THE SCIENCE OF SOLAR HURRICANES

2016 SWC Seminar Series

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Special thanks: Dr. Antti Pulkkinen, NASA/GSFC

Space weather research & forecasting at CUA

The newly opened CUA Space Weather Center (SWC) is a fully functional research and real-time analyses center dedicated to scientific investigations and forecasting of extreme space weather events – violent physical processes around the Earth driven by storms on the Sun.

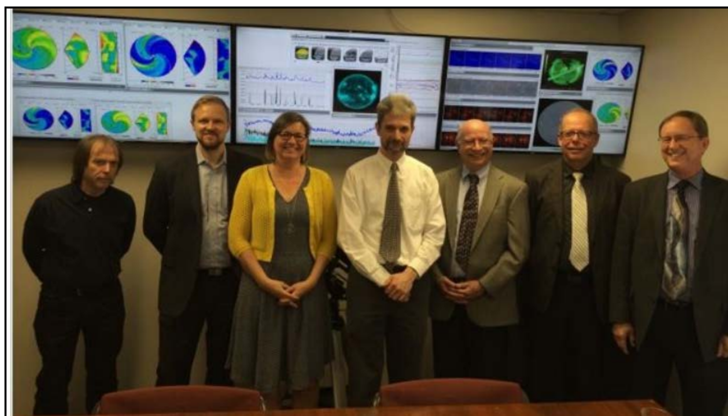
Space weather events present a growing hazard to human technologies and society by disrupting satellite communications and navigation systems, damaging power grids, exposing astronauts to a harsh radiation environment, and causing an array of other detrimental effects in space and on the ground. Understanding the physics of such events has become a priority of NASA science programs which welcome contributions from educational institutions. Space weather has gained recent high-level attention, leading to the release of the space weather action plan by the Office of Science and Technology Policy at The White House.

SWC will enable scientific investigations of extreme space weather events associated with major solar flares, large coronal mass ejections, solar energetic particle events, and intense geomagnetic perturbations and their ionospheric footprints. Data-driven simulations and an advanced statistical analysis of past events will be used to produce student-generated experimental space weather forecasts which will be posted online and disseminated throughout the space weather research community.

http://spaceweathercenter.cua.edu

2016 SWC SEMINARS

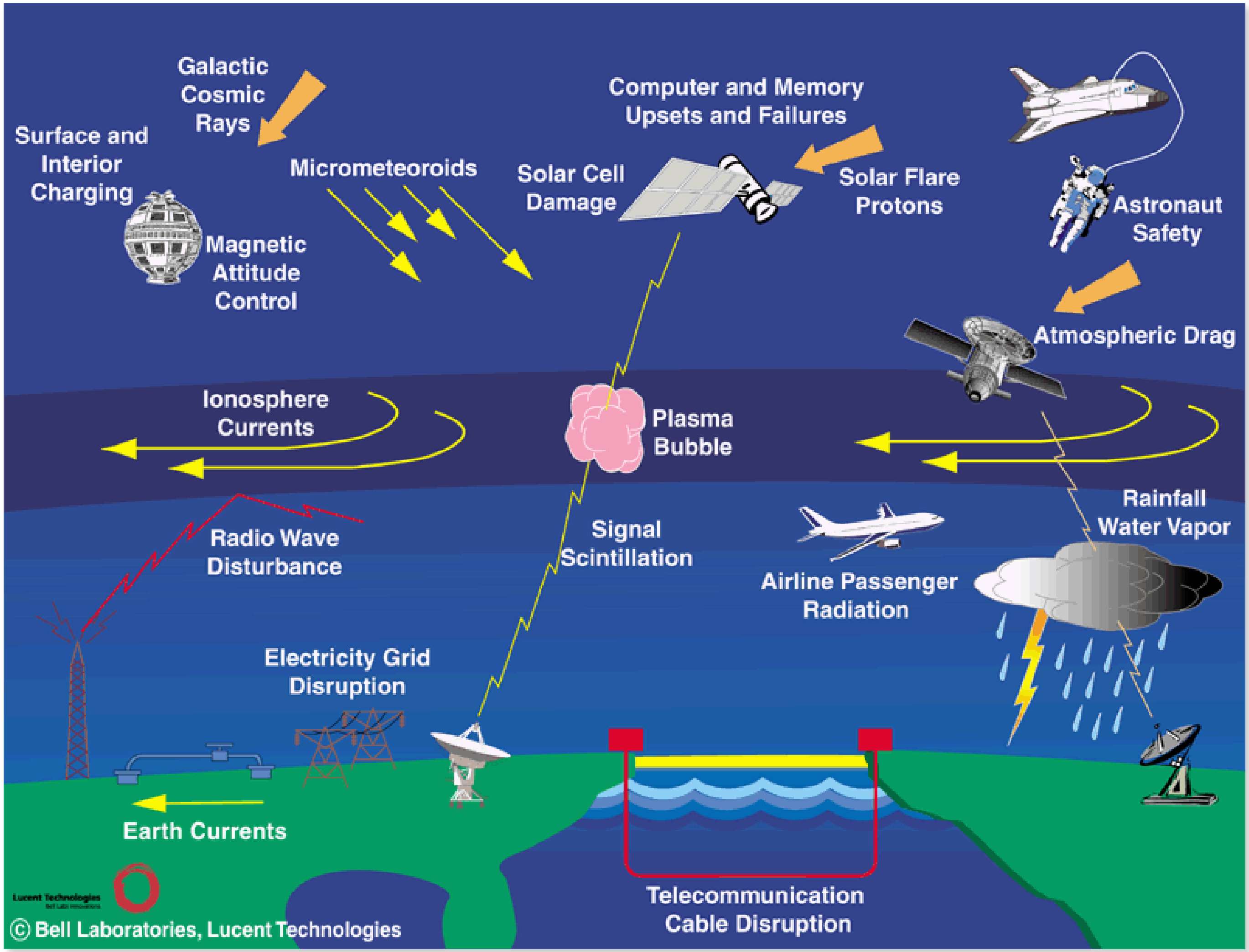
The Space Weather Center launches a series of educational seminar talks focused on scientific, engineering, and sociological aspects of cutting-edge space weather research.



At the opening ceremony, from left to right:

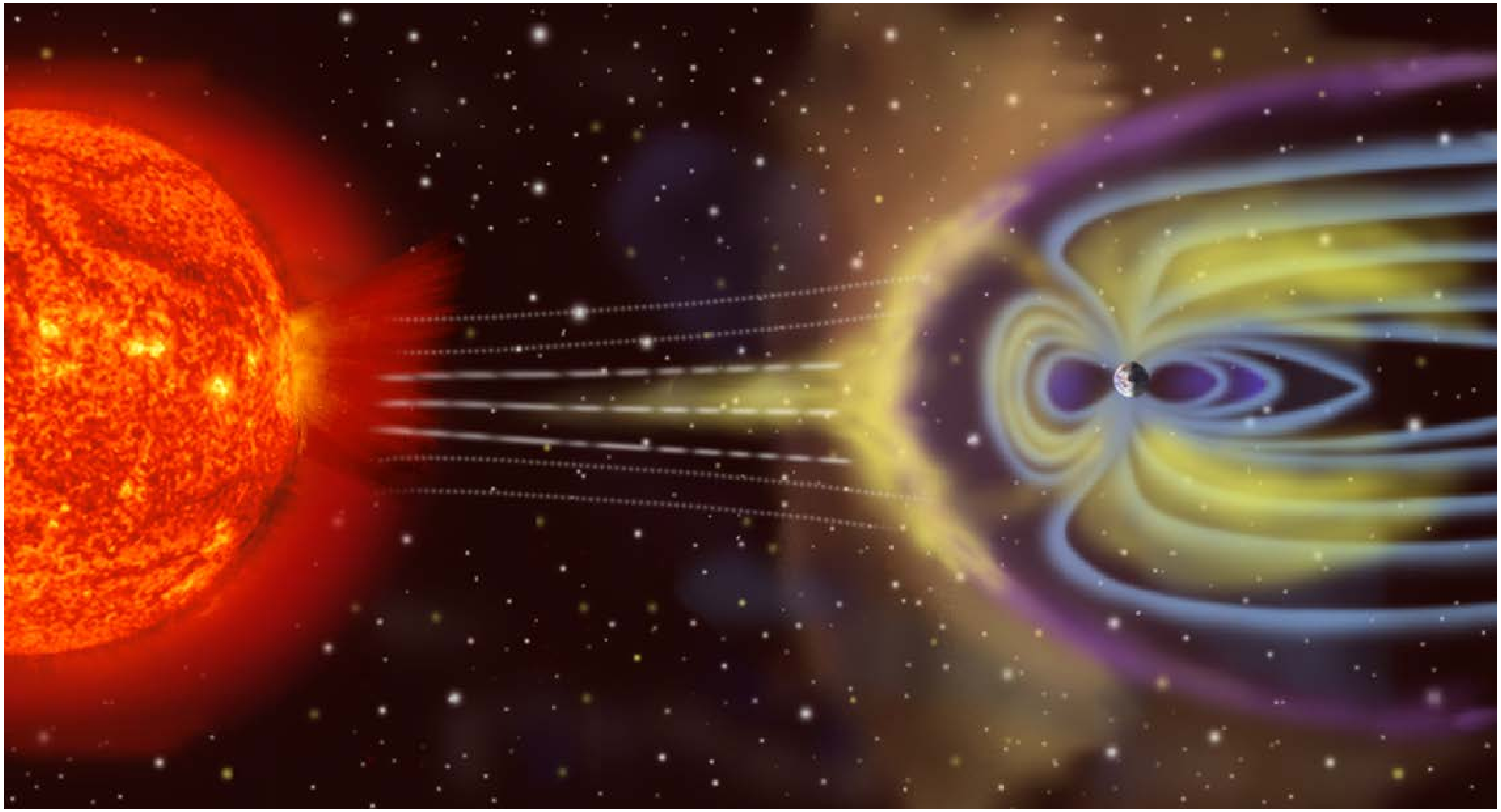
Steve Kraemer, Head of the Physics Dept., CUA
Antti Pulkkinen, Research Astrophysicist, NASA Goddard
Claudia Bornholdt, Acting Dean, School of Arts & Sciences, CUA
Vadim Uritsky, Head of the Space Weather Center, Physics Dept., CUA
Robert Robinson, Director of Institute for Astrophysics & Computational Sciences, CUA
Michael Hesse, Director of Heliophysics Science Division, NASA Goddard
Robert McCoy, Director of Geopyiscal Institute, U of Alaska Fairbanks

The space weather impacts



credit: L. Lanzerotti/Bell Labs

The Sun-driven space weather system



The 1859 Carrington event

Telegraph systems all over Europe and North America failed, in some cases giving telegraph operators electric shocks. Telegraph pylons threw sparks. Some telegraph operators could continue to send and receive messages despite having disconnected their power supplies.

Comparable solar storm: July 23 2012 (missed the Earth).

History channel VIDEO: The biggest Solar Storm in history **(5:46)**

THE SUN - the space weather driver

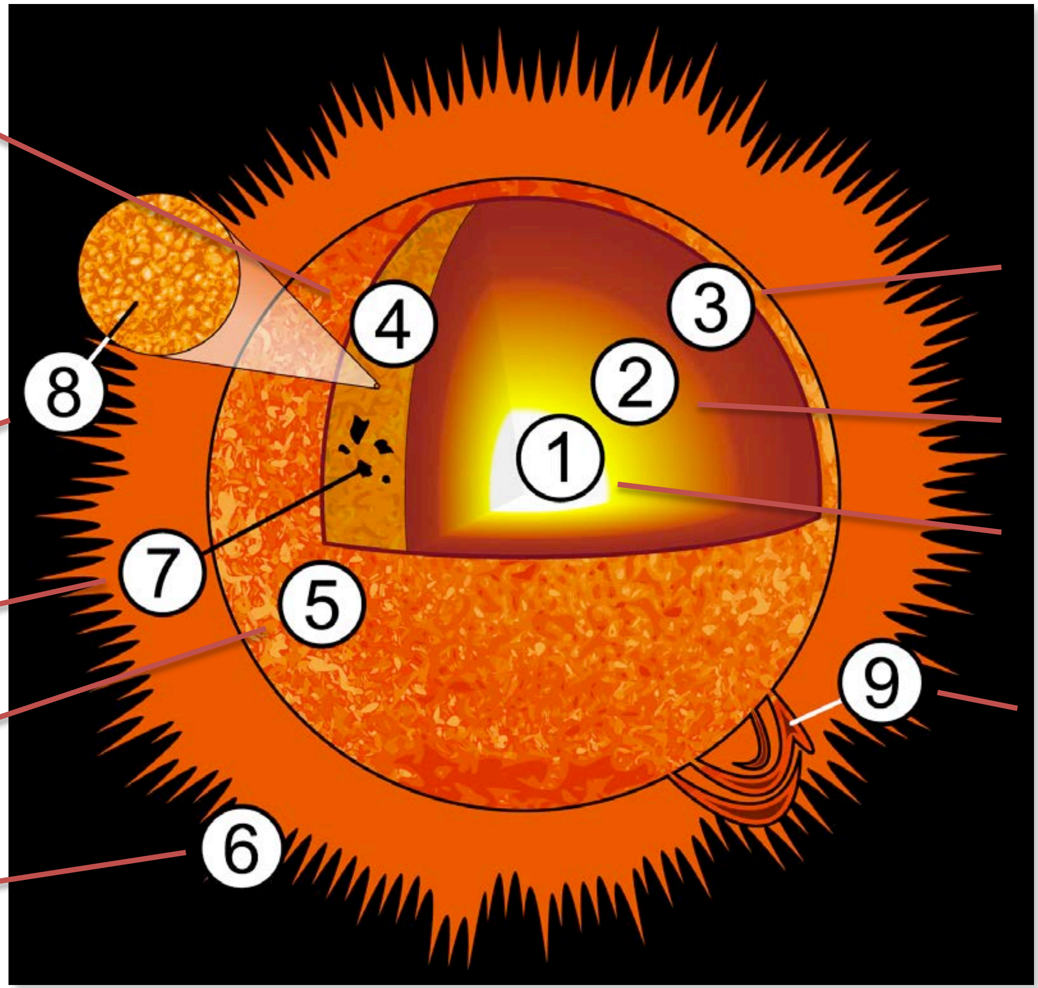
Photosphere at 4300 K (top)

Granulation

Sunspots

Chromosphere at 25000 K (top)

Corona at ≈10^6 K



Convection zone at 6600 K (top)

Radiation zone at $5 \bullet 10^5$ K (top)

Core (Hydrogen into Helium) at $1.5 \bullet 10^7$ K

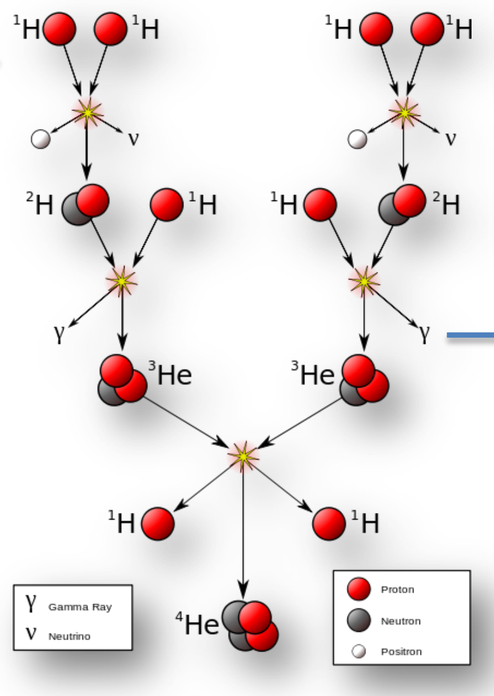
Prominence at about 5000-10000 K

Credit: Wikipedia/sun

Nuclear fusion in the core of the Sun

- (primarily) *Proton-proton fusion* process operating in the solar core fuels everything.

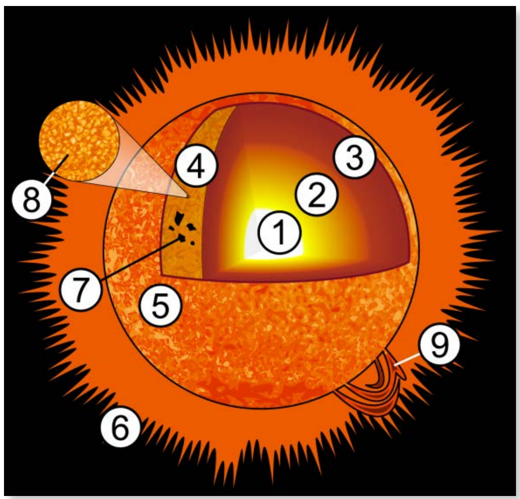
150 g/cm^3 hydrogen at 15 million Kelvin

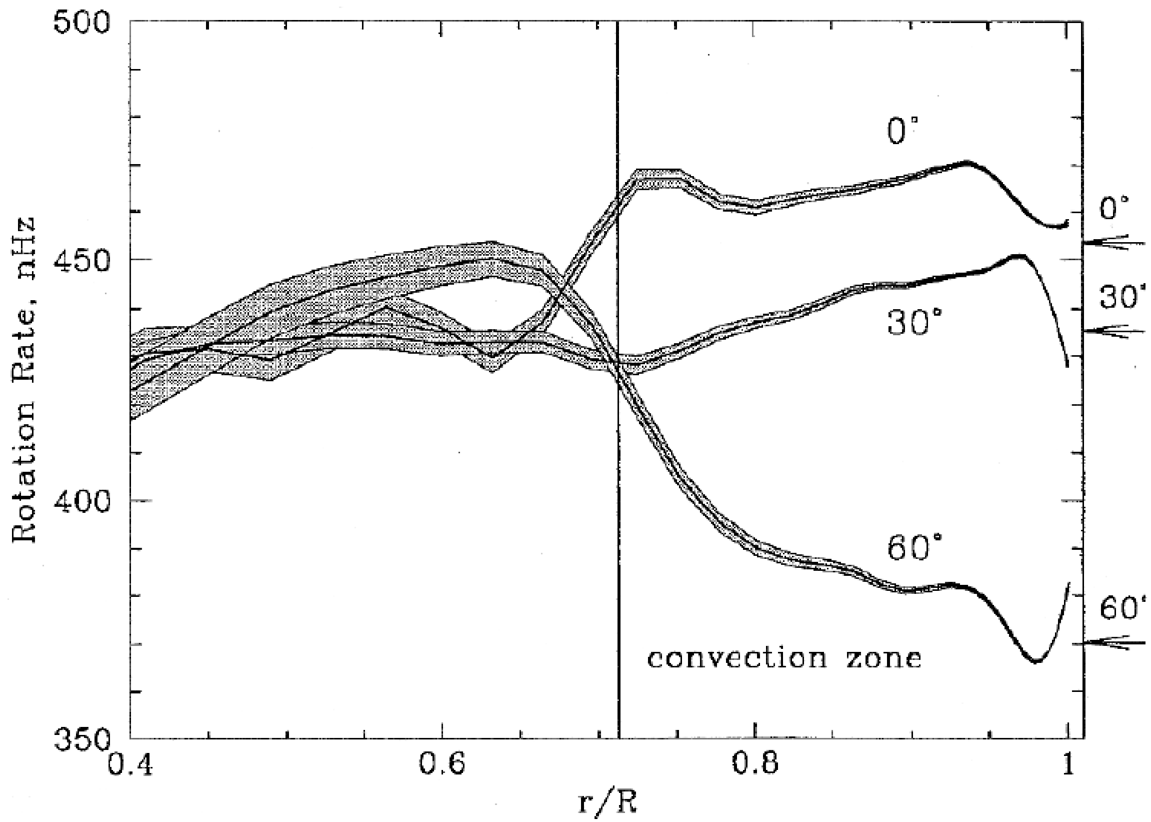


Electromagnetic radiation

Proton-proton fusion chain (credit: Wikipedia)

The internal rotation rate of the Sun. The radial profiles are calculated for three different latitudes (Kosovichev et al., 1997).





The magnetic field of the Sun

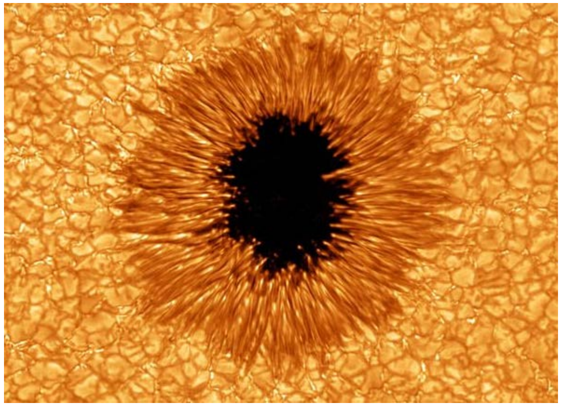
- The Sun's magnetism could be a remnant of the magnetic field in the interstellar cloud that once collapsed to form the Sun (Ohmic diffusion time ~ 10^{10} yrs)
- Differential rotation and its association to the migration of the sunspots point at a **dynamo process** near the bottom of the convection zone
- The problem of *dynamo theory* is to find solutions for the induction equation

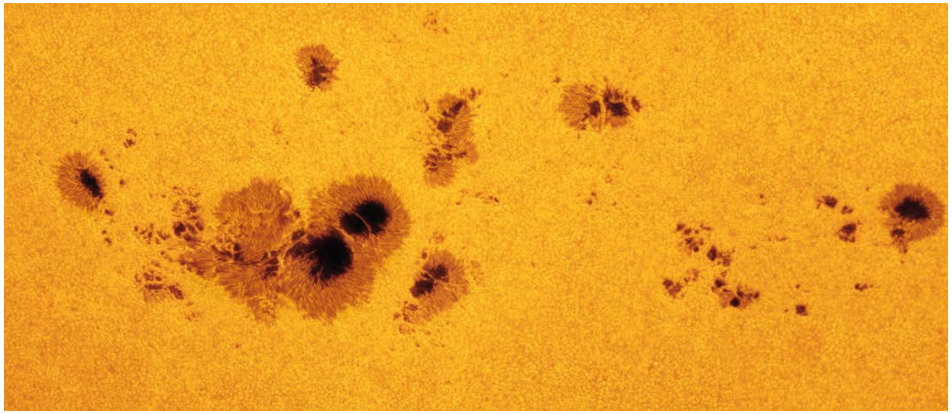
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

where the convection and diffusion together result in creation of new magnetic flux, or more exactly, **manifolding of the existing flux**.

Sunspots and solar magnetism

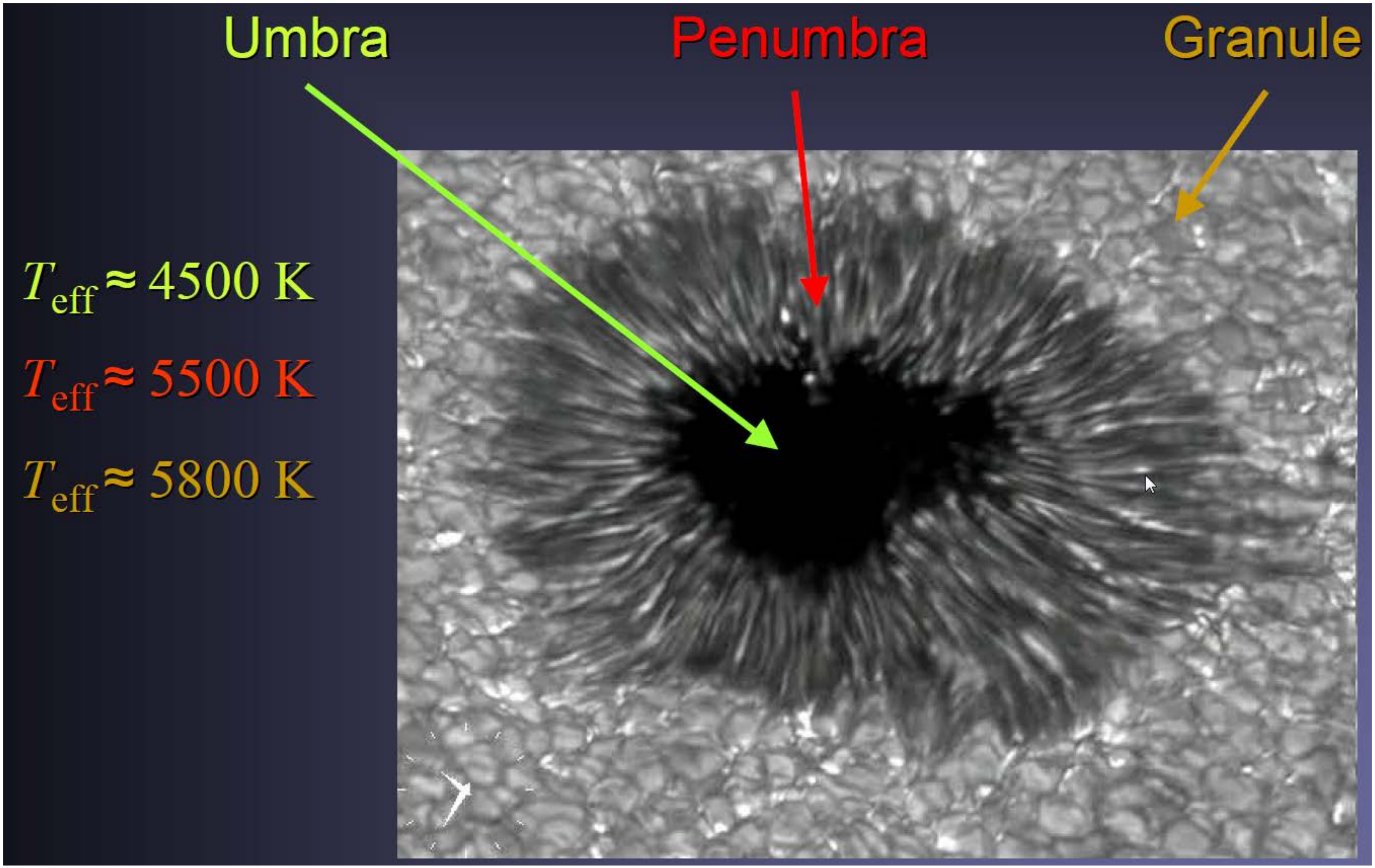
- A sunspot corresponds to an **intense magnetic flux** tube emerging from the convection zone to the photosphere.
- Diameter up to ~ 20 000 km
- The largest observed magnetic fields are about 0.3 T.
- Temperature is about 4100 K , lower than typical photospheric temperatures (4300K and up) due to strong B field.
- The magnetic field is measured by observing the *Zeeman splitting* of atomic spectral lines.





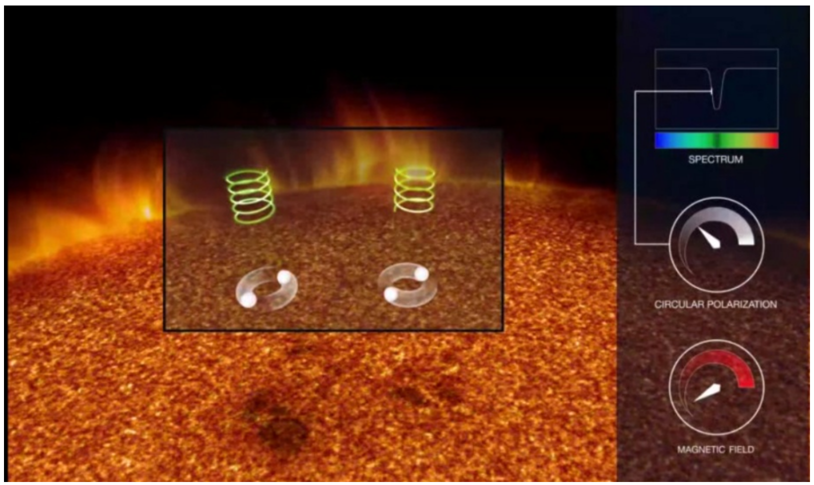
Sunspot, courtesy NJIT's New Solar Telescope

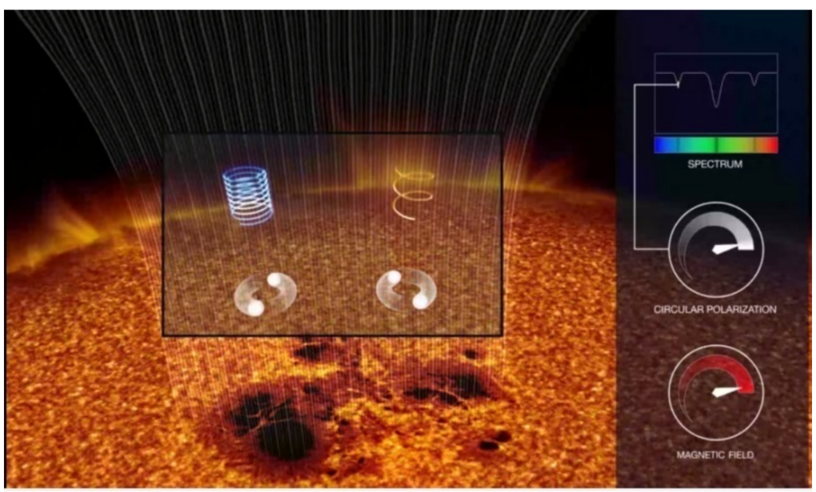
The structure of a sunspot

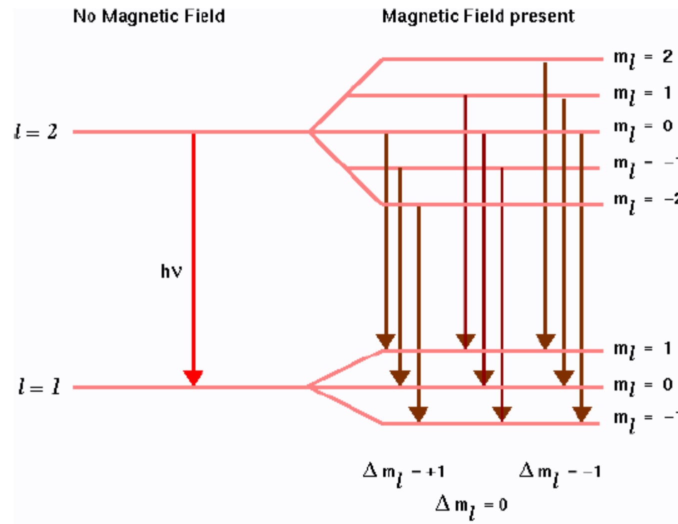


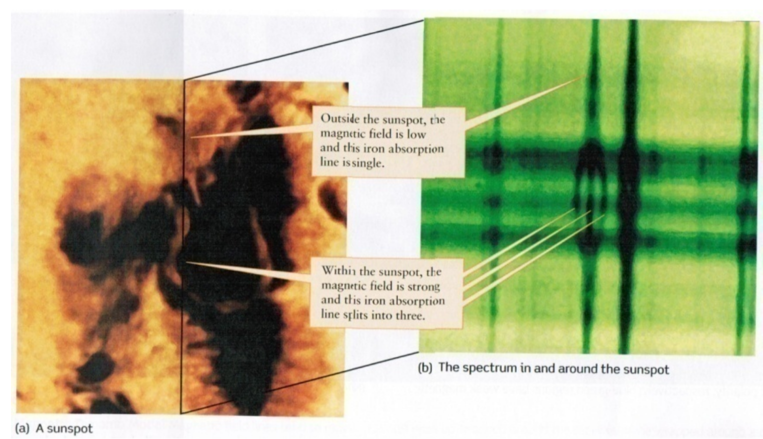
Zeeman splitting

* Splitting of a spectral in the presence of an external magnetic field
* The splitting is proportional to the magnetic field strength and the Lande factor.









(b) The spectrum in and around the sunspot

(a) A sunspot

[Animation of solar emission line splitting due to magnetic field]

Computing sunspot number

- The classic (since the 18th century) means to characterize the state of the Sun is the *relative sunspot number*:

$$R = k(10g + f) \tag{1}$$

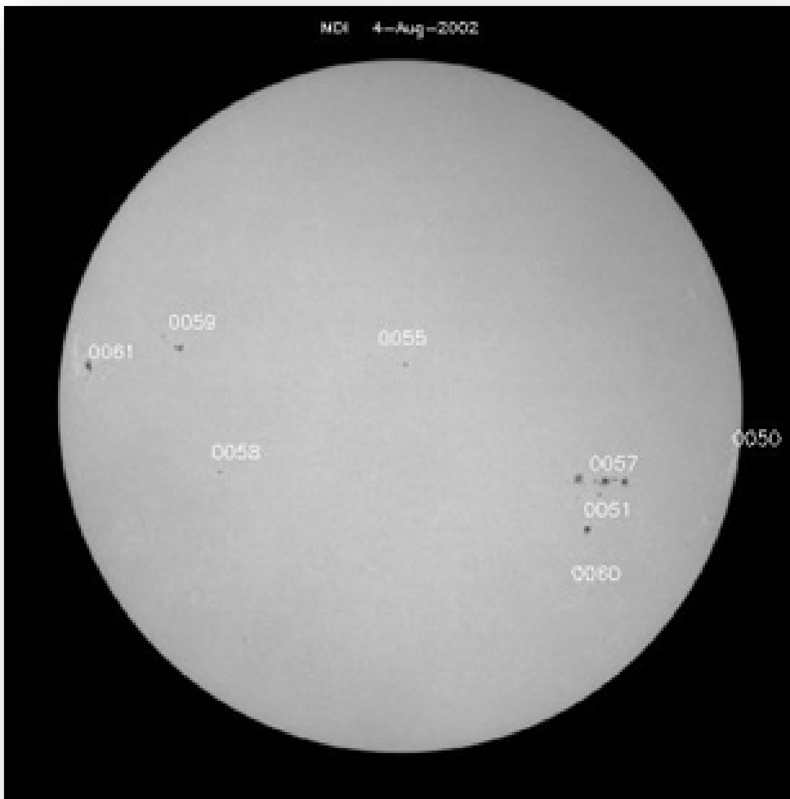
- k: Observatory-dependent calibration factor
- g: Number of spot groups
- f: Total number of spots

$$R = k(10g + f)$$

Observatory-dependent calibration factor

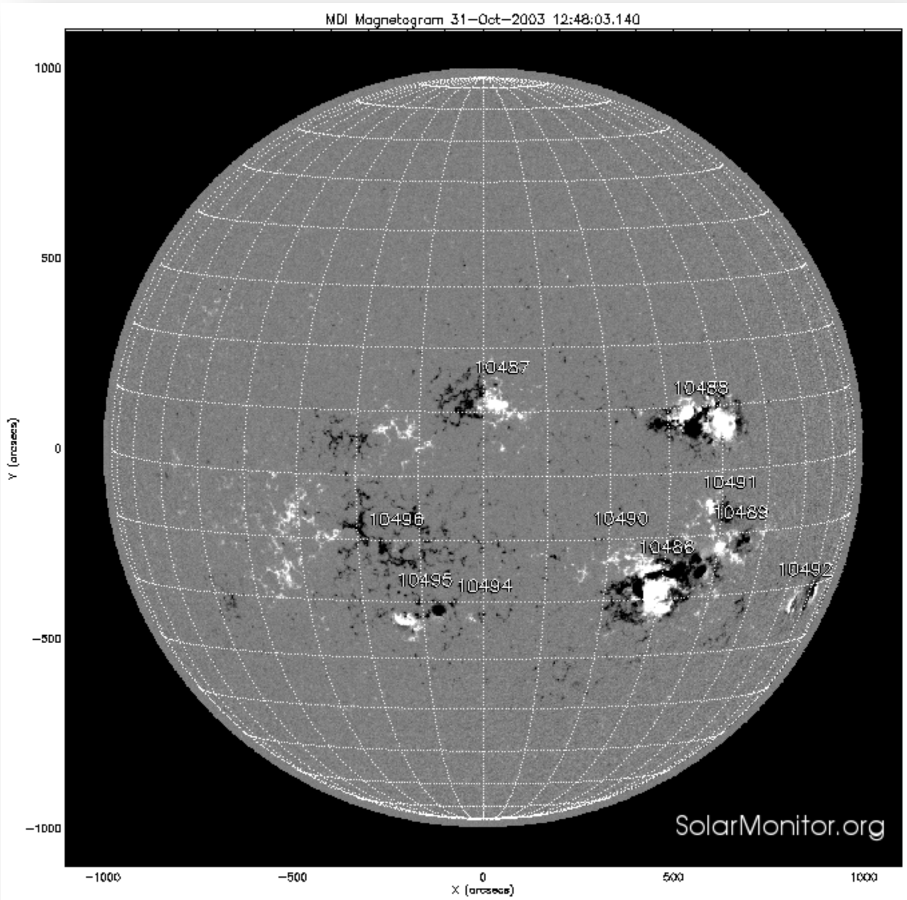
Number of spot groups

Total number of spots



8 groups and 15 individual spots: *R* = 95

Monitoring solar magnetic field



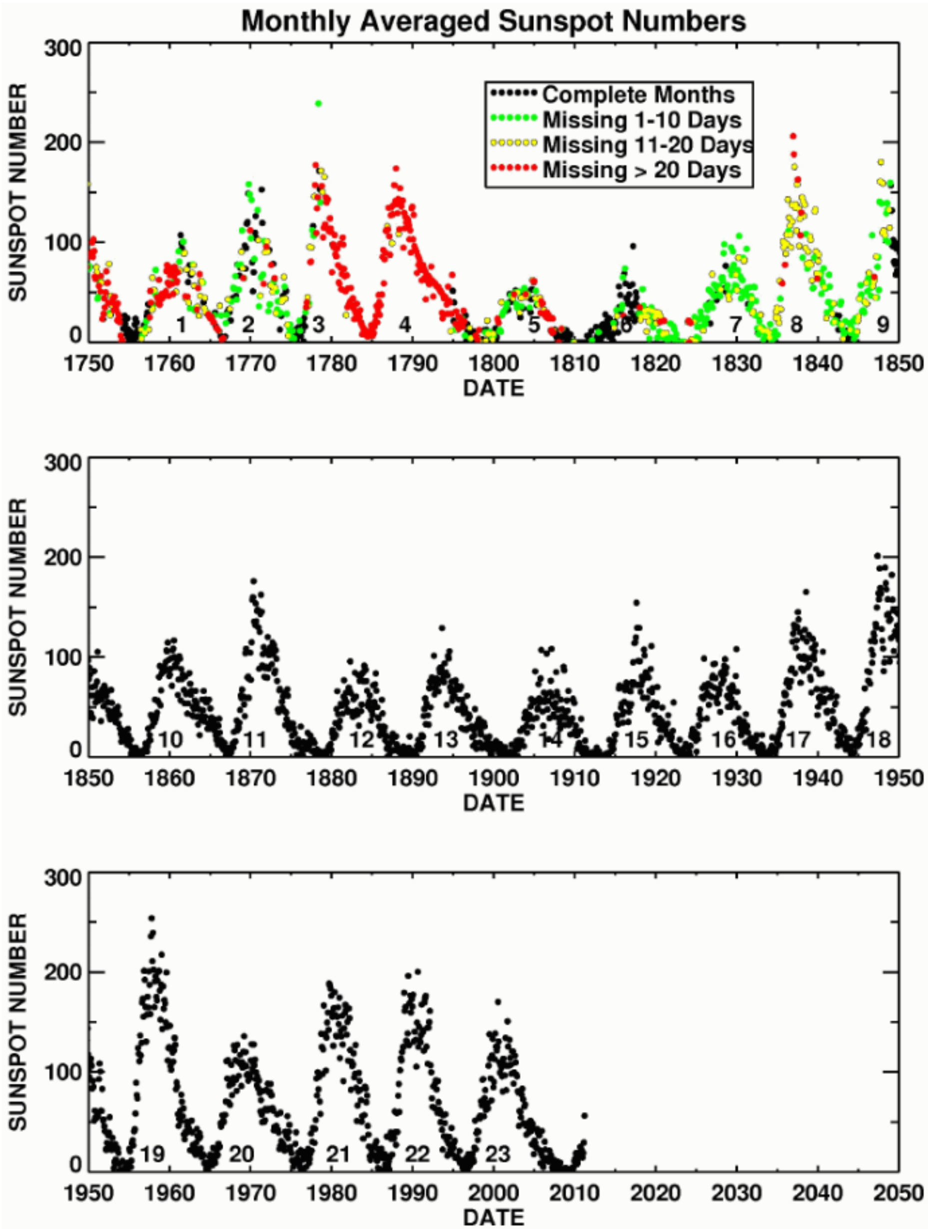
Credit: SolarMonitor.org

:Product: 20031031SRS.txt
:Issued: 2003 Oct 31 0030 UTC
Prepared jointly by the U.S. Dept. of Commerce, NOAA,
Space Environment Center and the U.S. Air Force.
#
Joint USAF/NOAA Solar Region Summary
SRS Number 304 Issued at 0030Z on 31 Oct 2003
Report compiled from data received at SWO on 30 Oct
I. Regions with Sunspots. Locations Valid at 30/2400Z

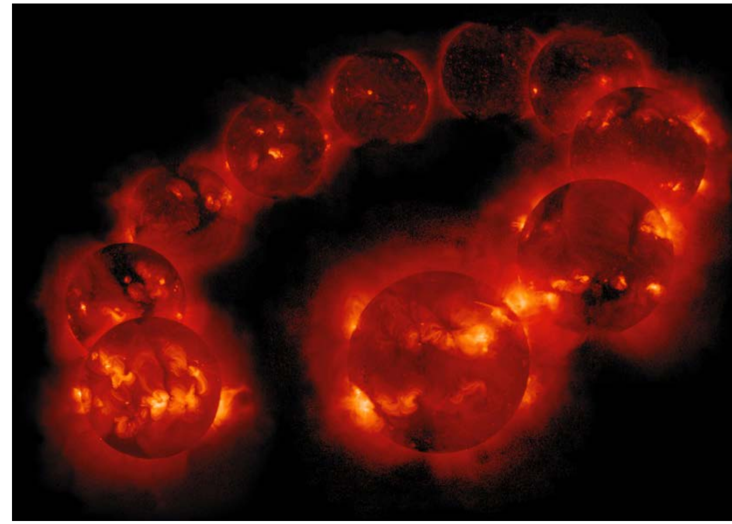
Nmbr	Location	Lo	Area	Z	LL	NN	Mag Type
0484	N01W95	356	0210	Dao	10	06	Beta-Gamma
0486	S18W23	284	2600	Fkc	18	80	Beta-Gamma-Delta
0487	N12E06	255	0280	Dko	07	23	Beta
0488	N08W28	289	1750	Fkc	17	34	Beta-Gamma-Delta
0489	S12W36	297	0130	Dao	06	09	Beta
0490	S12W14	275	0010	Hrx	01	03	Alpha
0491	S06W32	293	0120	Dso	07	10	Beta
0492	S23W62	323	0340	Eko	11	17	Beta
0494	S23E08	253	0010	Axx	00	01	Alpha
0495	S22E20	241	0240	Dso	08	10	Beta

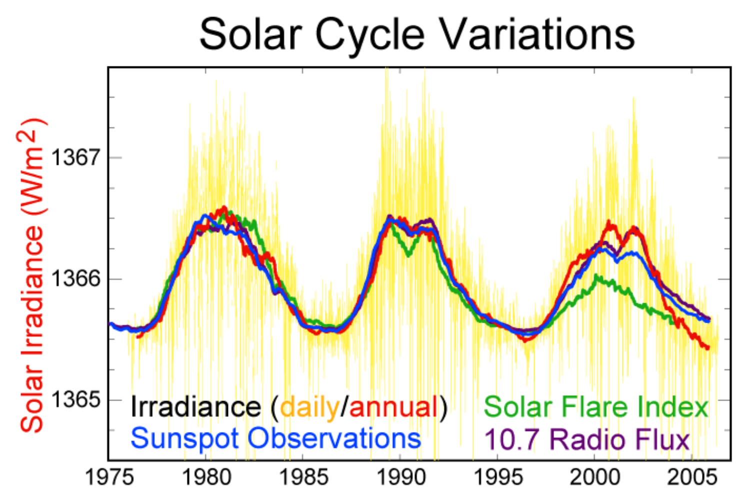
Credit: NOAA SWPC

The Zurich sunspot number time series

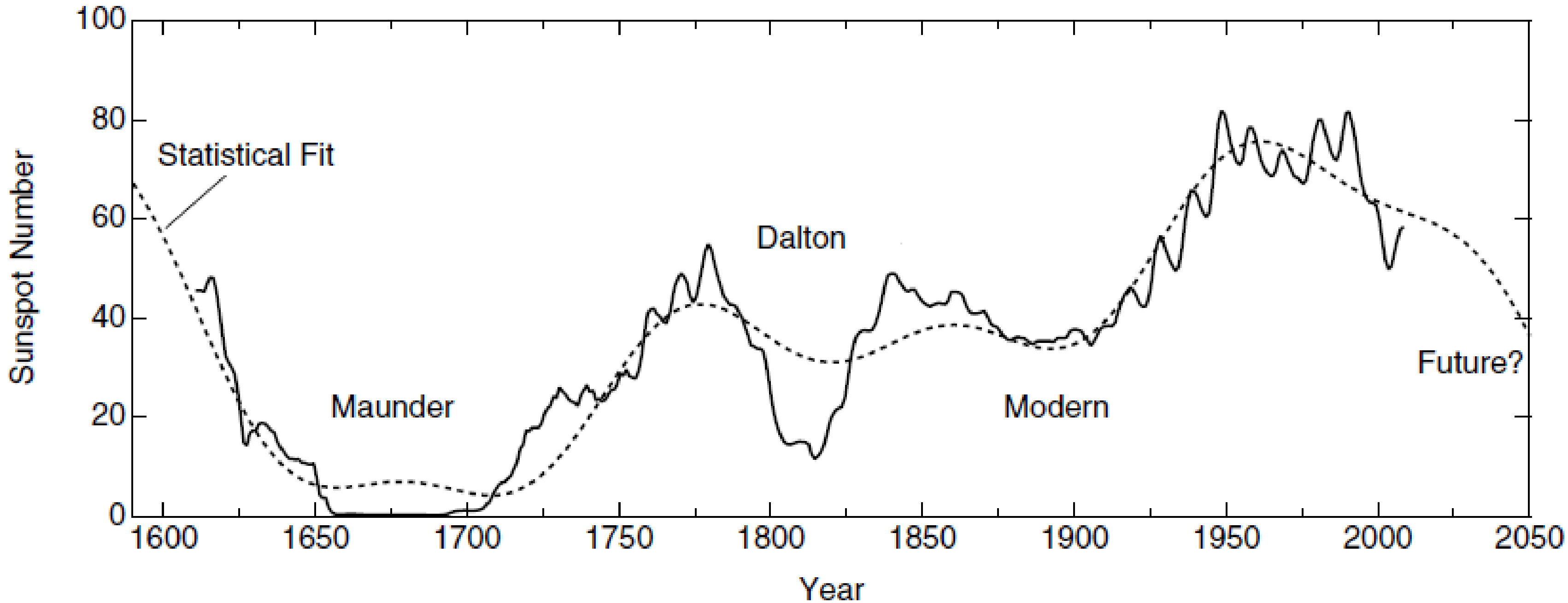


A montage of Yohkoh SXT images demonstrating the variation in solar activity during one sunspot cycle

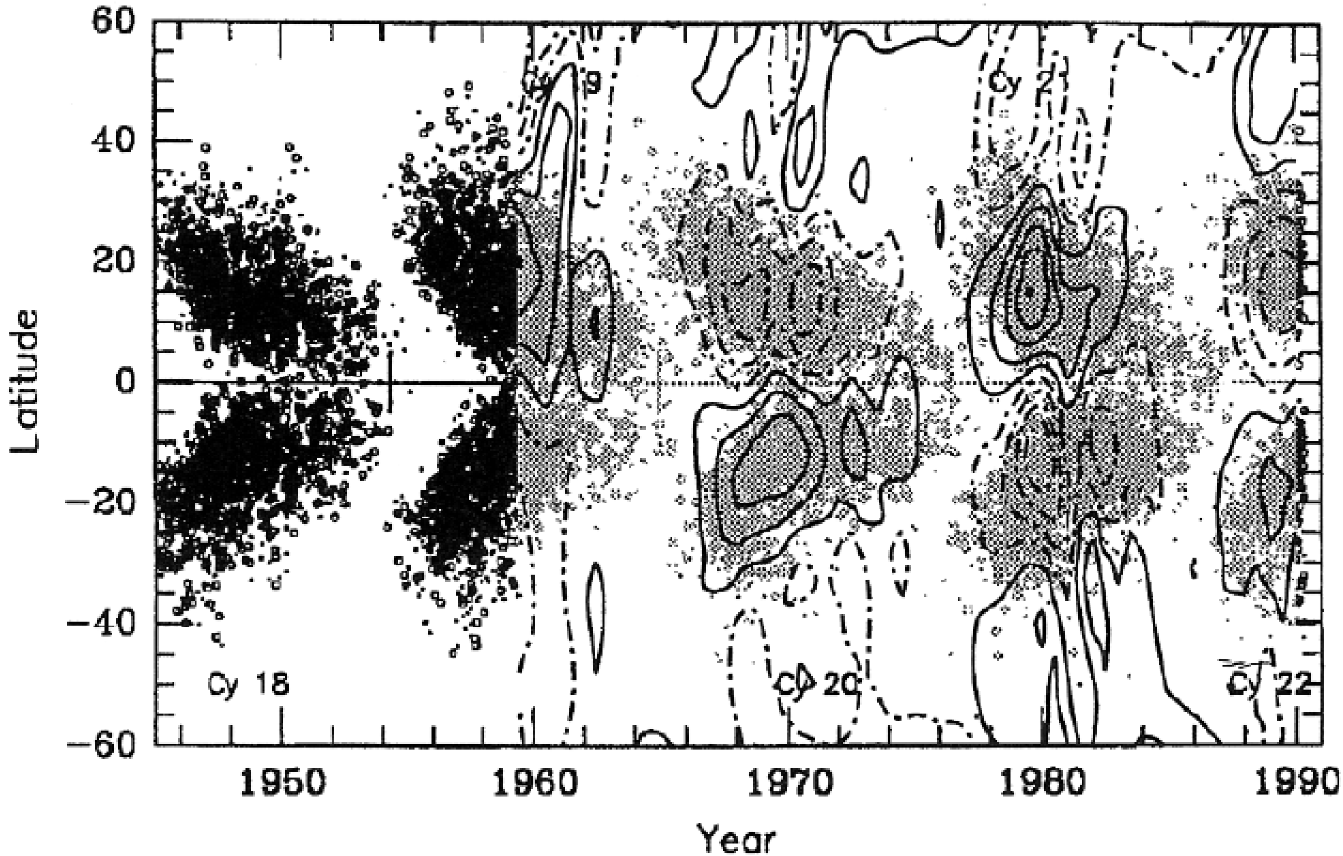




Long-term sunspot number variation after the 11-year cycle has been filtered away



The butterfly diagram of sunspot appearance. Solid/dashed lines are contours of positive/negative polarity (Schlichenmaier & Stix, 1995).



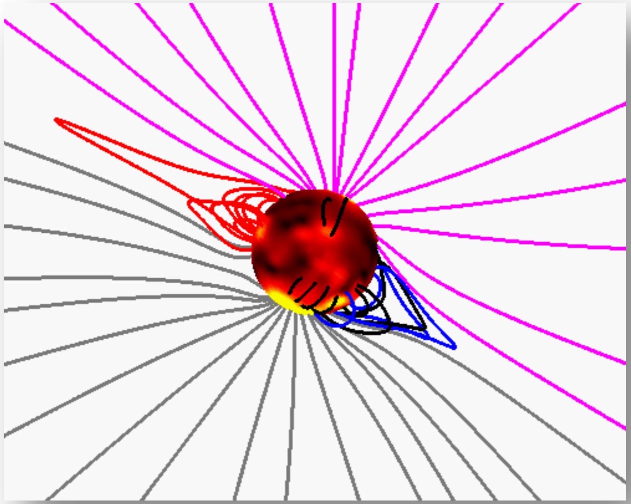
Relative sunspot number introduced by Wolf in 1848: $R = k\,(10\,g + f)$

g - number of spot groups , *f* - total number of spots
k - determined individually for each observatory.

Coronal magnetic field and the solar cycle

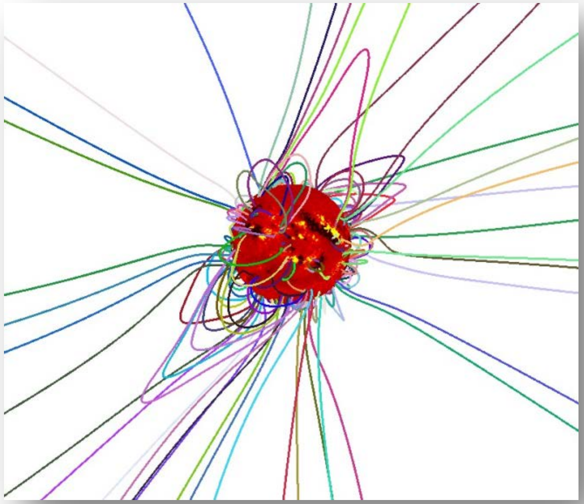
- Global structure of the solar magnetic field varies as a function of *solar cycle*.

Solar minimum



Credit: Predictive Science, Inc

Solar maximum



Credit: Predictive Science, Inc

The MHD energy balance describing coronal heating

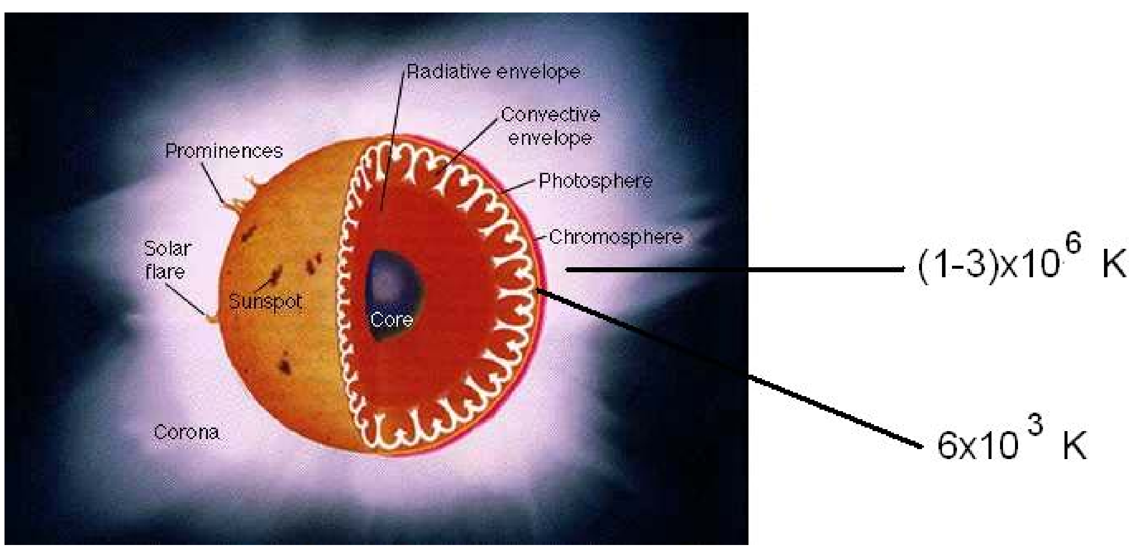
magnetic energy entering as Poynting flux through the surface $\partial\mathscr{V}$ of the volume $\mathscr{V}$

$$-\oint_{\partial\mathscr{V}} \mathbf{E}\times\mathbf{H}\cdot d\mathbf{a} = \frac{\partial}{\partial t}\int_{\mathscr{V}} \frac{B^2}{2\mu_0}\, d\mathscr{V} + \int_{\mathscr{V}} \frac{J^2}{\sigma}\, d\mathscr{V} + \int_{\mathscr{V}} \mathbf{V}\cdot\mathbf{J}\times\mathbf{B}\, d\mathscr{V}$$

increasing magnetic energy

energy dissipated through ohmic heating

energy dissipated through mechanical work by the magnetic force ($\mathbf{J}\times\mathbf{B}$)



Coronal heating mechanisms

- **Alfven waves**: can be nonlinearly damped as they propagate outward, with a fraction of wave energy transformed to heat.

  Damping mechanism involve ***phase-mixing* of Alfven waves** of different wavelengths and speeds propagating in the same spatial volume and ***cyclotron resonance with the plasma ions*** (Alfv'en waves become electromagnetic ion cyclotron waves at frequencies close to the local ion cyclotron frequency).

- **Nano- and microflares**: heating by larger numbers of (relatively) small explosive events (~20 000 events per minute). Nanoflares: energy ~ 10^{16} J; microflares: energy ~ 10^{19} J. To make a flare, one needs 10^6 micro- and 10^9 nano-flare events. These abundances remain to be proved. Magnetic reconnection (Parker's scenario) is a potential driver of such events.

- **Turbulent cascading**: combines the ideas of cyclotron heating and phase mixing. Short wavelength fluctuations are generated from the long wavelegth ones which are damped at scales close to the ion gyro radii.

Solar irradiance

- The total solar irradiance (TSI):

$$S = 1367 \pm 3\,\mathrm{W\,m^{-2}}$$

- $S \approx 1366\ \mathrm{Wm^{-2}}$ during solar minima
- $S \approx 1367\ \mathrm{Wm^{-2}}$ during solar maxima
- S varies by a factor of:

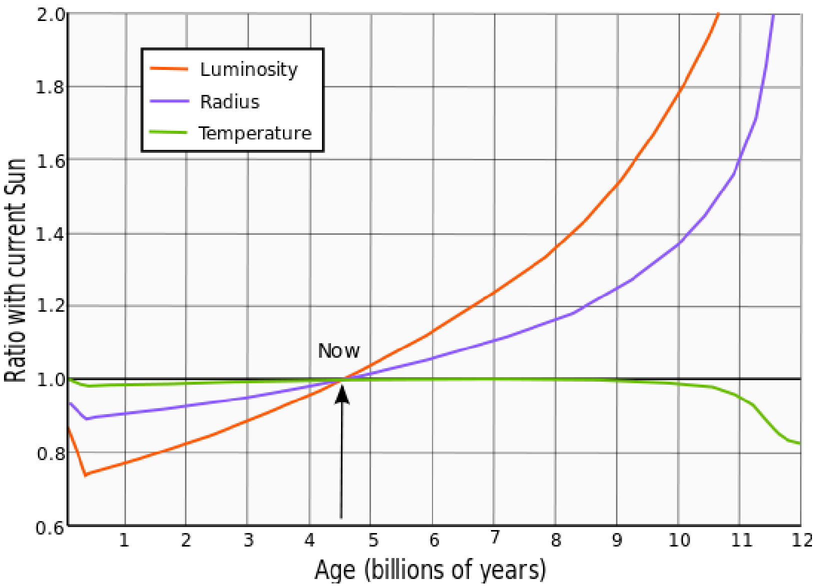
  10^{-6} over minutes

  2×10^{-3} (0.2%) over several days

  $\sim10^{-3}$ over a solar cycle

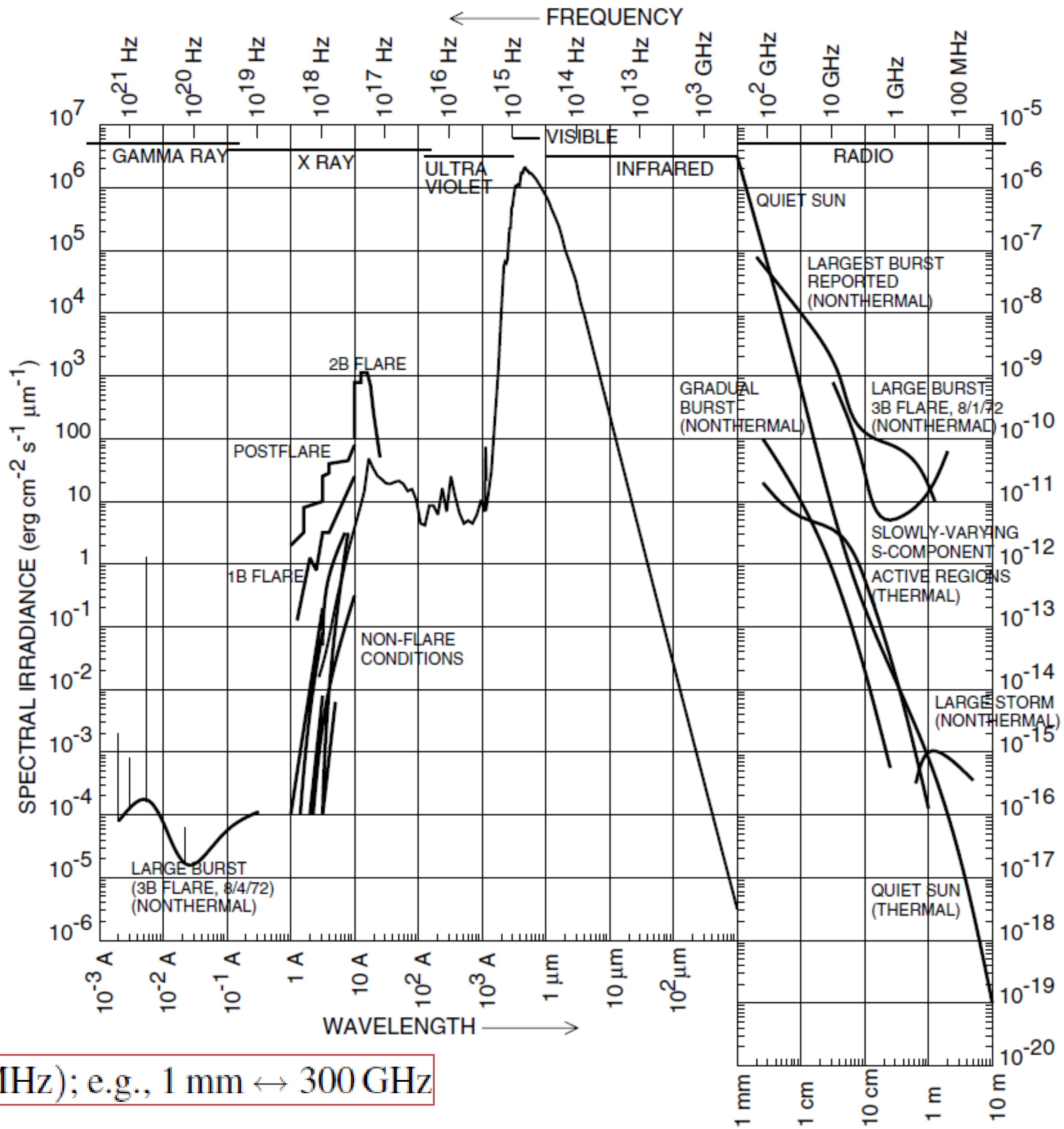
- The *luminosity* of the Sun:

$$L_\odot = 4\pi AU^2 S = (3.844 \pm 0.010) \times 10^{26}\,\mathrm{W}$$



(Ribas, 2010)

Solar spectrum from γ-rays to radio waves

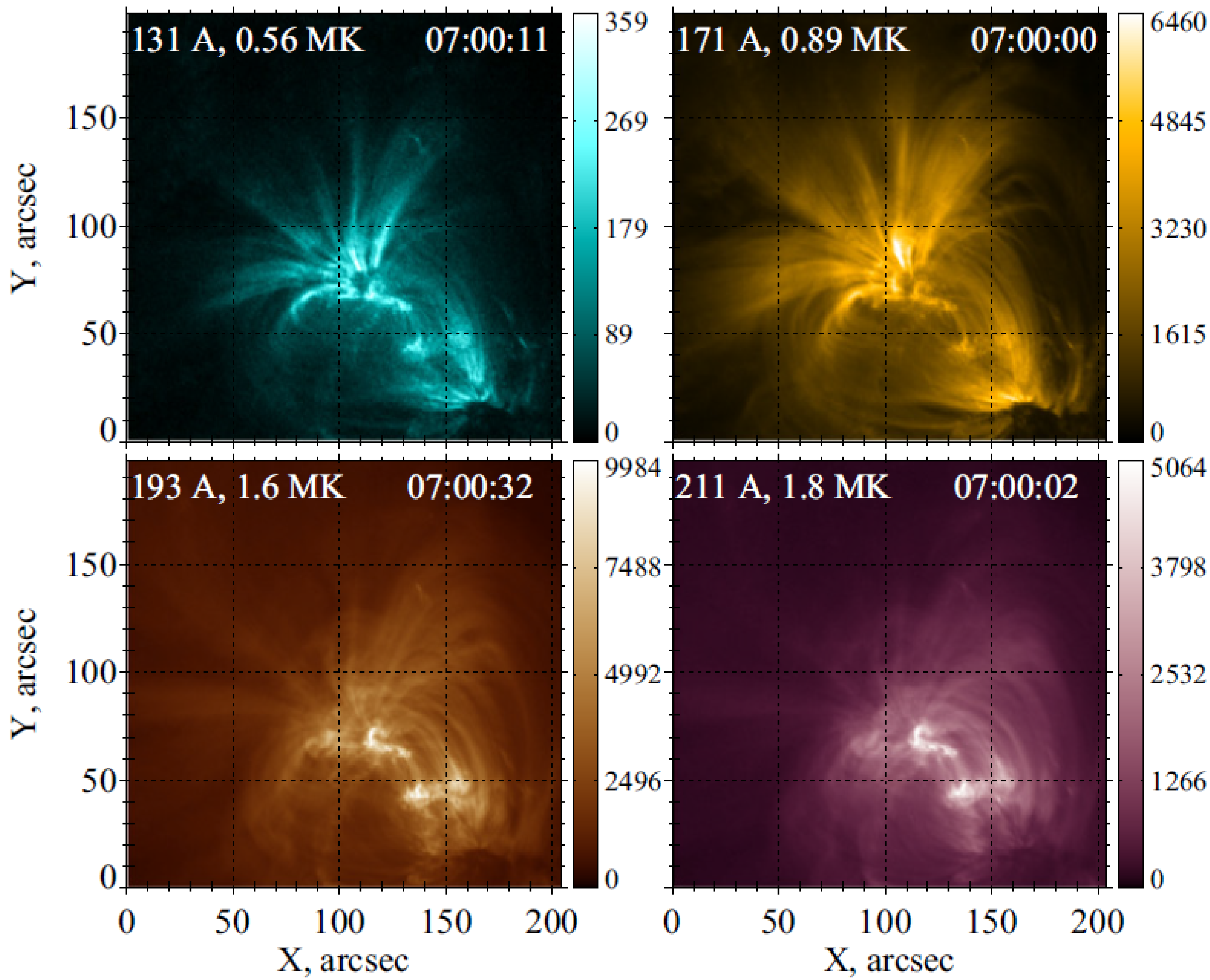


$$\lambda\,(\mathrm{m}) = 300/f\,(\mathrm{MHz});\ \text{e.g., } 1\,\mathrm{mm} \leftrightarrow 300\,\mathrm{GHz}$$

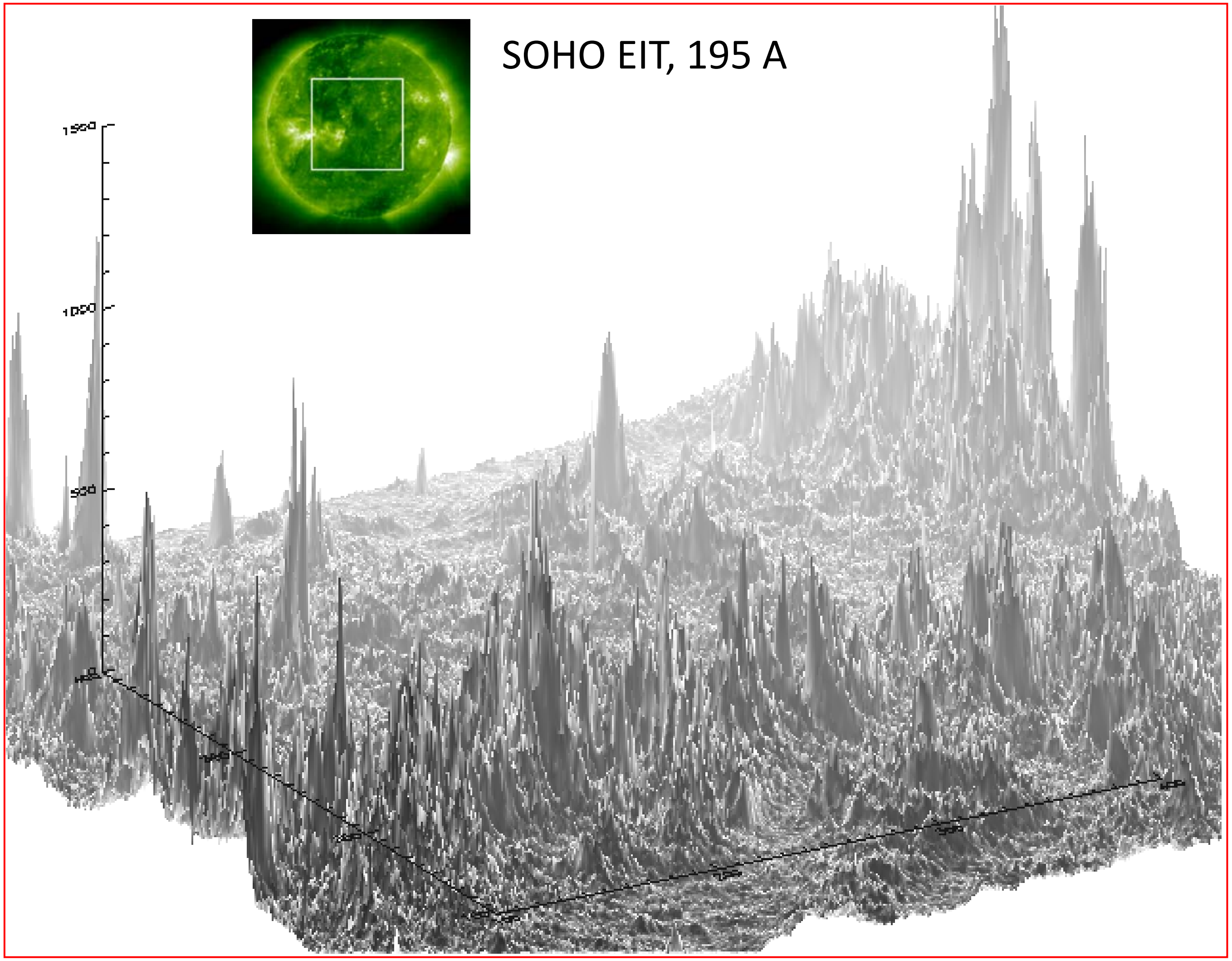
SDO Atmospheric Imaging Assembly (AIA) channels

AIA wavelength channel	Source[16]	Region of solar atmosphere	Characteristic temperature
White light	continuum	Photosphere	5000 K
170 nm	continuum	Temperature minimum, photosphere	5000 K
30.4 nm	He II	Chromosphere & transition region	50,000 K
160 nm	C IV + continuum	Transition region & upper photosphere	10^5 & 5000 K
17.1 nm	Fe IX	Quiet corona, upper transition region	6.3×10^5 K
19.3 nm	Fe XII, XXIV	Corona & hot flare plasma	1.2×10^6 & 2×10^7 K
21.1 nm	Fe XIV	Active region corona	2×10^6 K
33.5 nm	Fe XVI	Active region corona	2.5×10^6 K
9.4 nm	Fe XVIII	Flaring regions	6.3×10^6 K
13.1 nm	Fe VIII, XX, XXIII	Flaring regions	4×10^5, 10^7 & 1.6×10^7 K

Multi-spectral SDO AIA: NOAA AR 11082

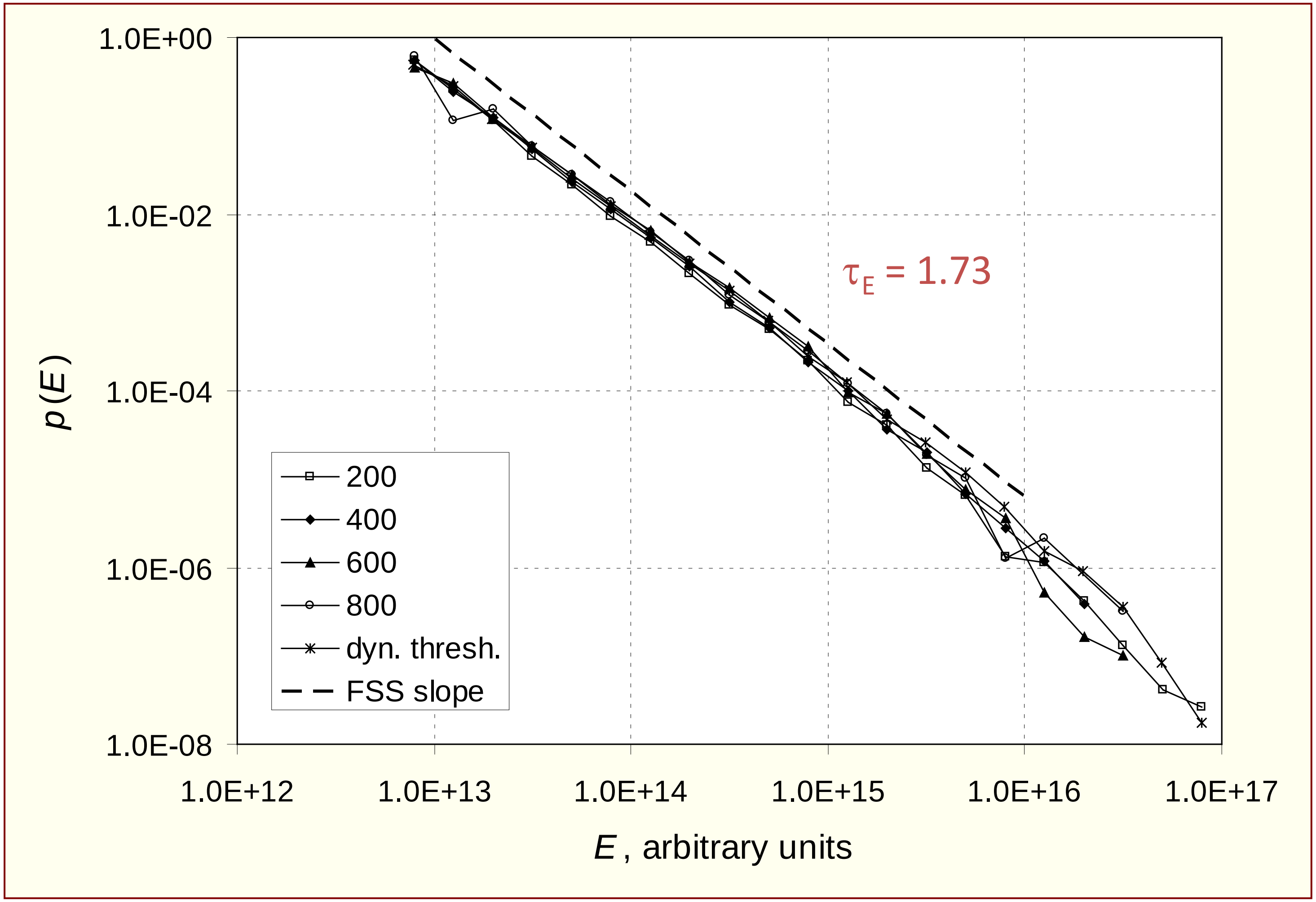


Multiscale intermittency in the solar corona



Uritsky, V.M., M. Paczuski, D. Davila, and S. I. Jones, *PRL*, 99(2), Art. No. 025001, 2007.

Probability distributions of coronal emission events (Uritsky et al, PRL 2007)

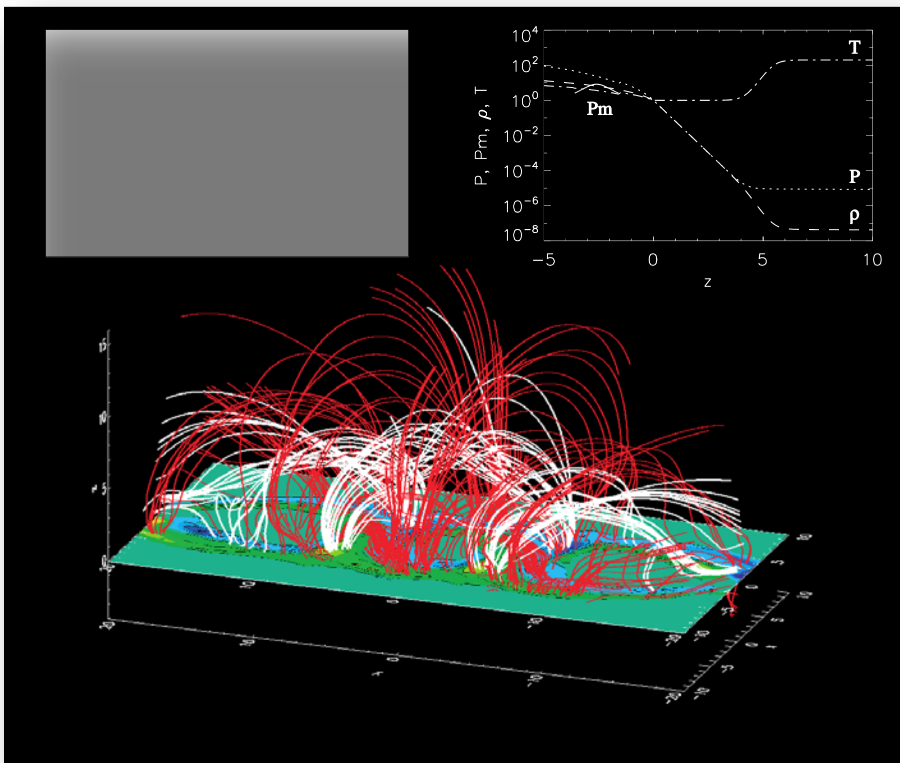


Solar flares

- Generally speaking in solar flares free magnetic energy converted into heat, non-thermal particle acceleration, electromagnetic radiation, waves and bulk flows.
- The flaring process can be divided into three steps:
  - Energy build-up.
  - Energy release.
  - Energy transport.

Complex magnetic fields produce solar eruptions

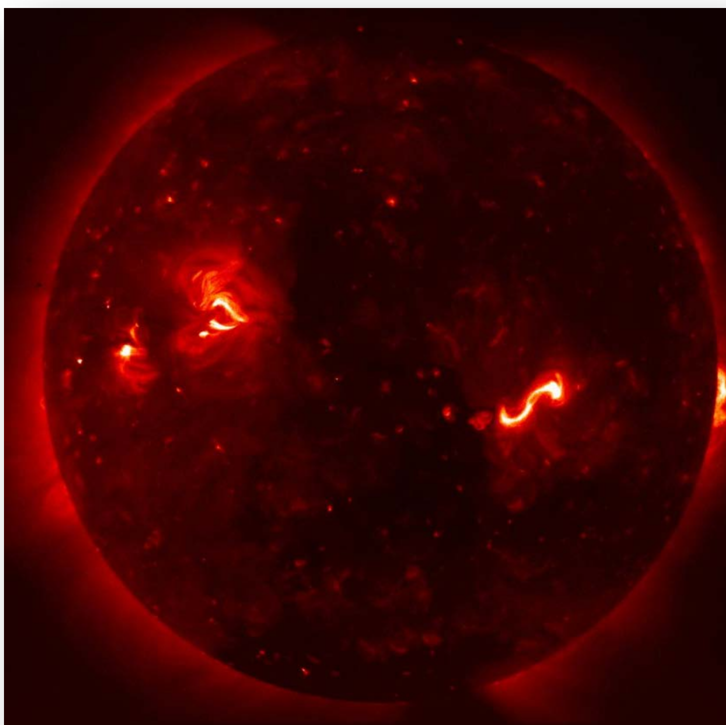
The emerging flux together with complex photospheric flows lead to complex structures such as filaments/prominences in the solar atmosphere.



Flux emergence in 3D MHD 80 Mm x 90 Mm x 68 Mm model (credit: *Magara*, 2007).

Unstable solar signatures

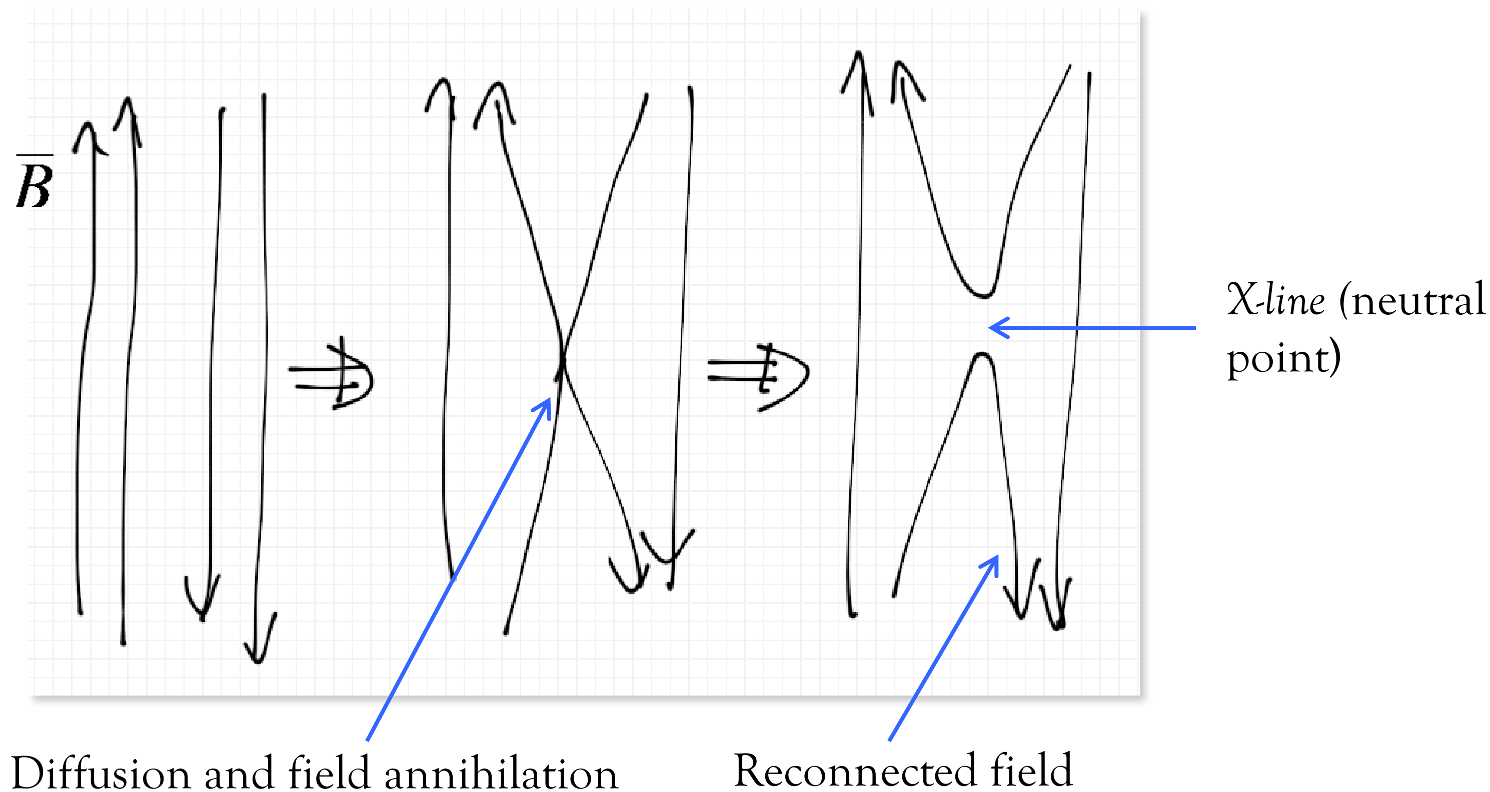
Complex solar atmospheric “beta-gamma-delta” structures having also, for example, *sigmoid* signature in soft X-rays (0.1 – 10 nm) indication of pending eruption.



Hinode 0.2–20 nm X-Ray Telescope (XRT) image of a sigmoid on February 12, 2007

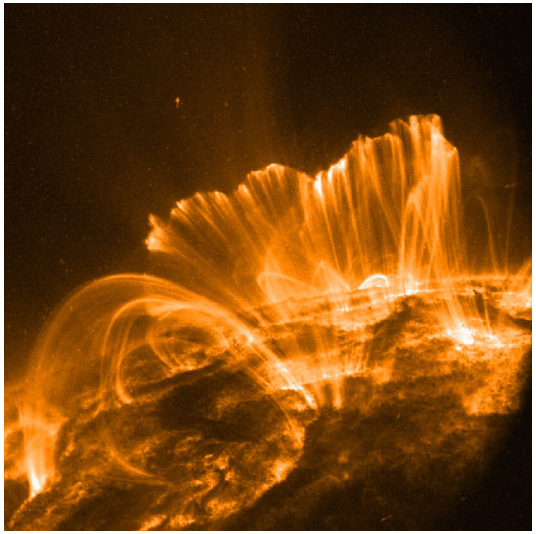
Magnetic reconnection

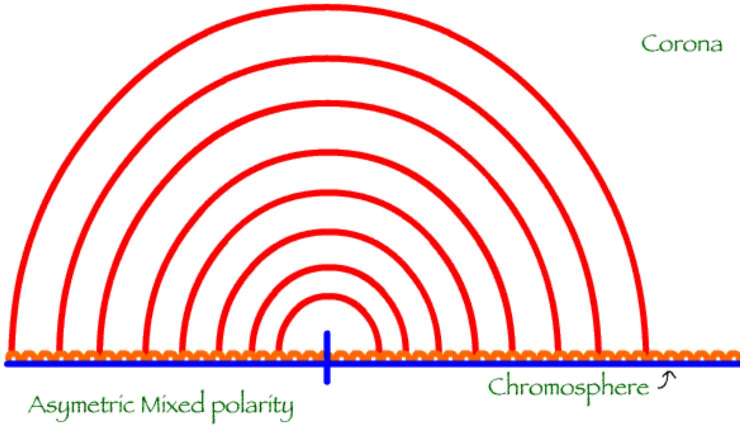
At the formed localized boundary layer diffusion may become important and lead to global reconfiguration of plasma:



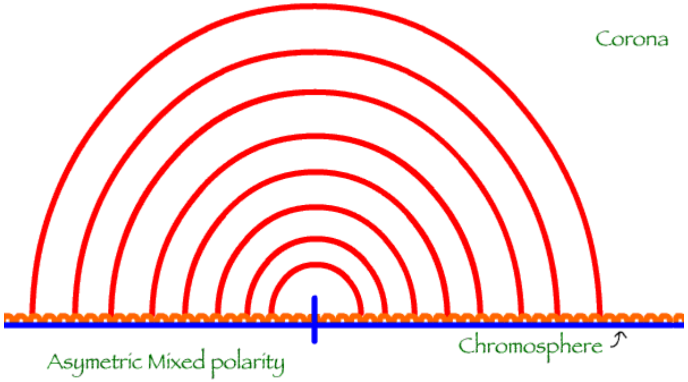
Examples of non-potential coronal structures

TRACE loop arcade

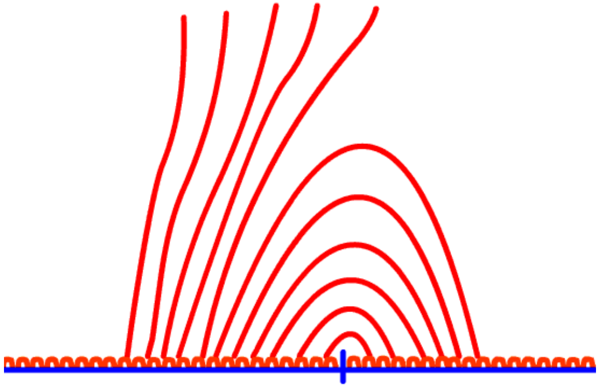




Convergent flow



Differential rotation

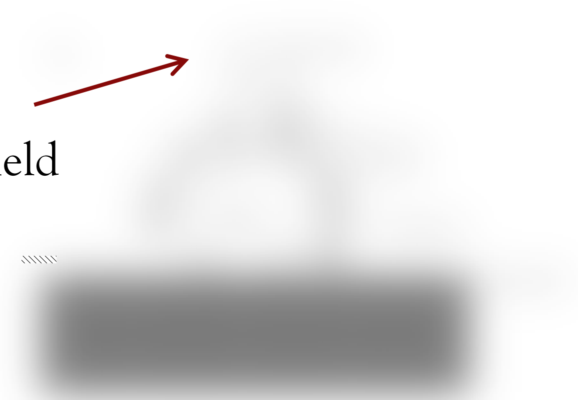


Neutral line + coronal hole

Reconnection events in the solar corona

- In flares energy build-up can generate these reconnecting thin current sheets and boundary layers in primarily two different ways (or combo):

Coronal magnetic field

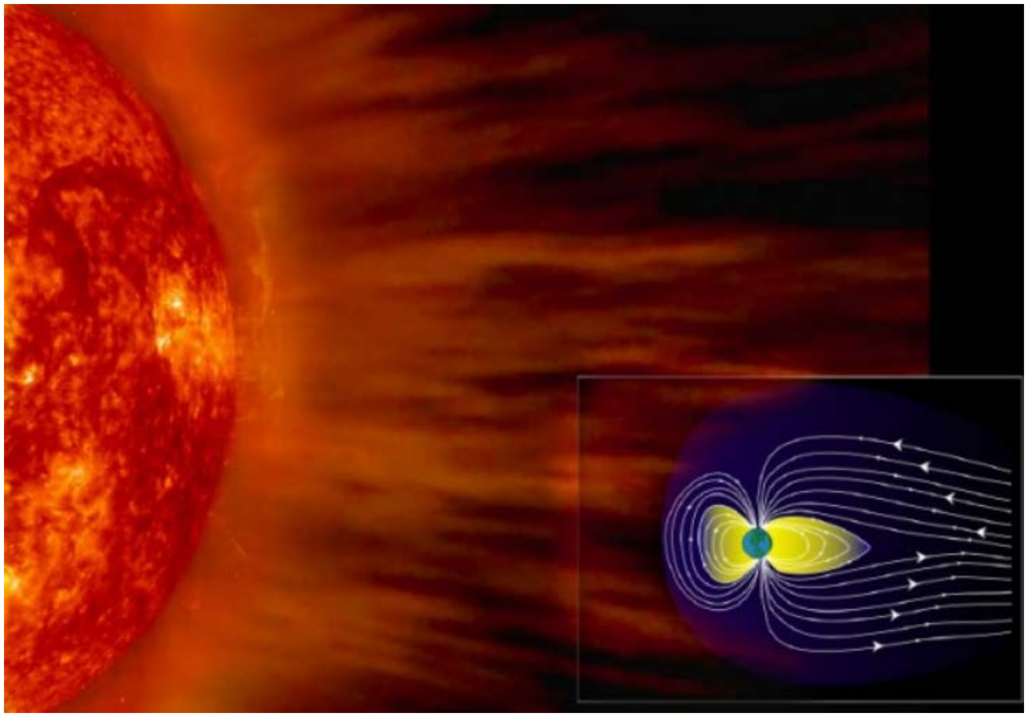


Single erupting magnetic domain
(credit: *Manchester*, 2001)

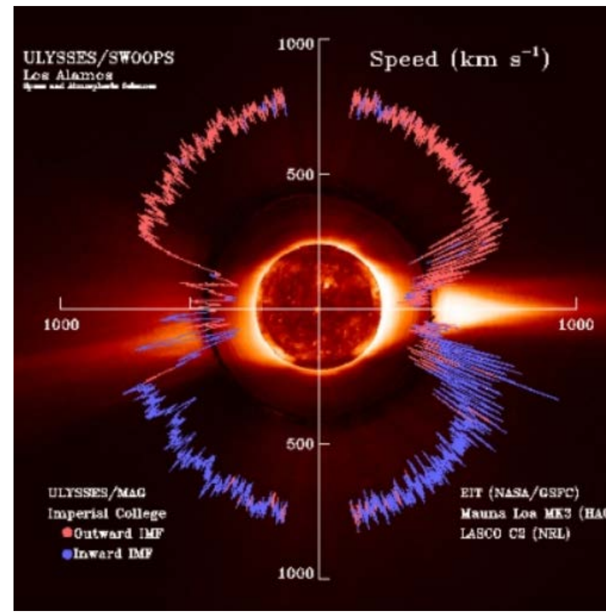
Current sheet and reconnection

Two interacting magnetic domains
(credit: *Shibata*, 2011)

THE SOLAR WIND



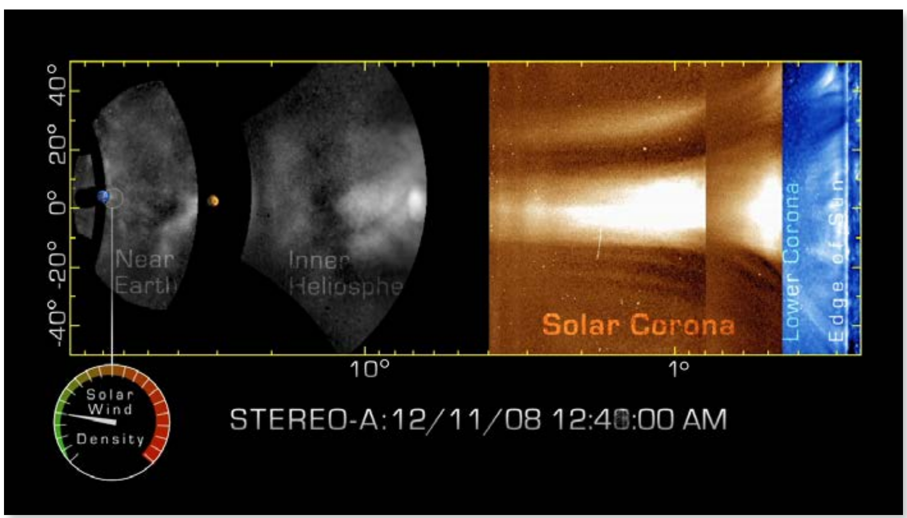
Polar overlay plot of Ulysses/SWOOPS solar wind speed data (Apr 1998) and EIT/LASCO/Mauna Loa images of the solar corona



Formation of the solar wind

- The million degree coronal plasma experiences continuous thermal expansion and escapes the gravitational potential → *supersonic solar wind.*

- Also other mechanisms such as plasma waves possibly contribute to the solar wind acceleration.



STEREO A white light coronagraphs and heliospheric imagers December 2008

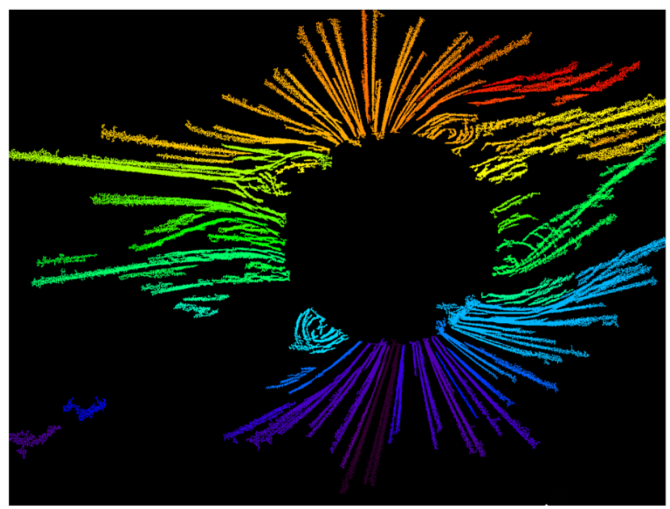
Credit: NASA GSFC

Coronal magnetic field

Total solar eclipse (08/01/2008), Miloslav Druckmuller et al.

Idenifying open field coronal loops (V Uritsky et al, 2015)

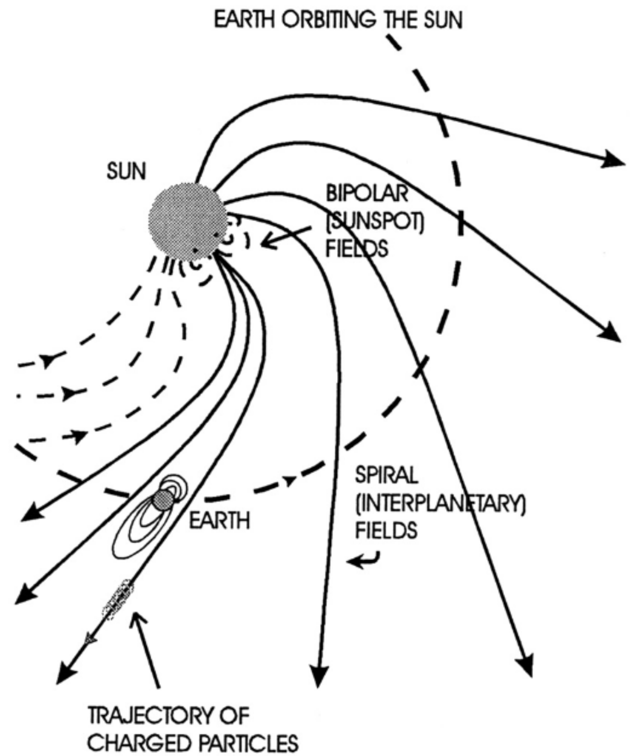
First-order angular differencing ($\Delta\phi$=1 deg)



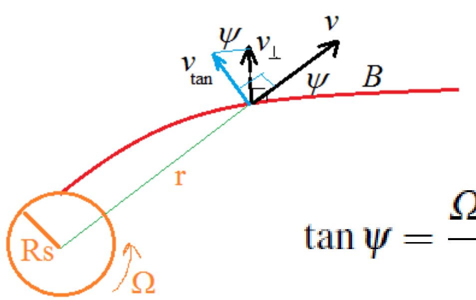
Typical solar wind parameters at 1 *AU*

	slow wind	fast wind
V (km s^{-1})	350	750
n_e (m^{-3})	1×10^7	3×10^6
T_e (K)	1.3×10^3	1×10^5
T_p(K)	3×10^4	2×10^5
B (nT)	3	6
v_A (km s^{-1})	20	70

$v_A = B/\sqrt{\mu_0 \rho_m}$ is the Alfvén velocity



The ***Parker spiral***



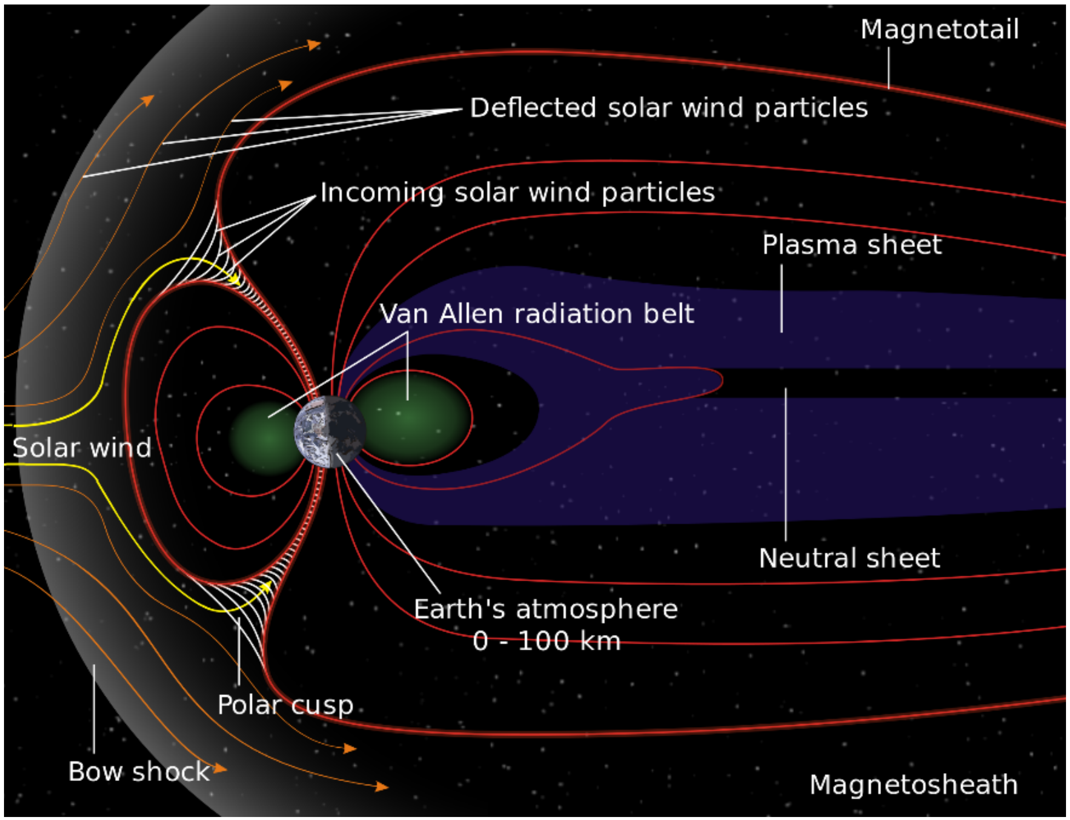
$$\tan\psi = \frac{\Omega\,(r - R_\odot)}{V}$$

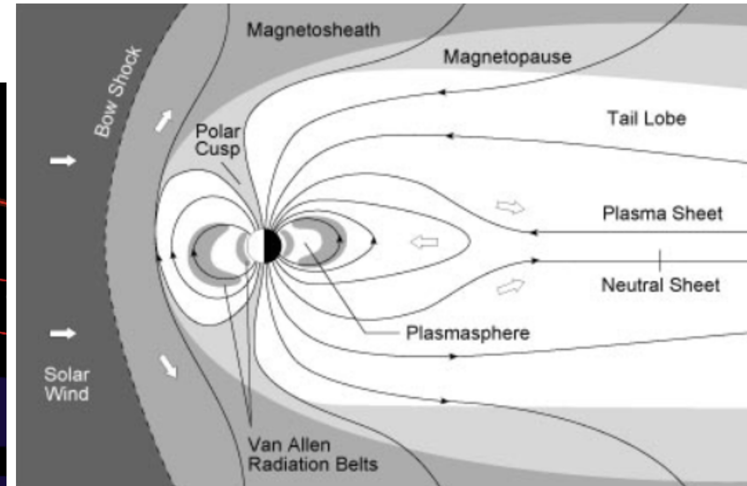
Turbulent space environment

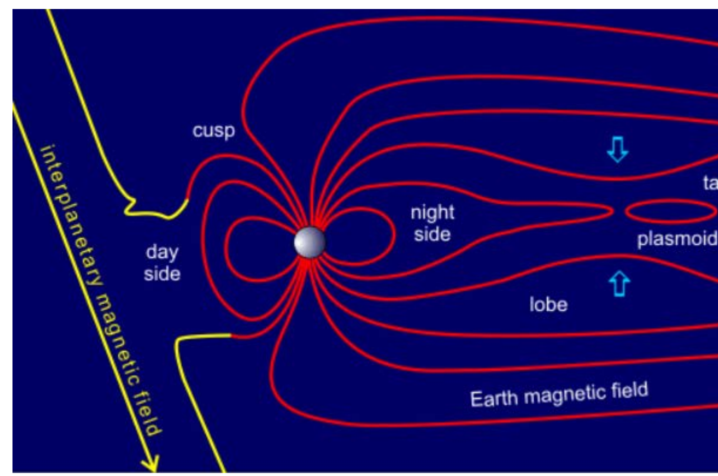
	Solar Wind	Magnetosheath	Magnetotail
Re	1×10^{14}	1×10^{12}	5×10^{12}
Re_m	3×10^{14}	1×10^{13}	1×10^{13}

J Borovsky, H. Funsten JGR 2003

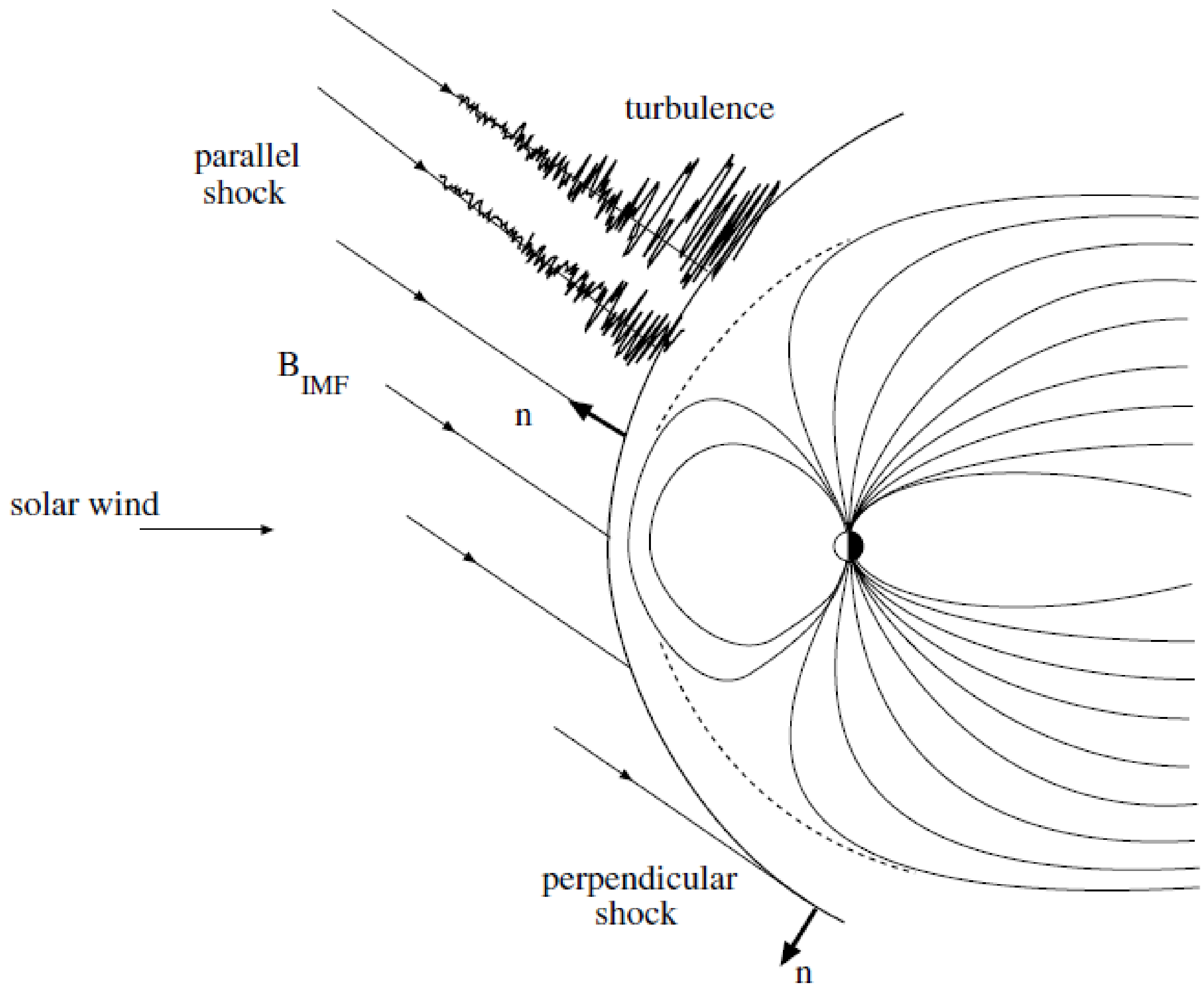
THE MAGNETOSPHERE





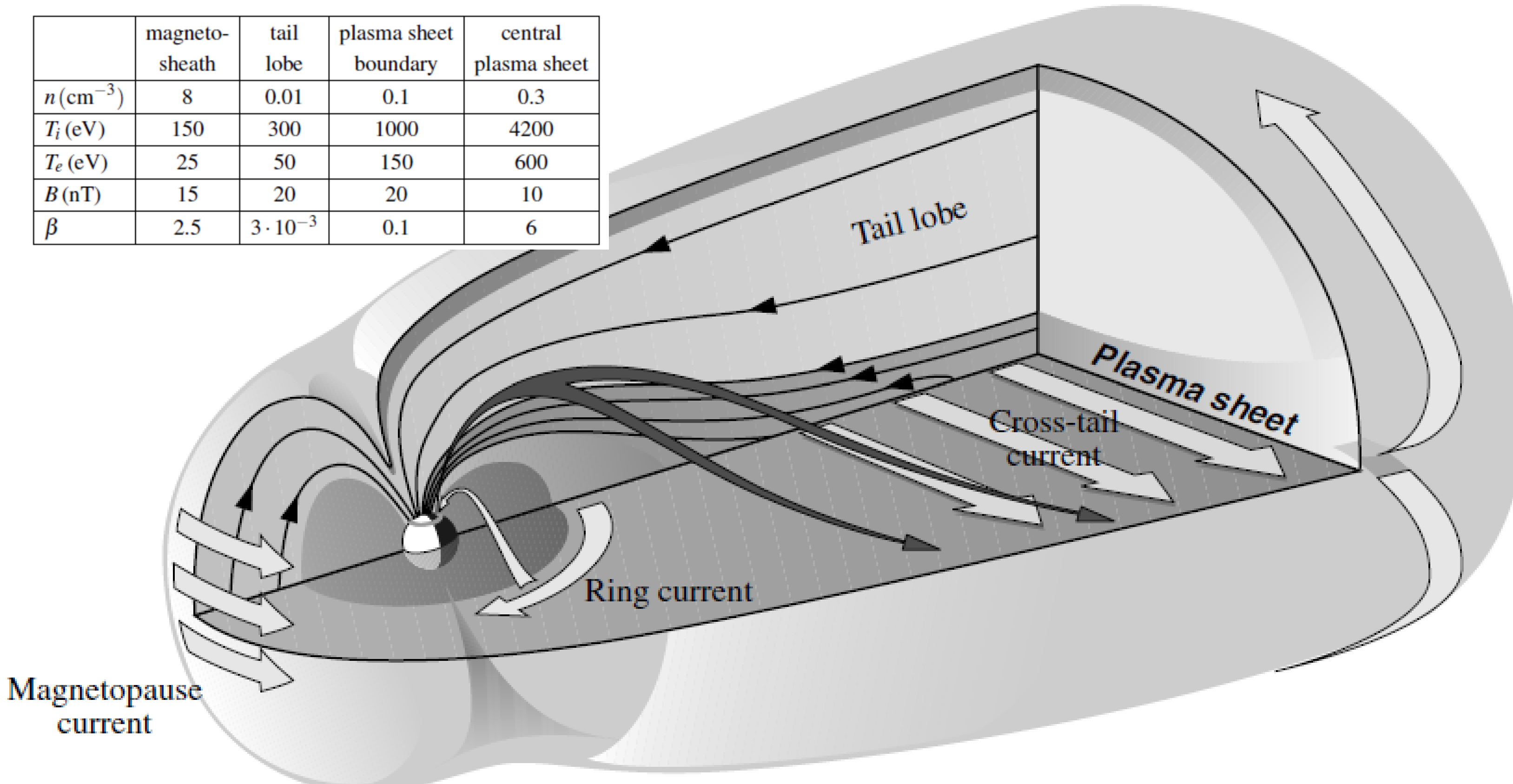


A magnetosphere and its bow shock



The magnetosphere and the large scale magnetospheric current systems.

	magneto-sheath	tail lobe	plasma sheet boundary	central plasma sheet
$n\,(\mathrm{cm}^{-3})$	8	0.01	0.1	0.3
$T_i\,(\mathrm{eV})$	150	300	1000	4200
$T_e\,(\mathrm{eV})$	25	50	150	600
$B\,(\mathrm{nT})$	15	20	20	10
β	2.5	$3 \cdot 10^{-3}$	0.1	6



Space weather and electric power

NOAA VIDEO: Space Weather Impacts (2:48)

NEXT SWC seminar

Schedule of talks

October 25, 1016 (Tuesday):	**AN INTRODUCTION TO SPACE WEATHER**
November 01, 2016 (Tuesday):	**THE SCIENCE OF SOLAR HURRICANES**
November 16, 2016 (Wednesday):	**FORECASTING EXTREME SPACE WEATHER**
November 30, 2016: (Wednesday):	**SPACE HAZARDS AND THE HUMAN SOCIETY**

Location: Rm 106, Hannan Hall **Time**: 7:00pm

Practical experience

Students with sufficient backgrounds in physics and math will be offered a unique **hands-on experience with space weather forecasting tools** available at the SWC through its collaboration with the Community Coordinated Modelling Center at NASA Goddard Space Flight Center.

Contact information: **Dr. Vadim Uritsky**, 206 Hannan Hall, uritsky@cua.edu

THANK YOU !