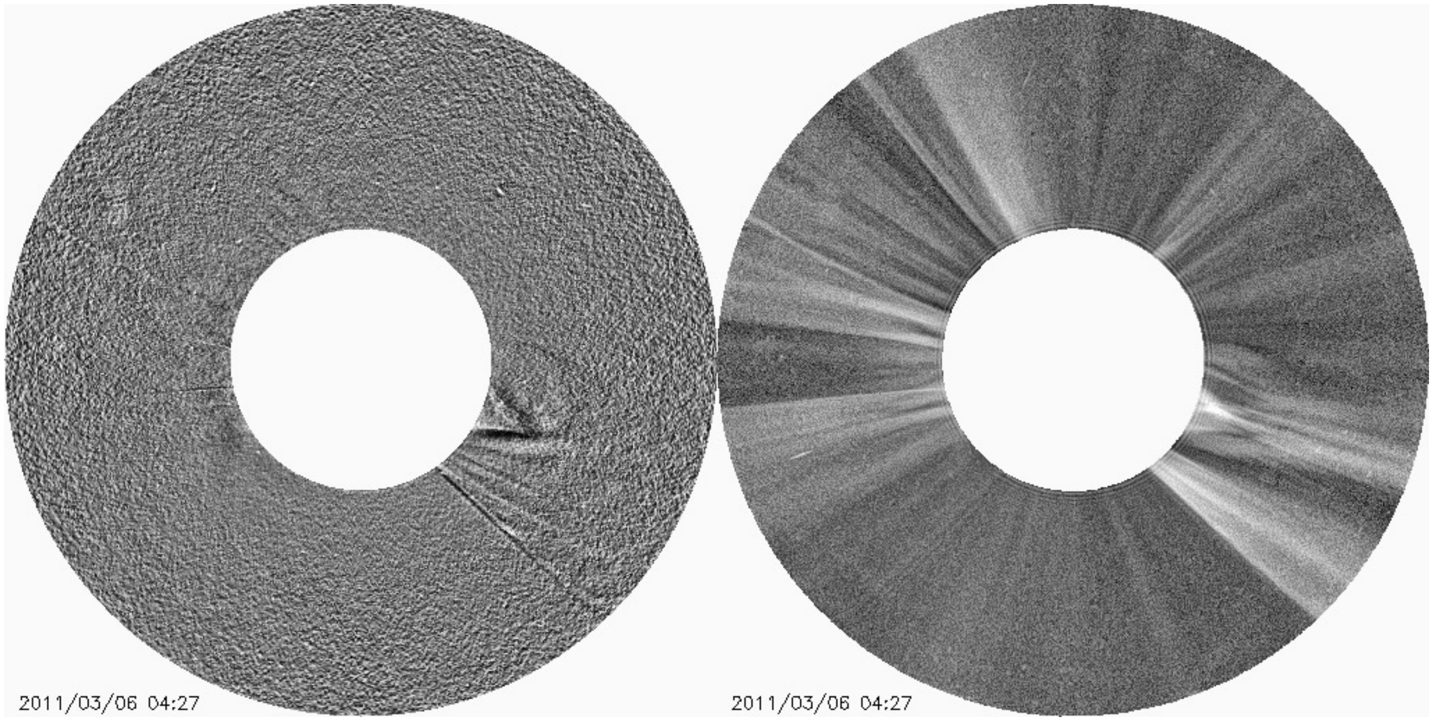
Narrow flux tubes prior and during eruption?

Disruption of 3-part CMEs during initiation?

Line-of-sight issue?



A family of CMEs – small-scale stuff



Blobs
- Low-mass, narrow
- Often formed at cusp of helmet streamers – pinch reconnection
- Very narrow flux tubes?
- Blobs from jets

Expanding loops
- Expansion for hours/days
- Very faint
- Helmet streamers
- Prior to large eruption?
- Emerging flux in active regions

Other
- Inflows
- Failed eruptions
- Rays
- General ‘blobby’ flows at current sheet
- Wave fronts

Some stuff I've neglected

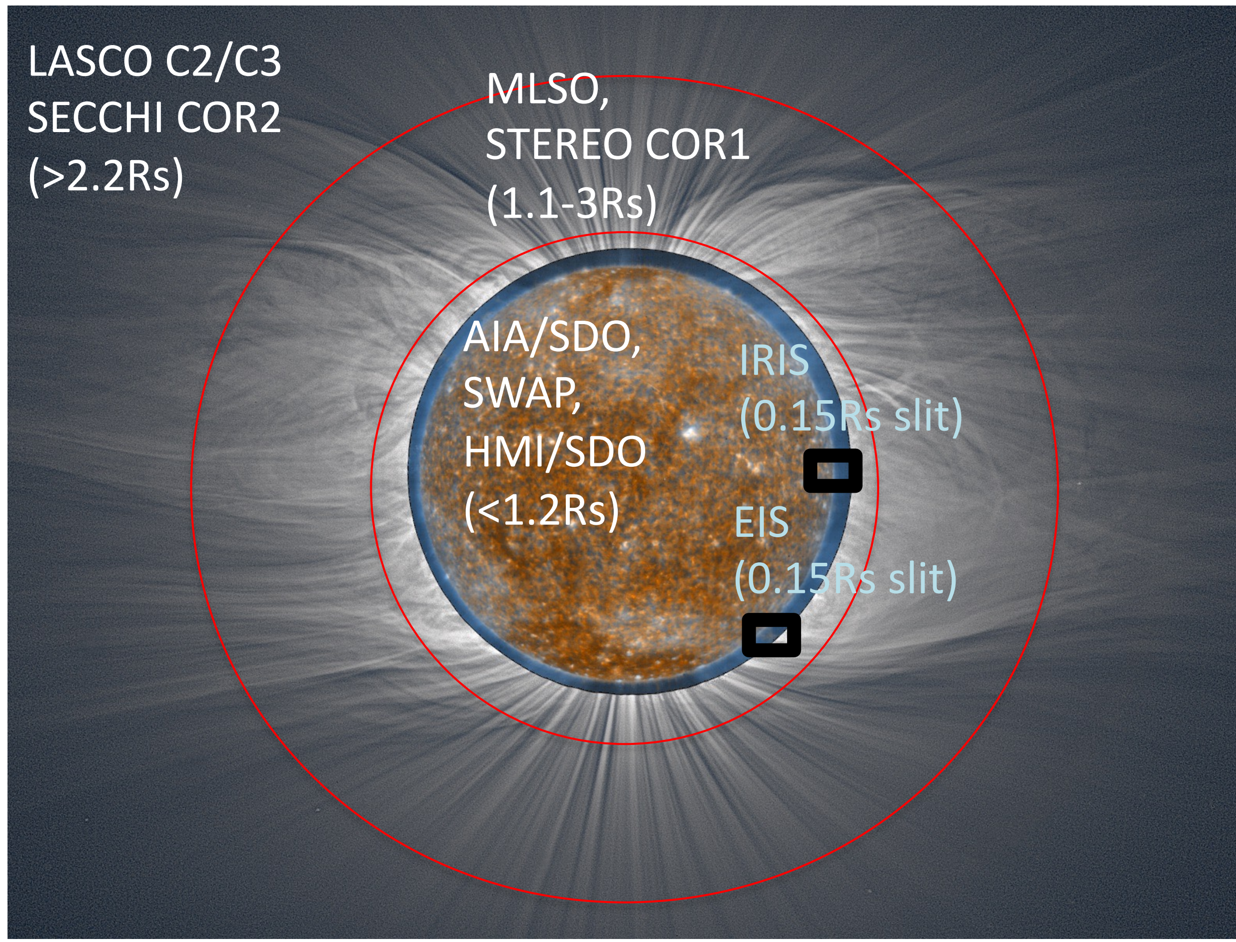
- Properties of Interplanetary CMEs (ICMEs)
- MHD modelling of CME initiation & propagation
- Shocks
- Relationship to flares and other phenomena
- Interaction with planetary magnetospheres/atmospheres

Current observational challenges

In situ measurements – detailed & precise, but measure one point only at 1AU

Remote-sensing observations – measure broad regions, but line-of-sight integrated. Coronagraph observations of lower corona (1.1-2Rs) very challenging.

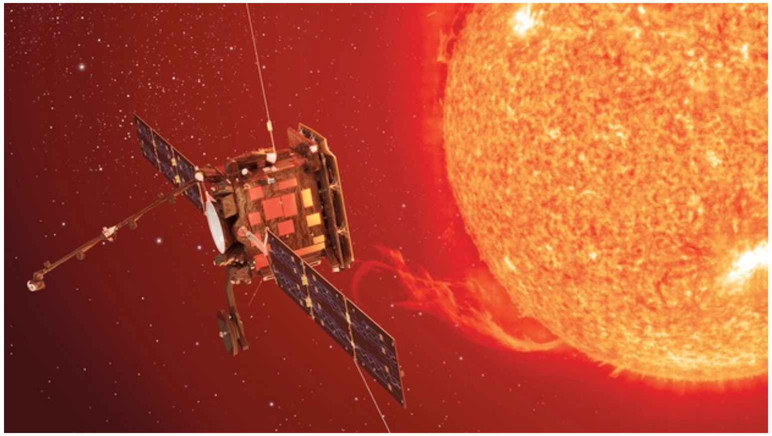
- No direct measurements of the corona – depend on remote sensing
- Gap between lower coronagraph field-of-view and upper EUV FOV. This is where a lot of the interesting stuff happens!
- No direct observations of coronal magnetic field
- LINE-OF-SIGHT. Corona optically thin



Current advances

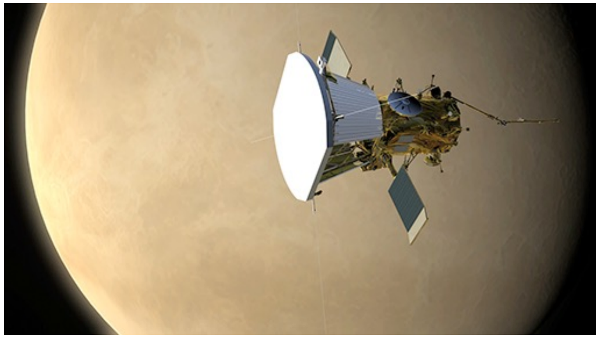
Solar Orbiter

- Remote-sensing & in situ
- Out-of-ecliptic, up to ~30 deg
- Minimum perihelion ~0.3AU
- Occasional heliostationary orbit

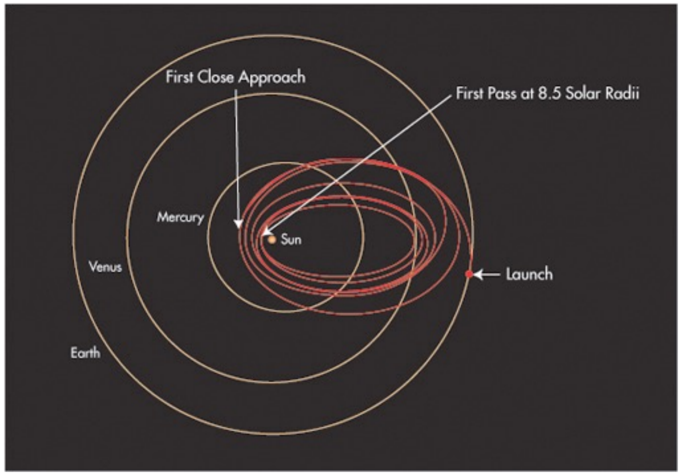


Parker Solar Probe

- In situ mostly, one wide-field imager
- Ecliptic orbit
- Minimum perihelion ~3.7million miles (2024)

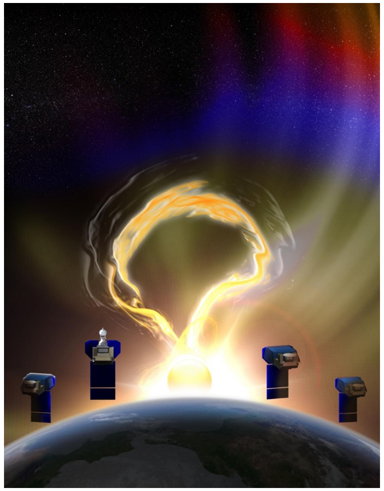


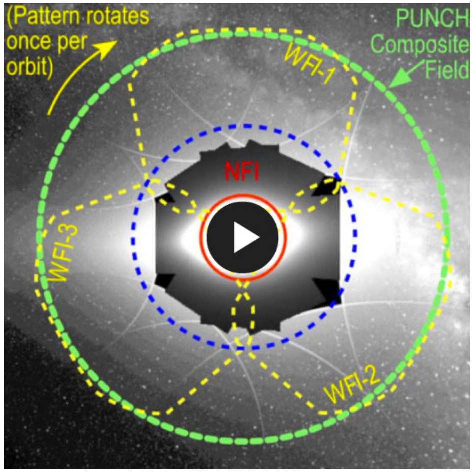
- Has measured slow wind from equatorial coronal holes
- Measurements inconsistent with current PFSS models (need non-constant source surface height)
- Unexpected azimuthal component to proton velocity distribution



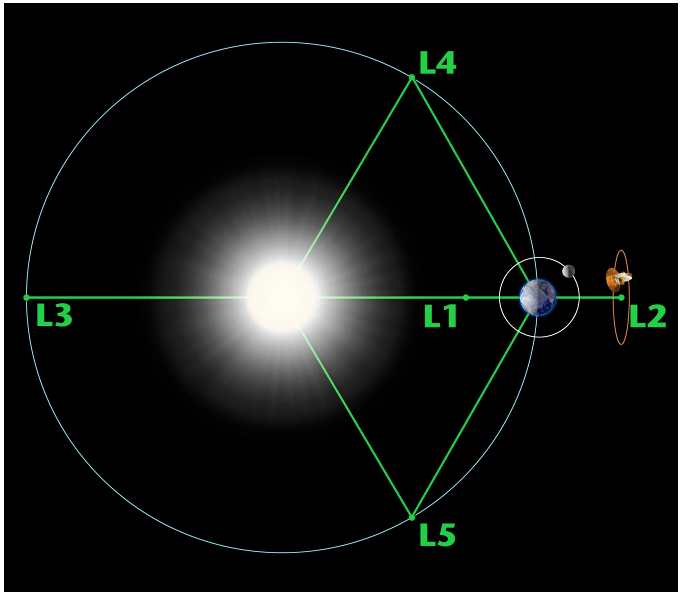
Near-future

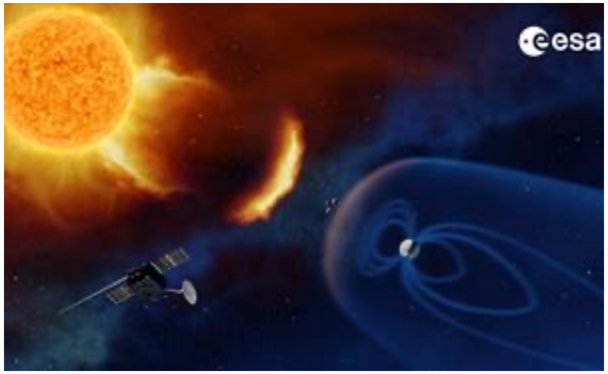
Punch
- Narrow-field and wide-field imagers
- Launch 2025
- High-resolution polarimetry, visible light





Vigil / Lagrange L5
- Launch ~2031
- Space weather mission
- Coronagraphs, Heliospheric Imagers





Thanks for your attention!

Contact me with any questions:
hmorgan@aber.ac.uk

Or ask me directly now...