Physics of the Sun-Earth System
SOHO and Cluster

Ester Antonucci   INAF-OATO, Turin

Symposium in honor of Roget Bonnet
ESTEC 8-9 February 2018

Space Science 'Horizon 2000'
1st Cornerstone

- SOHO - Solar and Heliospheric Observatory

  ESA-NASA - launch 1995

  For the first time a star could be studied from its deep interior, via helioseismology, to the cavity cointaining the solar wind

  Uninterrupted observation of the Sun from L1
- Cluster

  ESA - launch 2000

  First 3D plasma physics in space, in situ study of the key plasma regions of the Earth magnetosphere

  4 identical spacecraft with variable relative distance and evolving orbits to resolve the temporal and spatial evolution of magnetospheric structures

SOHO, Ulysses, Cluster

Solar/heliospheric/magnetospheric system

Primary role of Europe in this field at the start of this century

SOHO - 3rd Large Solar Observatory in Space

❑NASA Solar Observatories

I ATM (Apollo Telescope Mount) on Skylab 1973-1974

final step of the long-term strategy for solar physics set by the Space Science Board of the National Academy of Science

II SMM (Solar Maximum Mission) 1980-1989

devoted to explore the most energetic part of the electromagnetic spectrum from UV to γ rays (160 MeV)

❑ESA(led)-NASA Solar and Heliospheric observatories

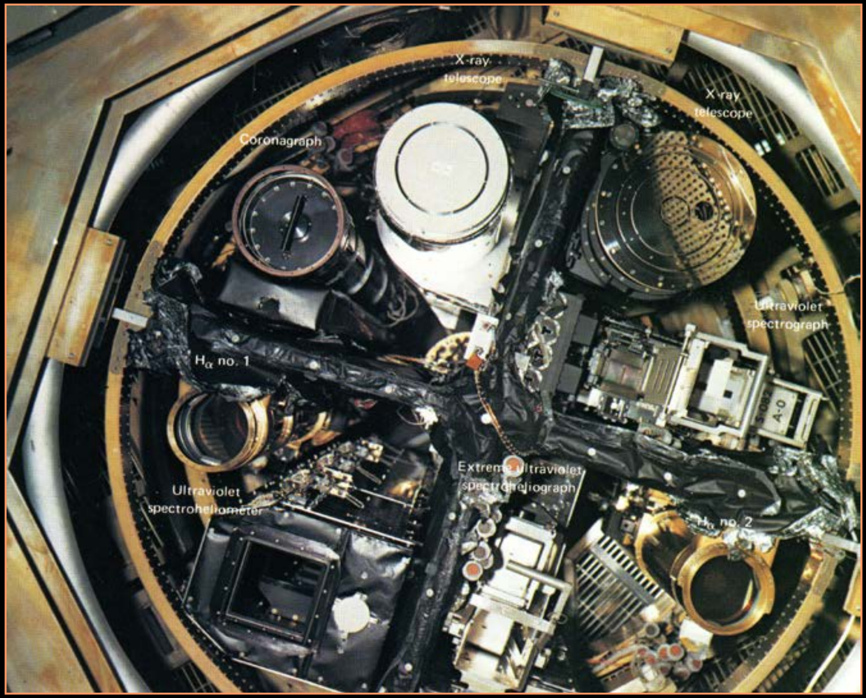
III SOHO (Solar and Heliospheric Observatory) 1995 on

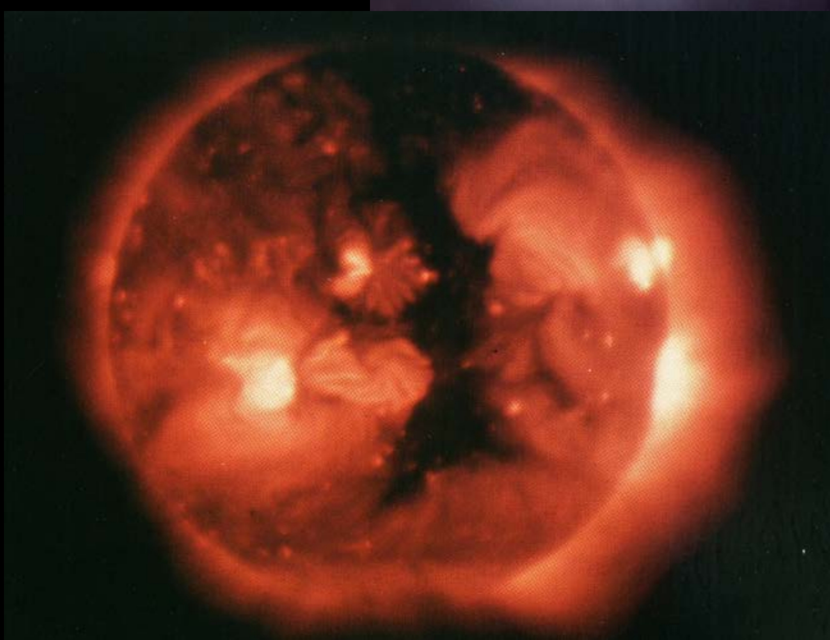
from the the core of the Sun to the L1 point

IV Solar Orbiter - next solar cycle

exploring the solar poles and the inner part of the heliosphere (in synergy with the Parker Solar Probe)

Apollo Telescope Mount Skylab1973-1974





First US manned space observatory

- *3 Skylab crues*
- *171 days total manned operation time*
- *8 complementary telescopes*
- *wavelength coverage 2-7000 Å*
- *900 kg scientific payload*
- *no power restriction*

Solar Maximum Mission 1980-1989

The high energy Sun from UV to γ rays

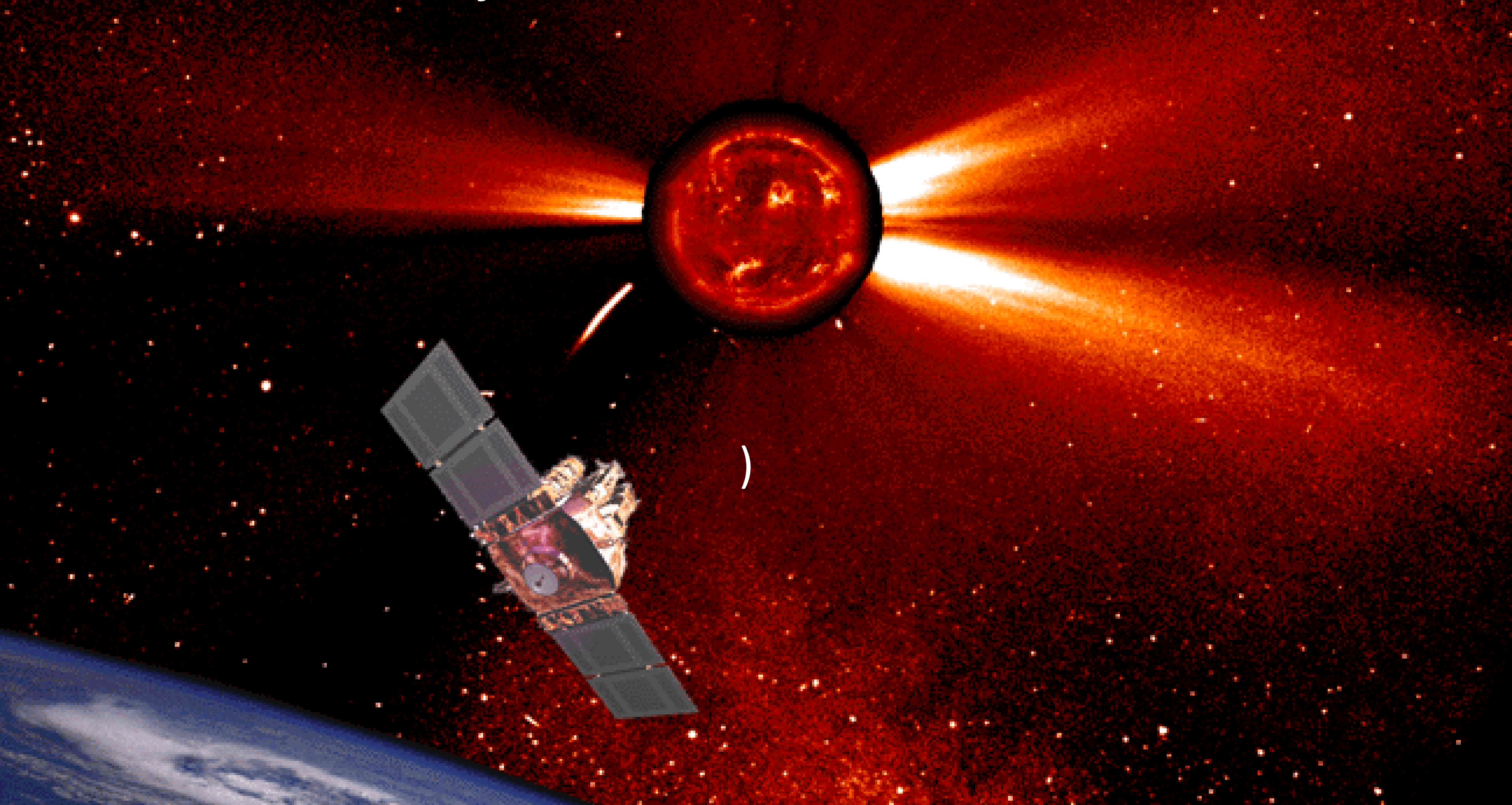
Second large space observatory for solar physics devoted to explore the most energetic part of the electromagnetic spectrum from UV to γ rays

The observatory hosted 7 instruments

SMM was the first satellite to be repaired in orbit by the crew of Challanger on mission 41.C. The pilot F.R. Scobee was the commander of the Challanger last flight.

SOHO ESA-NASA
1995 - 2018 (... and beyond)

continuous view of the Sun @ L1 since 14 February 1996
record of 2 solar cycles of observations



The SOHO Mission

The SOHO mission was first proposed in response to an ESA call in 1982 (Malinovsky-Arduini et al.)

SOHO (Solar High Resolution Observatory) proposal was in a first time aimed at coronal and solar wind studies and including the objectives of GRIST (Grazing Incidence Solar Telescope – ESA Phase A study), focused on UV spectroscopy.

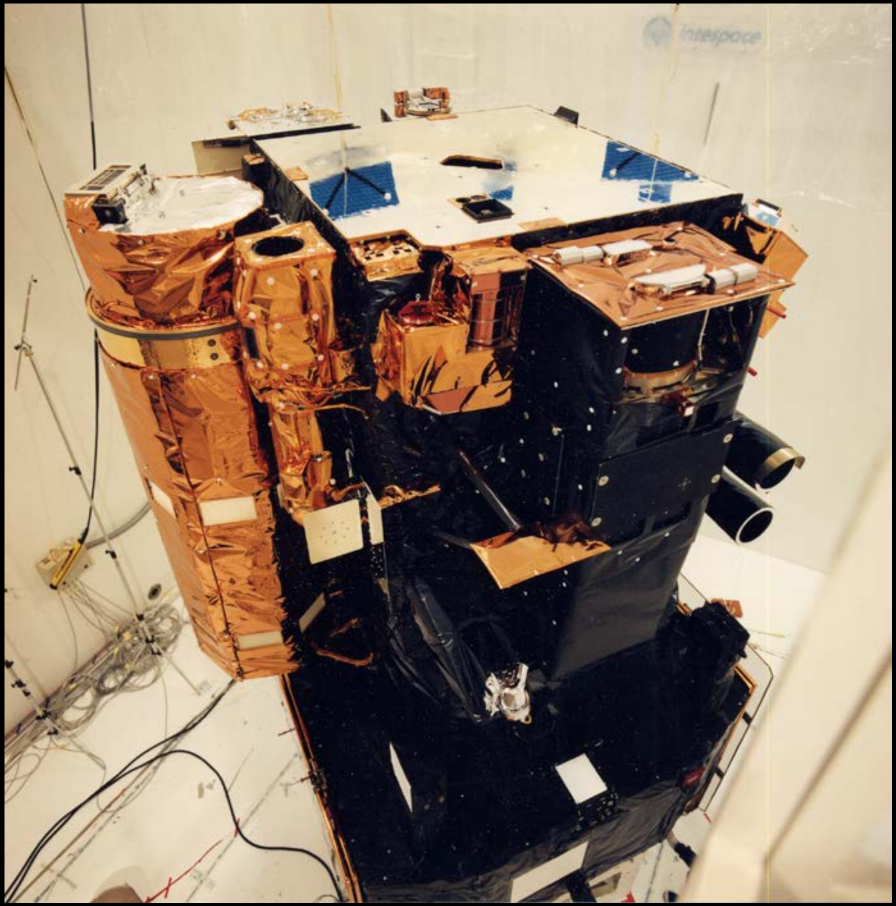
During the assessment study (1983) the original scientific goals were merged with those addressed during the ESA Phase A study of DISCO (Dual Spectral Irradiance and Solar Constant Orbiter), focused on helioseismology @ L1.

SOHO was thus renamed
'Solar and Heliospheric Observatory'

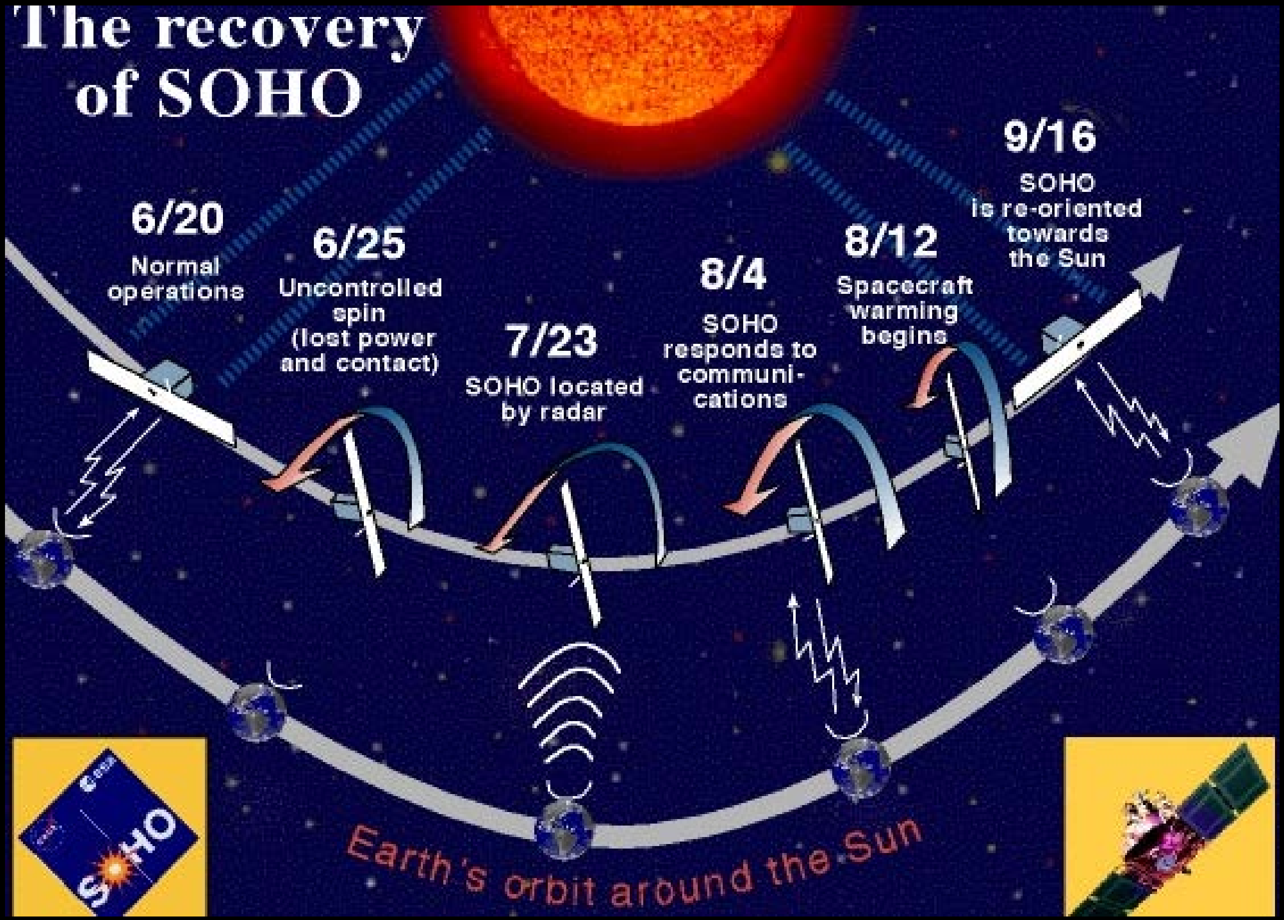
In February 1986 the Science Programme Committee of ESA approved the Solar/Terrestrial Physics Programme (SOHO & Cluster) as the first cornerstone of the Space Science Horizon 2000 Programme, to be implemented in collaboration with NASA.

The SOHO Spacecraft

- built in Europe
- 12 instruments onboard - remote sensing & in situ - 600 kg science payload
- launched by NASA on 2 December 1995
- operated from NASA GSFC
- nominal mission 2 years
- extended mission 6 years



SOHO Lost in Space in Summer 1998



SOHO was

- *lost in June 1998*
- *located with the Arecibo radar*
- *reoriented and fully recovered in September 1998*

20 y later: SOHO as a Space Weather Mission

SOHO at present is considered by NASA senior review

‘infrastructure that must be maintained’
due to
critical importance to ‘the Nation (US) space weather architecture’

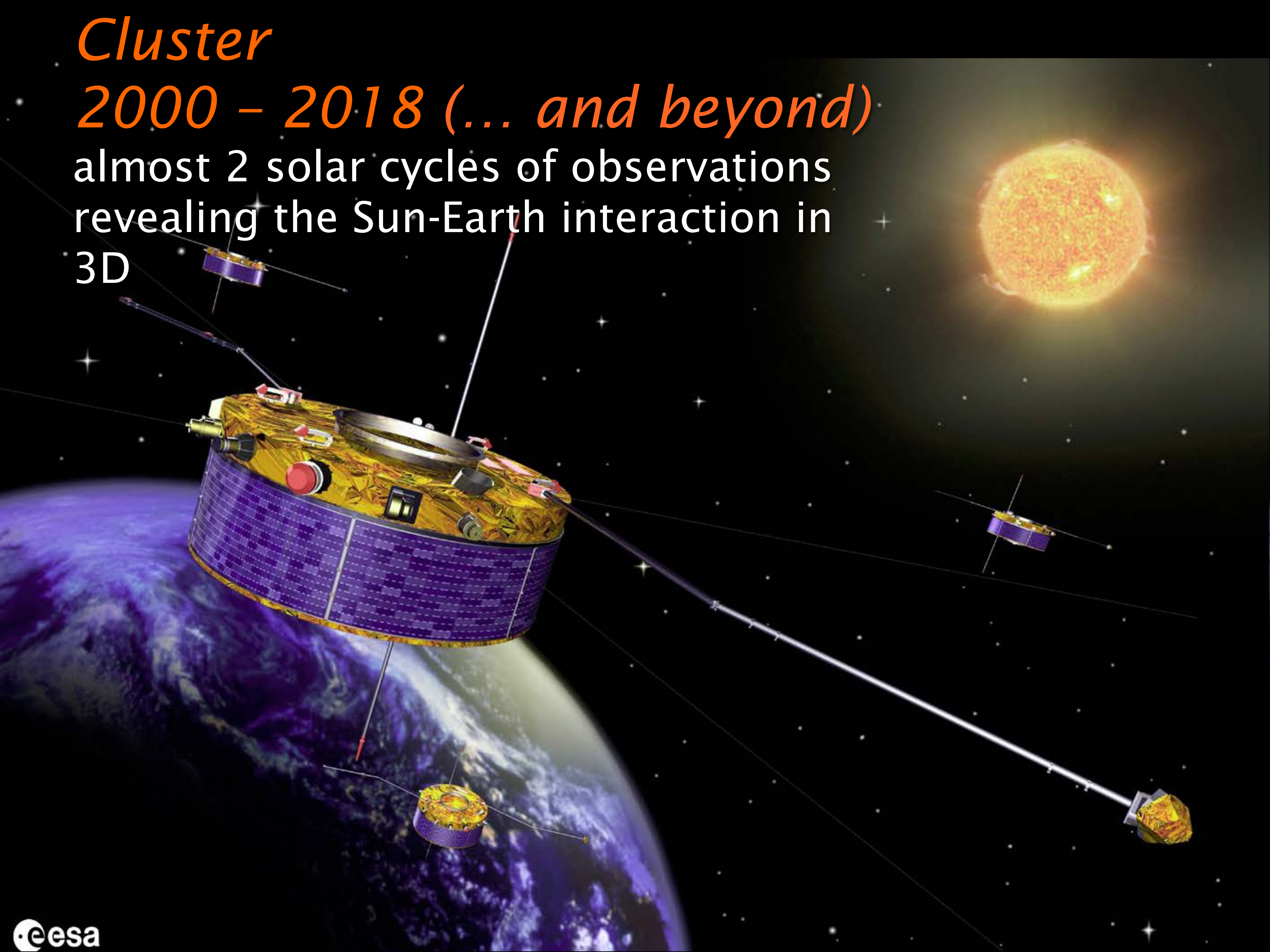
According to the ‘Space Weather and Forecasting Act’ of the US Senate Commerce, Science and Transportation Committee, on April 2016

“In order to sustain current space-based capabilities, the Administrator of NASA shall maintain operations of the SOHO LASCO coronagraphs as long as the satellite continues to deliver quality observations ..”

In 2015

Cluster
2000 – 2018 (... and beyond)

almost 2 solar cycles of observations revealing the Sun-Earth interaction in 3D



The Cluster Mission

The Cluster mission was first proposed in response to an ESA call in 1982 (Haerendel et al., 1982) and approved in 1986 as element of the 1st cornerstone.

In 1996 the four spacecraft were destroyed in the failure of Ariane 5 launch.

Roger Bonnet commitment
"I made on that occasion a promise that Cluster would be rebuilt and re-launched, even though I did not yet know how to realize this. This, indeed, was done in just four years, and in July and August of 2000 the mission was re-launched using two consecutive launches of a Soyuz rocket and the ESOC control capabilities."

The rebuild of Cluster was approved in 1997. Cluster spacecraft were successfully put in orbit by two Soyuz-Fregat launches from Baikonur on 16 July and 9 August 2000.

The mission has been extended to 2018.

1996 Cluster 1st Launch

Cluster I
Ariane 5 launch Failure 1996

Due to a software specification error the first Ariane 5 launch was not successful and the four Cluster spacecraft were destroyed

2000 Cluster 2nd Launch

Roger Bonnet after his television speech following the successful launch of the second Cluster spacecraft.

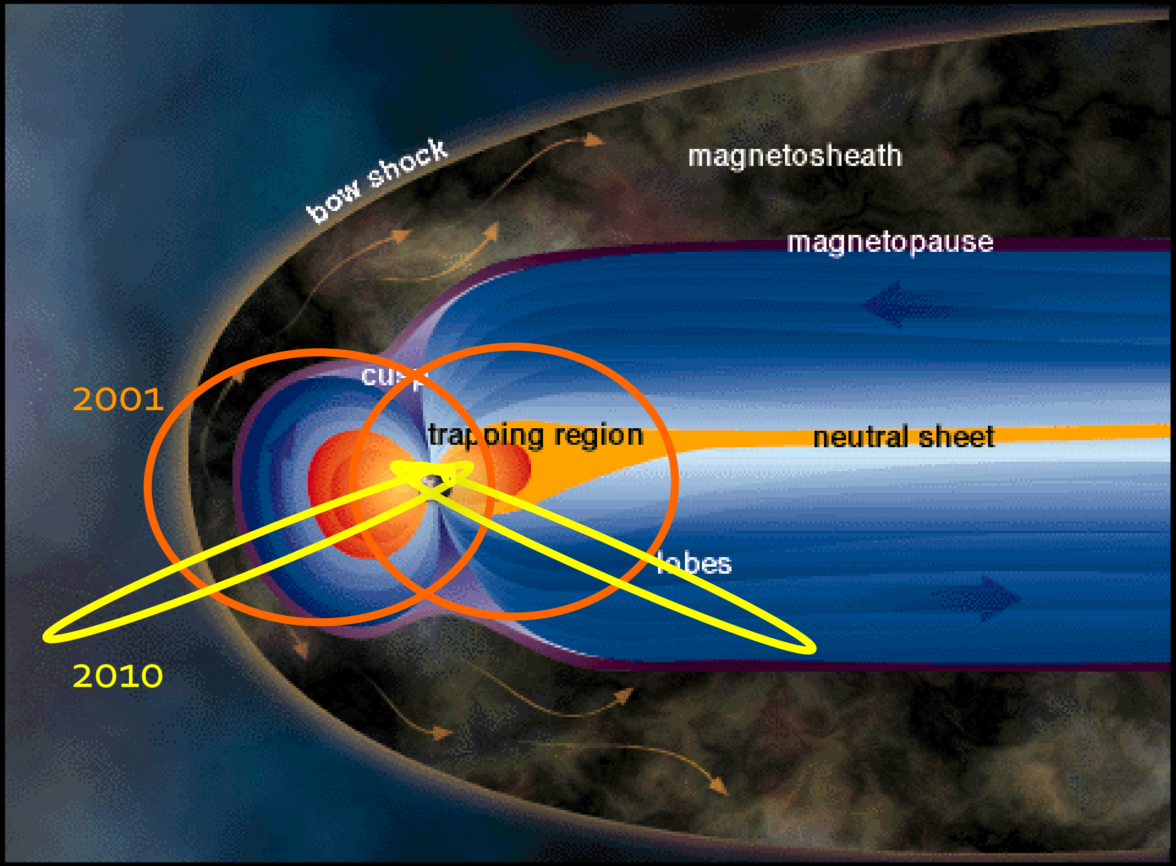
The Cluster Flotilla

- Flotilla of 4 identical spacecraft flying in formation
- 44 instruments (11 on each spacecraft)
- Measure:
  - Magnetic fields
  - Electric fields
  - Electromagnetic waves
  - Charged particles
- Unprecedented 3D study the Earth's protective bubble in space – the magnetosphere - and of its interaction with the solar wind

The Variable Flight Formation

Four spacecraft, with adjustable separations and orbit evolution, permit to study the physics of three-dimensional structures in the different regions of geospace.

Plasma processes in geospace are three-dimensional and occur on a wide range of spatial and temporal scales.



The First Cornerstone Success Story

- *IAA prize - 'Laurels for Team Achievement Award of the International Academy of Astronautics'*
  - *SOHO in 2003*

    first team of either ESA or NASA led missions to be awarded
  - *Cluster & Double Star in 2010*

    … among the many awards

- *Publications*

  >8000 refereed papers

  > 5412 papers have been published based on SOHO data

  > 2587 papers have been published based on CLUSTER data

- *Scientists*

  > 6000 scientists involved in data analysis

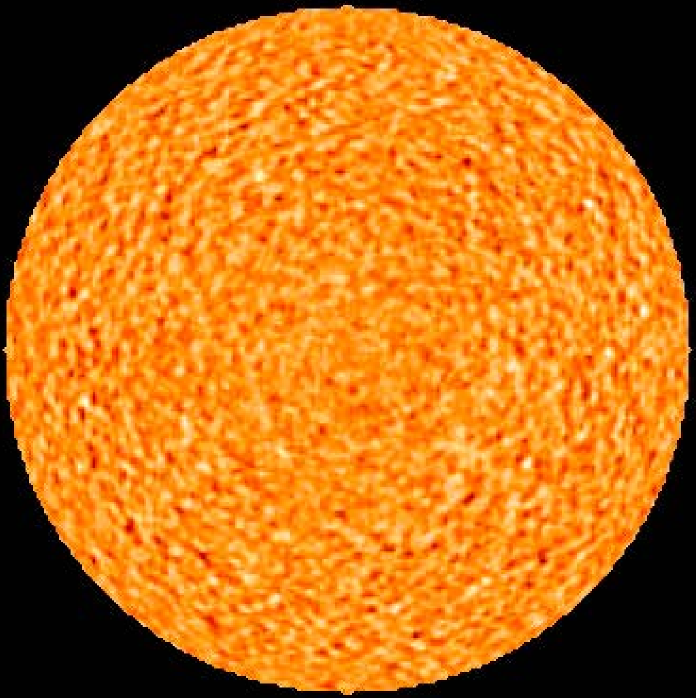
  > 3500 SOHO

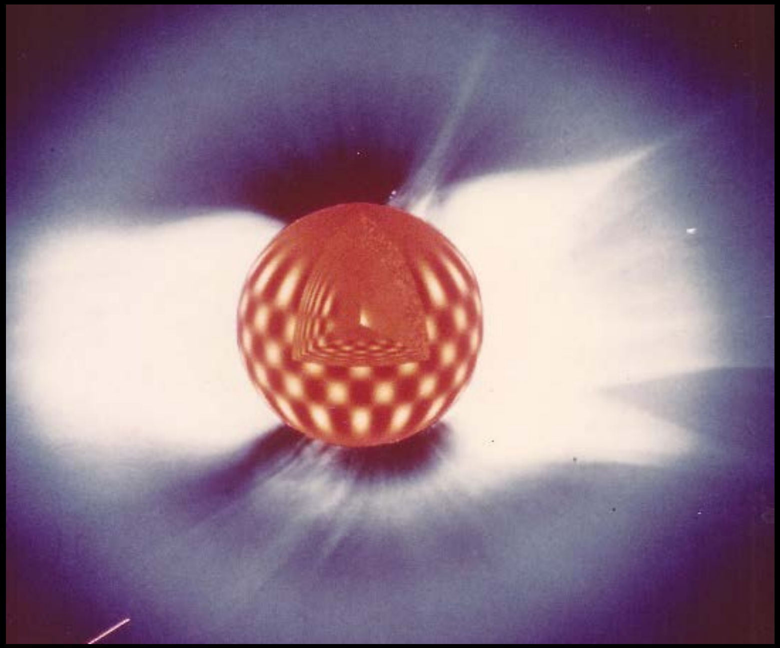
  > 2715 Cluster

2 Solar Cycles of Scientific Results from the Sun Core to the Earth Magnetosphere

Helioseismology from the Lagrangian Point L1

Helioseismology at L1





Global properties of the Sun's interior can be measured with helioseismology.

SOHO provided unprecedented continuous coverage of solar oscillations

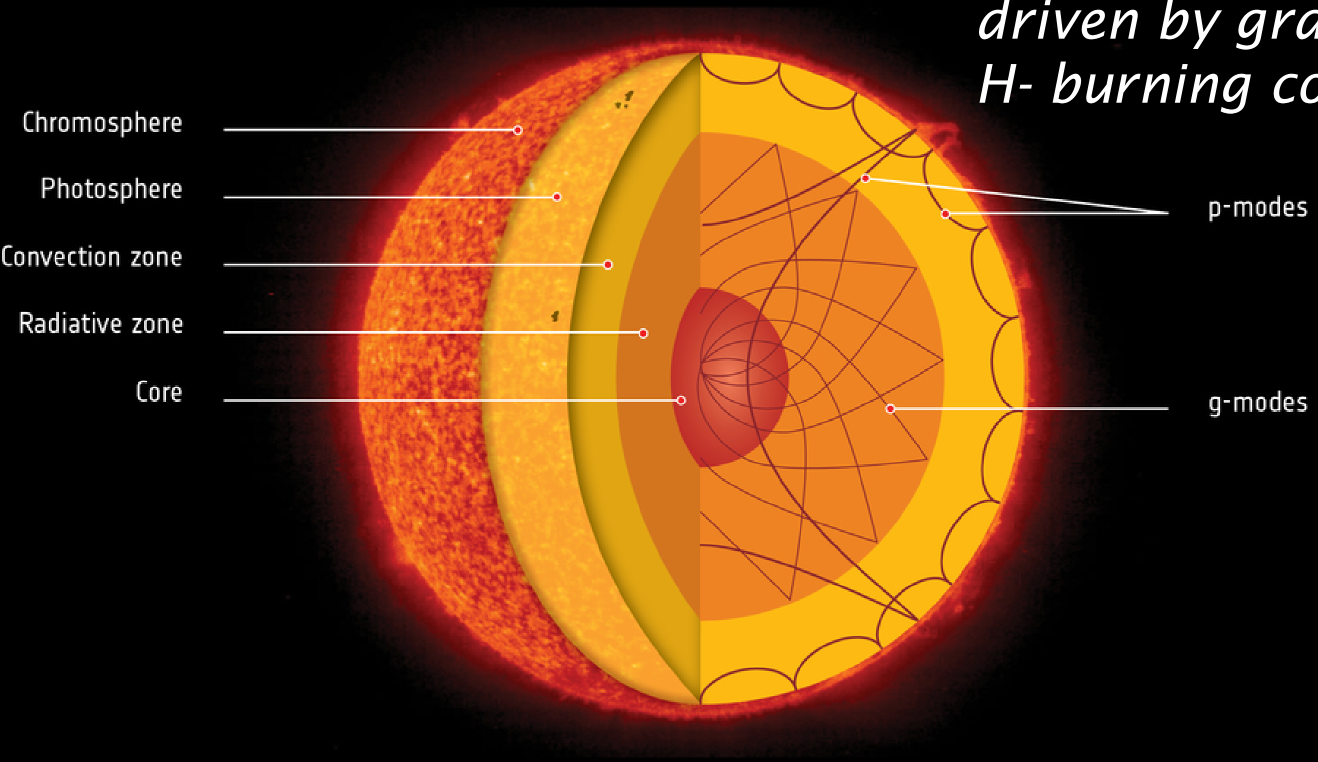
- *2 decades of full-disk helioseismic data*
- *more than a decade of continuous view of the oscillating solar surface*

The entire Sun vibrates according to a complex pattern of acoustic waves
The Sun's acoustic waves bounce from one side of the Sun to the other, causing the Sun's surface to oscillate up and down
The sound waves are influenced by conditions inside the Sun

GOLF

Sun Core
G-modes Discovery

- *Evidence for rapid rotation of the solar core ≈7 days*
- *Detection of g-modes, oscillations driven by gravity and hidden in the H- burning core*

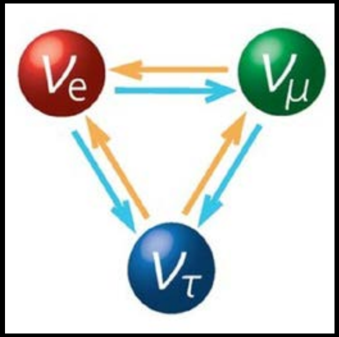


g-modes detected by analyzing collective frequency modulations of the p-mode that are produced by periodic changes in the deep solar structure over 16.5 years of data observed from the L1 point

Solution of the Solar Neutrino Problem

GOLF
MDI

- SOHO and GONG data provided constraints on solar seismic models, proving that the deficit of neutrino flux can be explained by "classical" solar models + neutrino flavour transitions



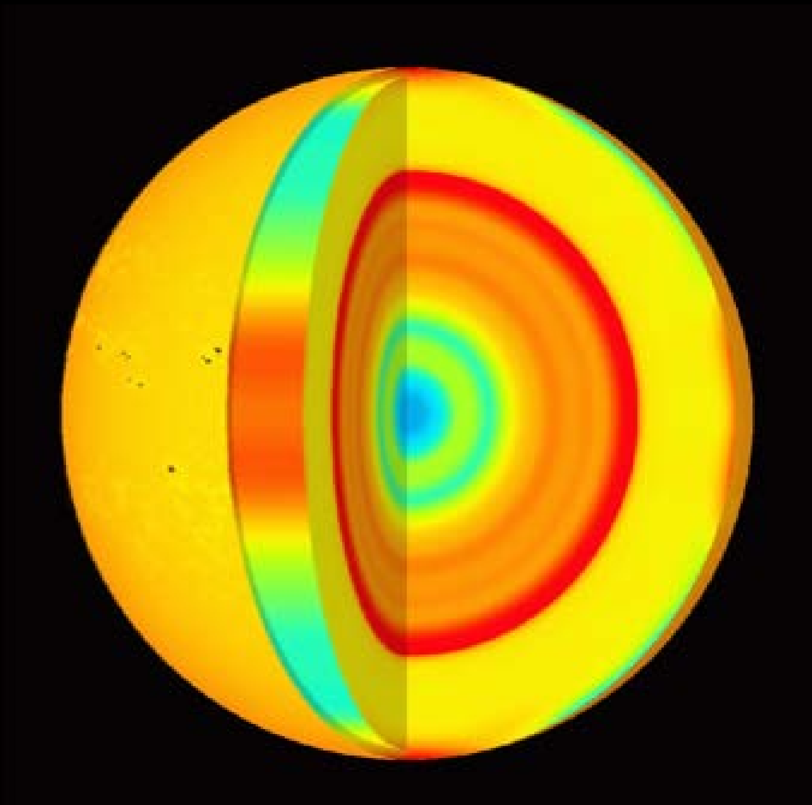
- Neutrino problem was definitively solved by measurements at the Super-Kamiokande facility and Sudbury Neutrino Observatory, which provided compelling evidence for solar ν_e flavour transitions

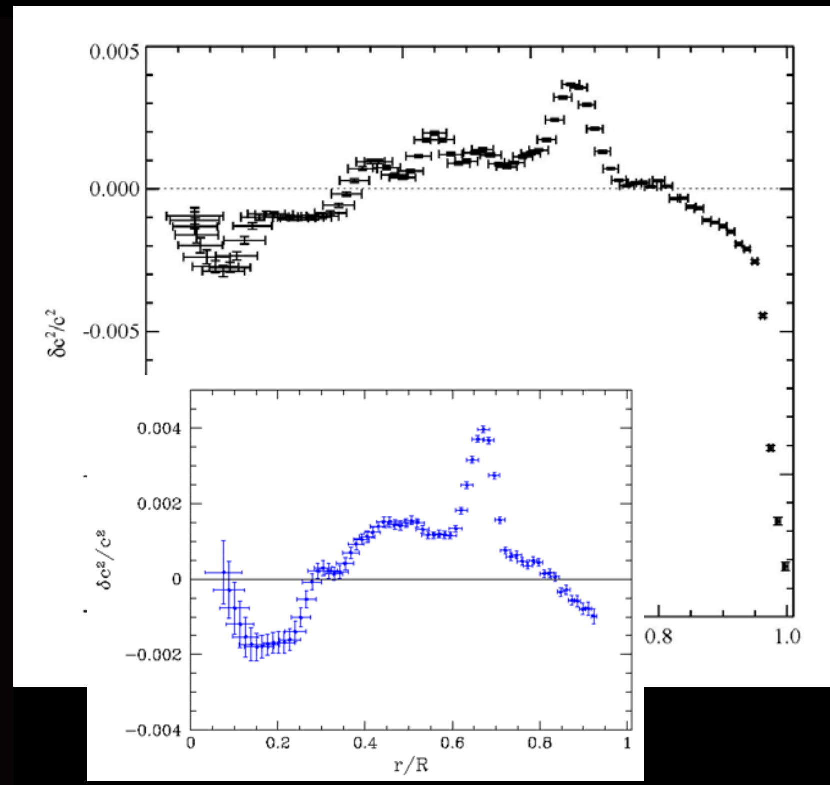
- *Nobel Prize 2015: T. Kajita and A. B. McDonald 'detection of neutrino oscillations'*
- *Nobel Prize 2002: R. Davis and M. Koshiba 'detection of cosmic neutrinos'*
- *Bruno Pontecorvo first proposed neutrino oscillations*

Solar Internal Structure

MDI

Structure and temperature of the stellar interior





Difference of sound speed detected using helioseismic data and sound speed obtained from the model based on the classical hypothesis of stellar evolution as a function of radial distance
Improvement of the measurements with improving helioseismic techniques

Red: means the Sun is "hotter" than expected by 0.2% at that depth.

Sun Internal Dynamics

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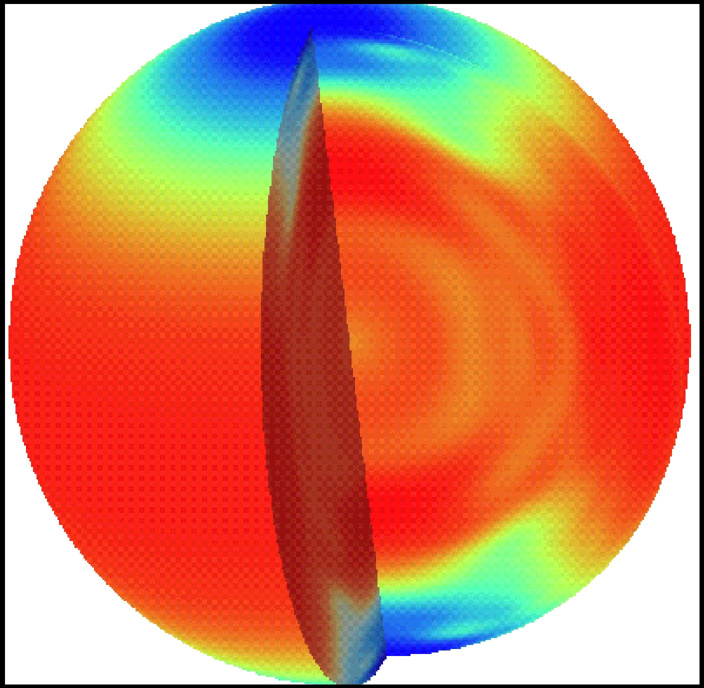
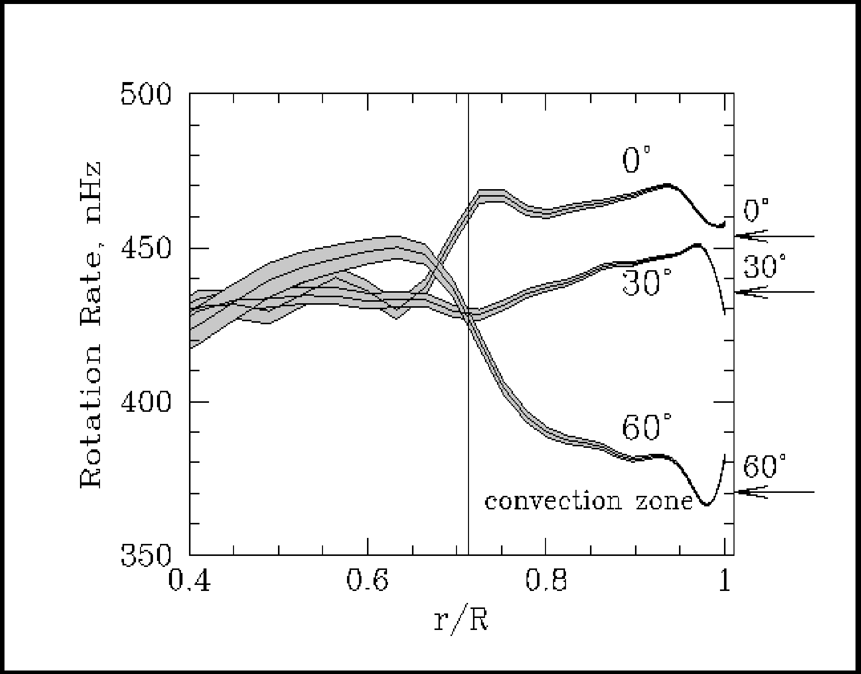
- *core - rapid rotation 7 days*
- *radiative zone - quasi solid body rotation 26.7 d*
- *convection zone – differential rotation*





The radiative interior is found to rotate roughly uniformly
Layers of rotation shear have been discovered at the base of the convection zone and in the sub-photospheric layers. Tachocline varies with latitude.
Differential rotation in the convection zone

Rotation rate: red faster, blue slower

Plasma Flows in the Convection Zone

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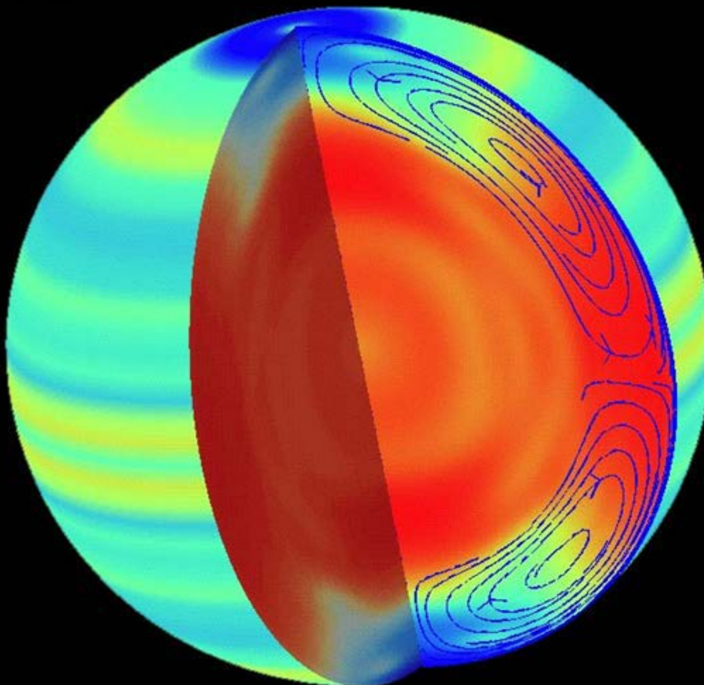
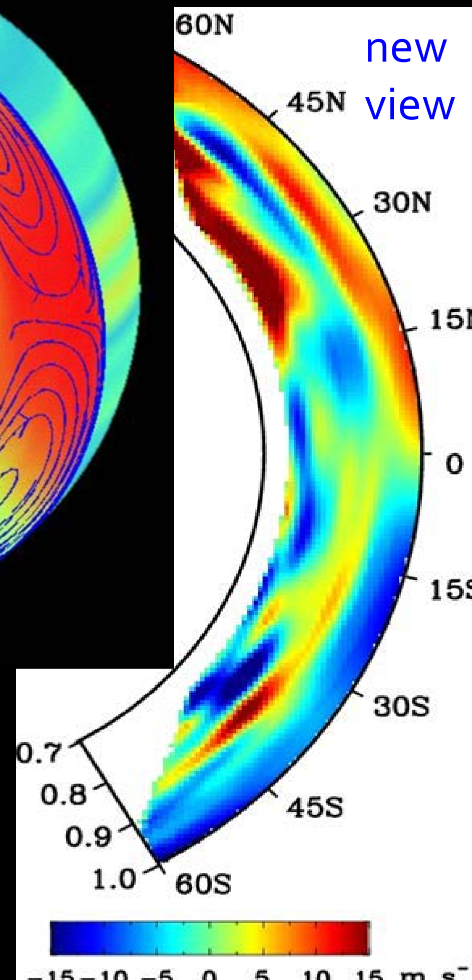
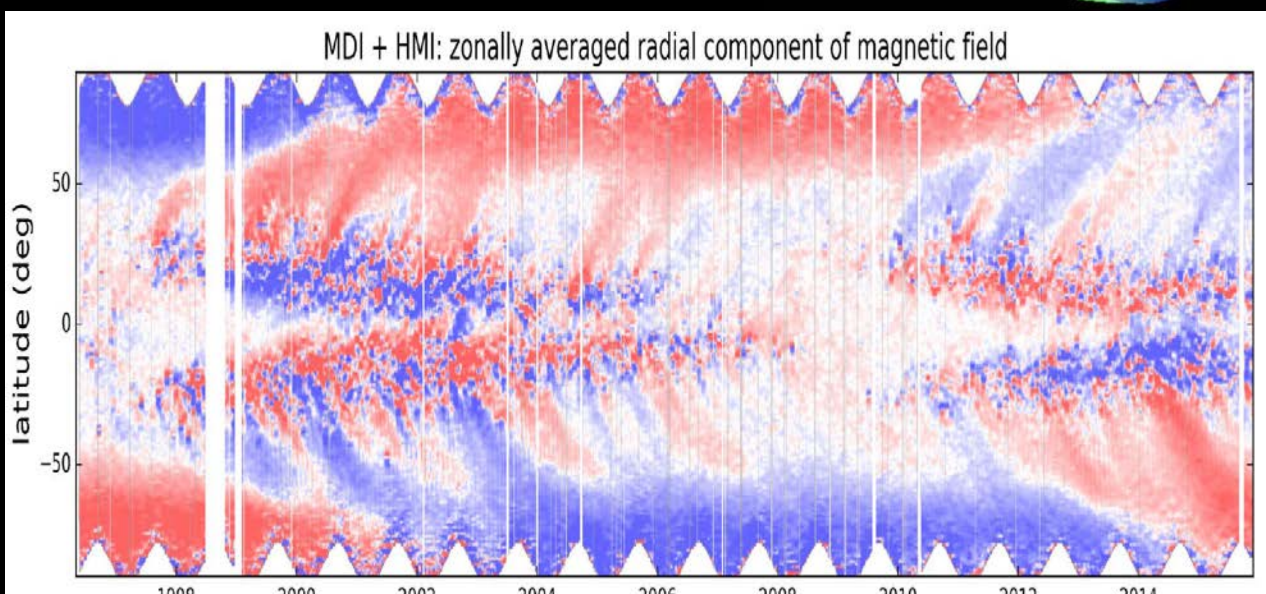
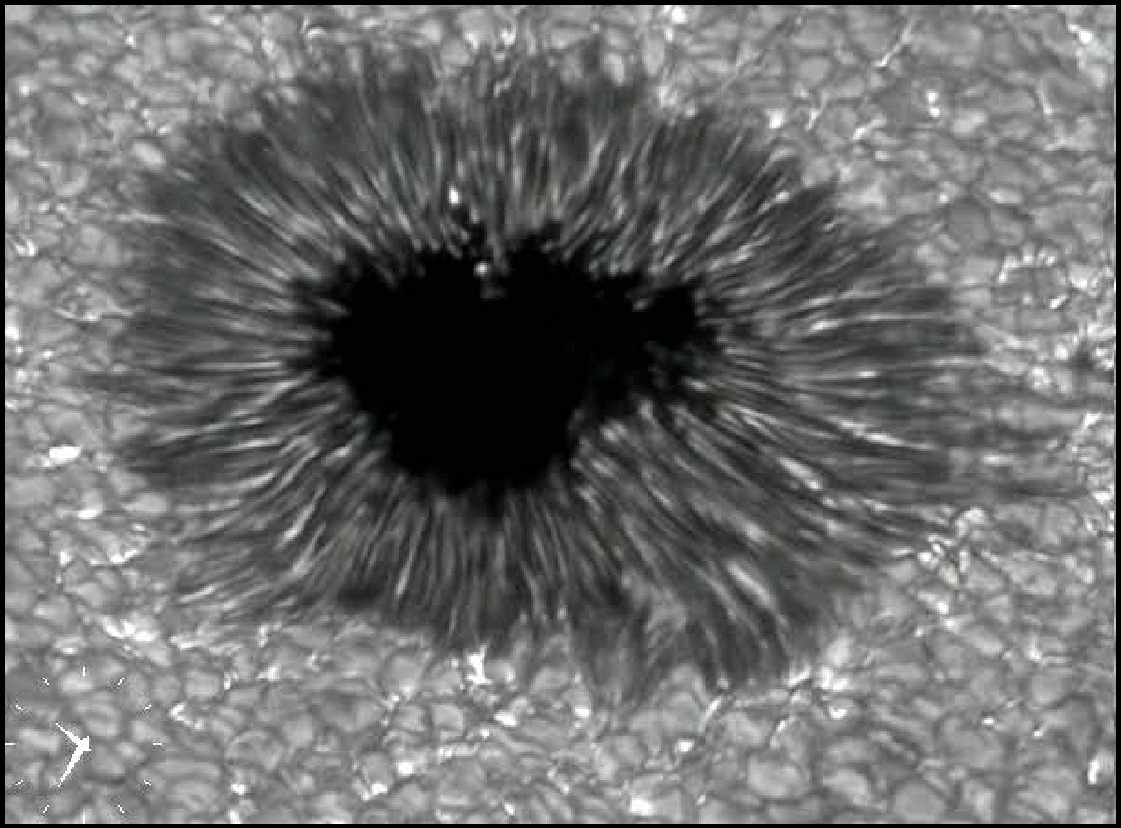




Important dynamical role in generating 22 y solar magnetic cycle



Magnetic Field Emergence



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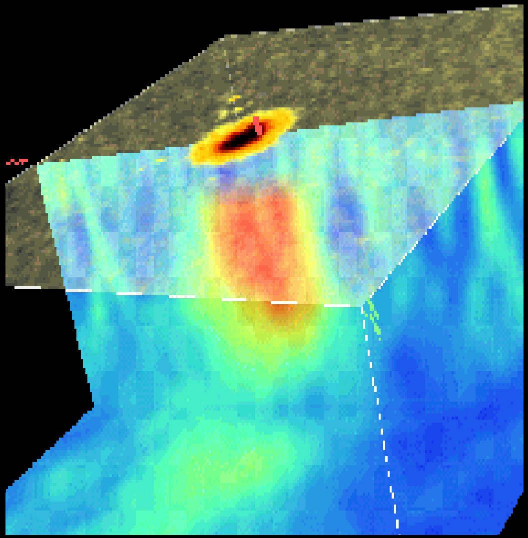
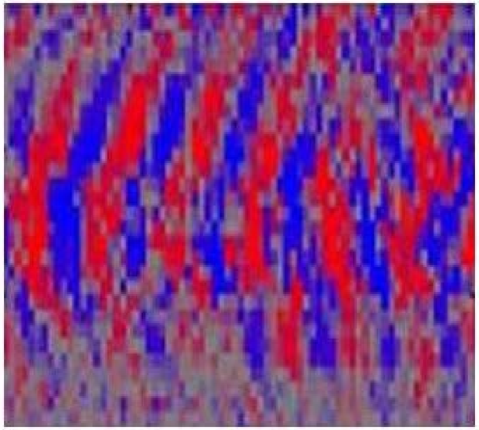


Sunspot oscillations

- *Local helioseismology: beneath strong magnetic field the sound speed is higher (red-fast)*

- *Upward propagating acoustic waves observed in the transition region above a sunspot umbra (170 s)*

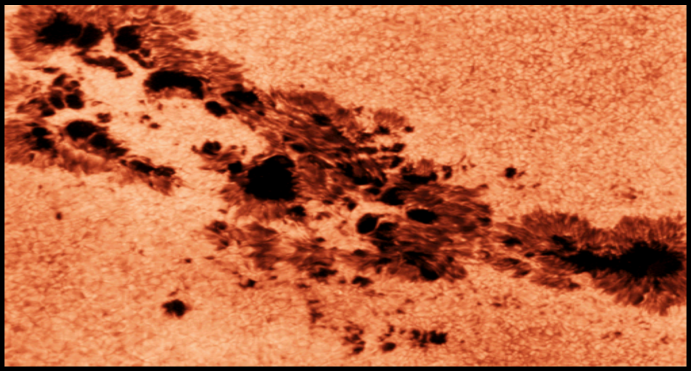
SUMER

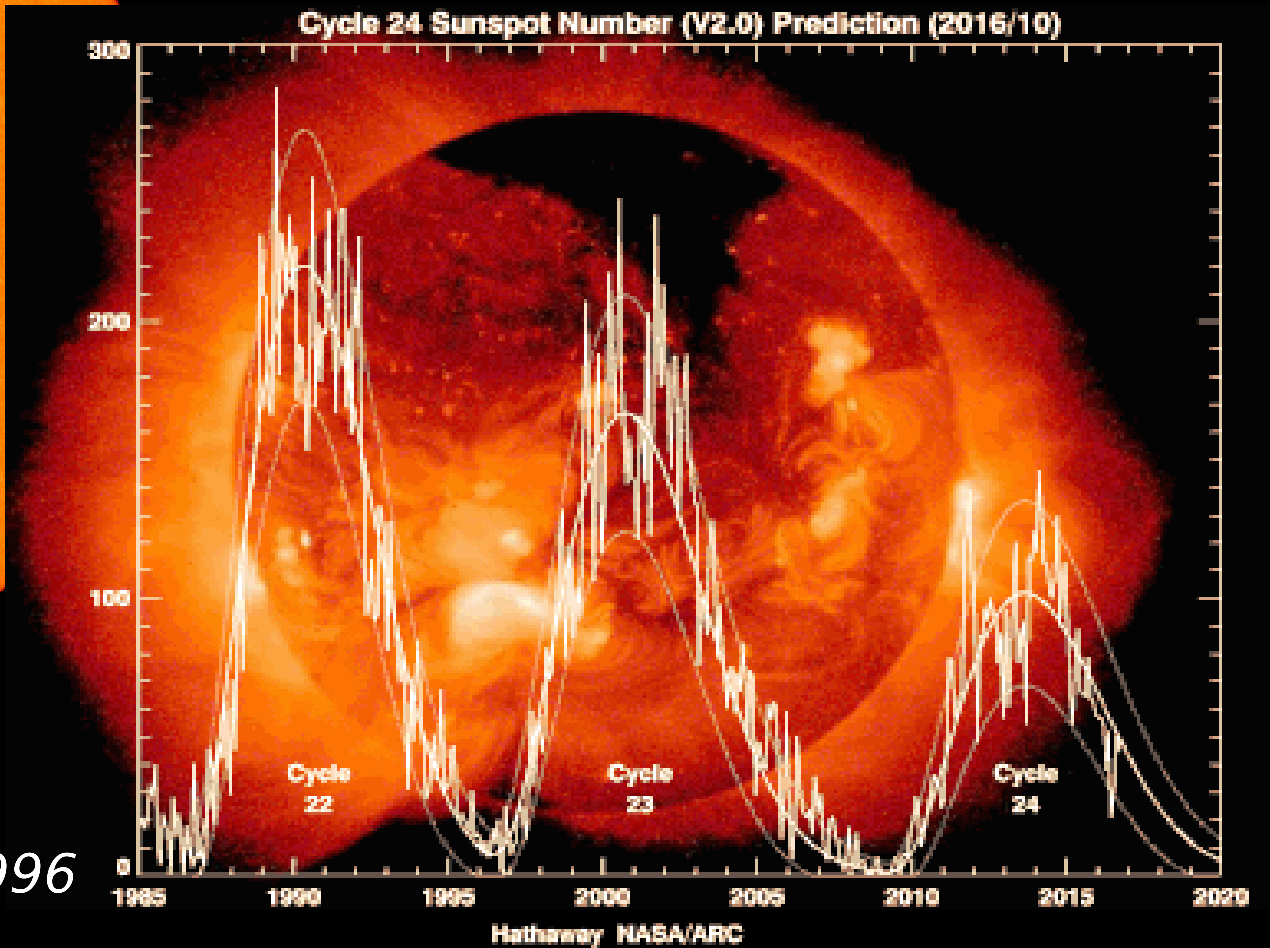


Sunspot oscillation - Coherent oscillation of the sunspot umbra during a time series of 20 min seen in O V (629.48 Å) Doppler shift (Maltby et al. 1997, Sol.Phys. 190,437). The oscillation amplitude is 8 km/s.

Two Cycles of the Variable Sun

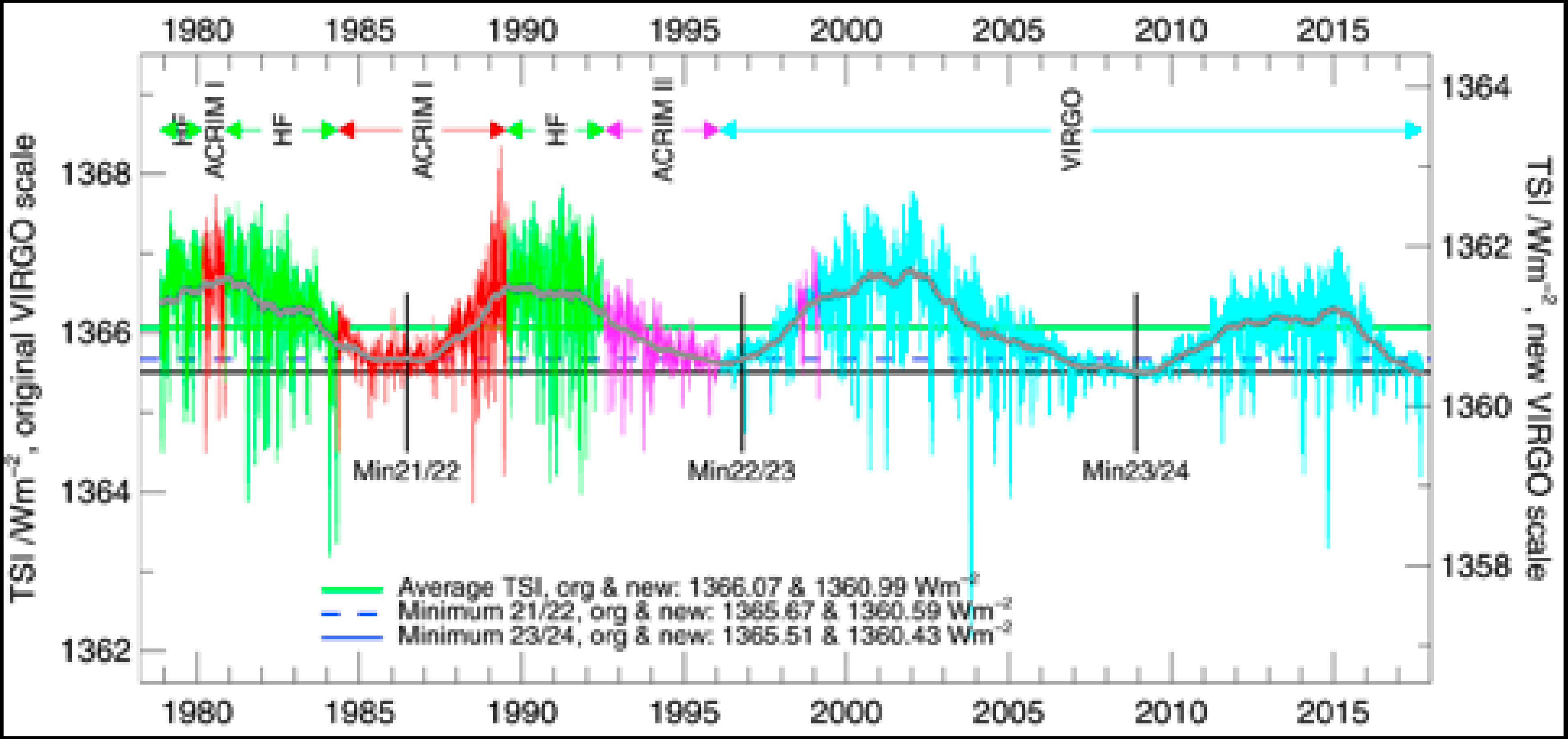
Solar Magnetic Cycles





SOHO launch 1995
L1 insertion 14 Feb 1996

Total Solar Irradiance

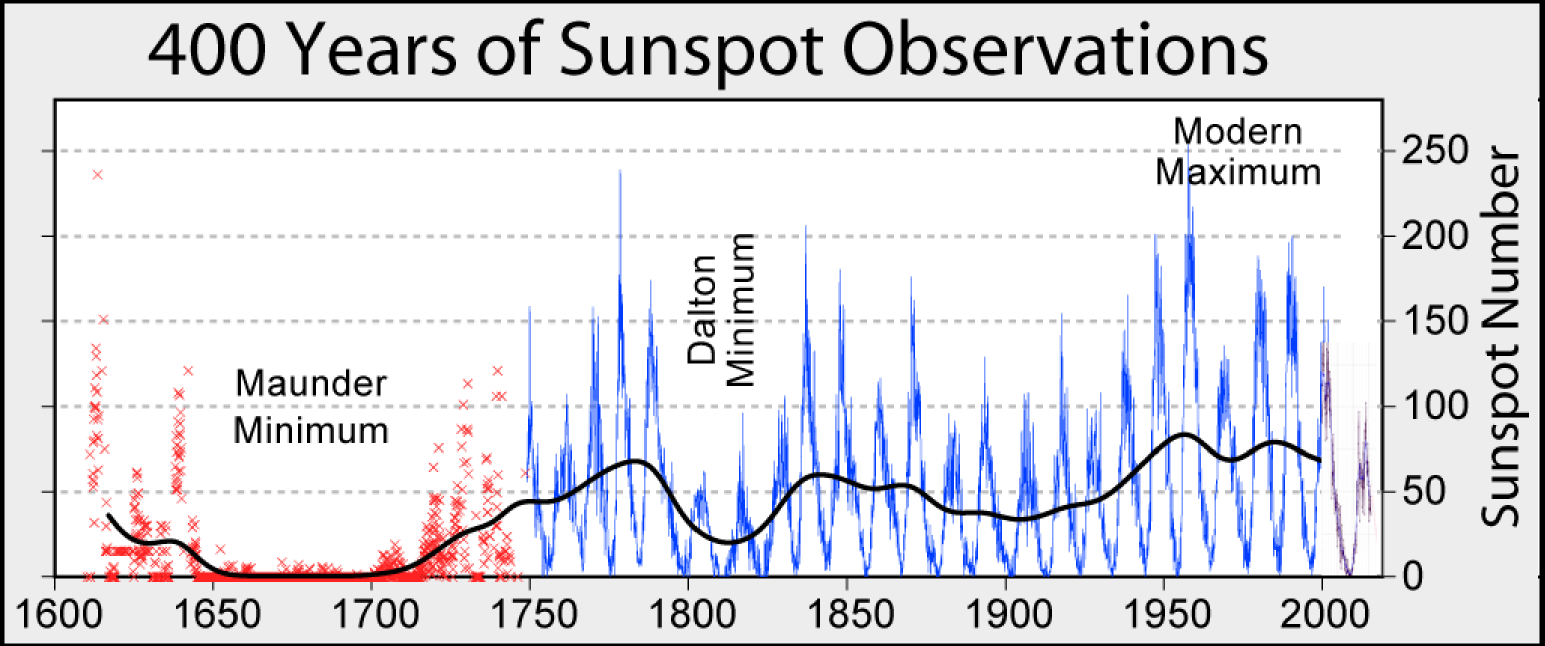


- *Solar irradiance modulated by the 11 year solar activity cycle*
  Four solar cycles of total solar irradiance measurements
  Two cycles with SOHO
- *Solar cycle variation 0.90±0.02 W m^{-2} (0.06 %)*
- *Slight cooling of Earth temperature, although weak climate forcing compared to anthropogenic component*

VIRGO

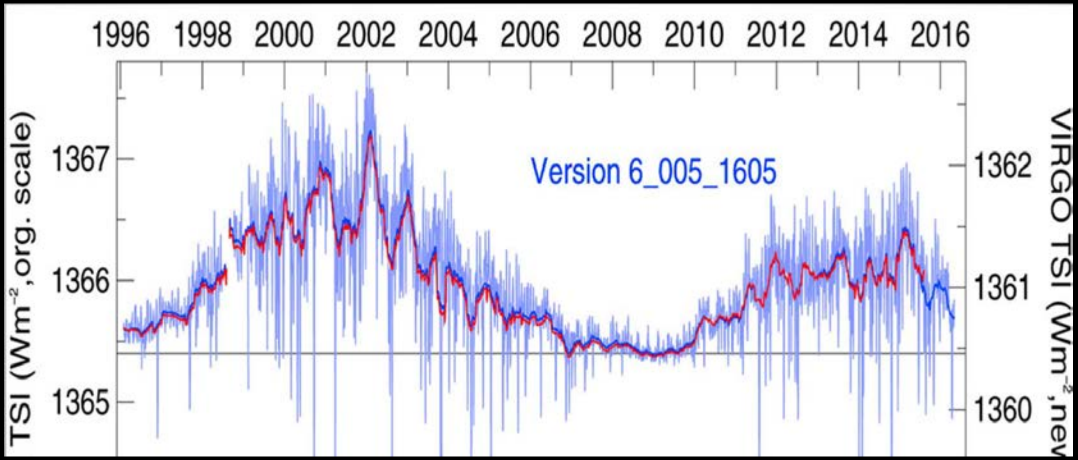
SOHO Weak Solar Cycles

VIRGO



SOHO provided first:

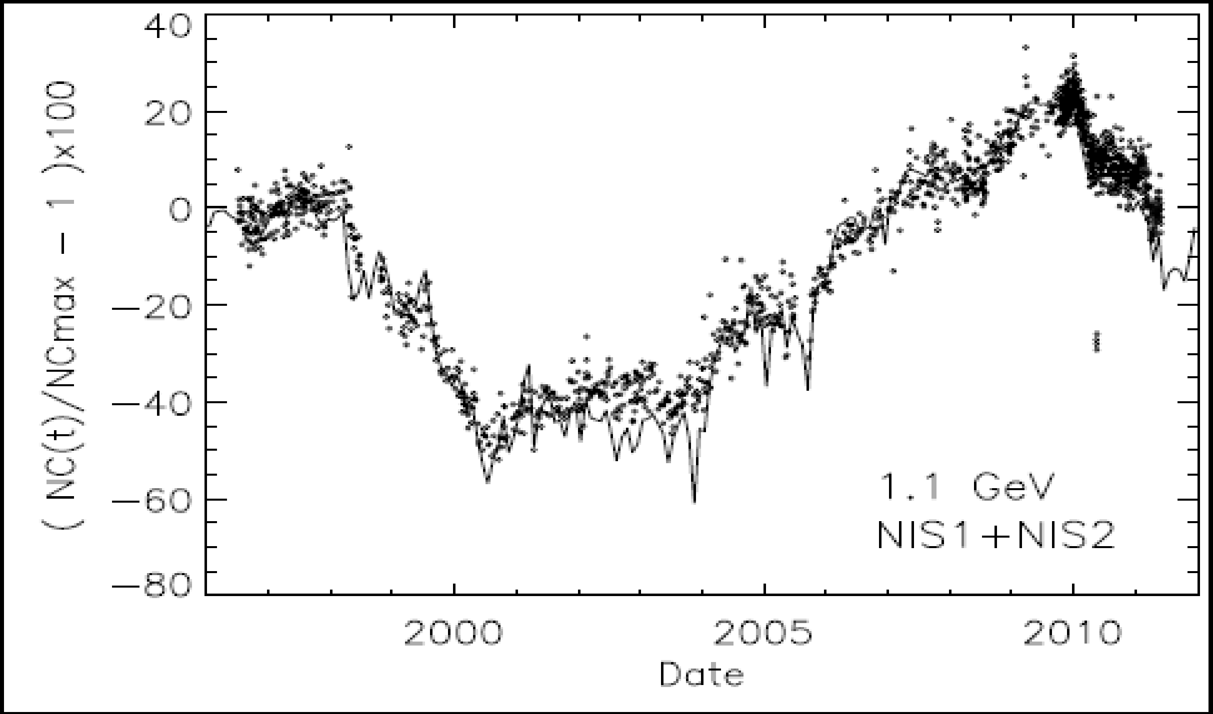
- *full-sun radiance measurements, spanning an entire solar cycle, in strong EUV lines*
- *coronal brightness variation through the cycle*



CDS - EIT - LASCO

Galactic Cosmic Rays in Deep Solar Minimum

CDS



Record high galactic cosmic ray flux observed in deep 2009 solar minimum, when the flux was 25% higher than in 1997 minimum

SOHO obtained the only space record of high energy protons in cycle 23

The number of GCRs depends on the strength and 3D structure of the heliospheric magnetic field

SOHO observes the hot corona expansion

Heating of the Corona

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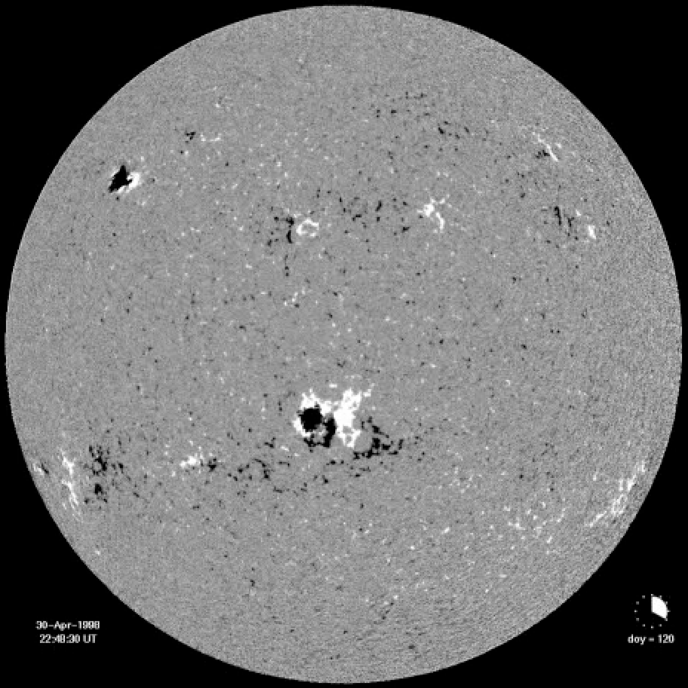
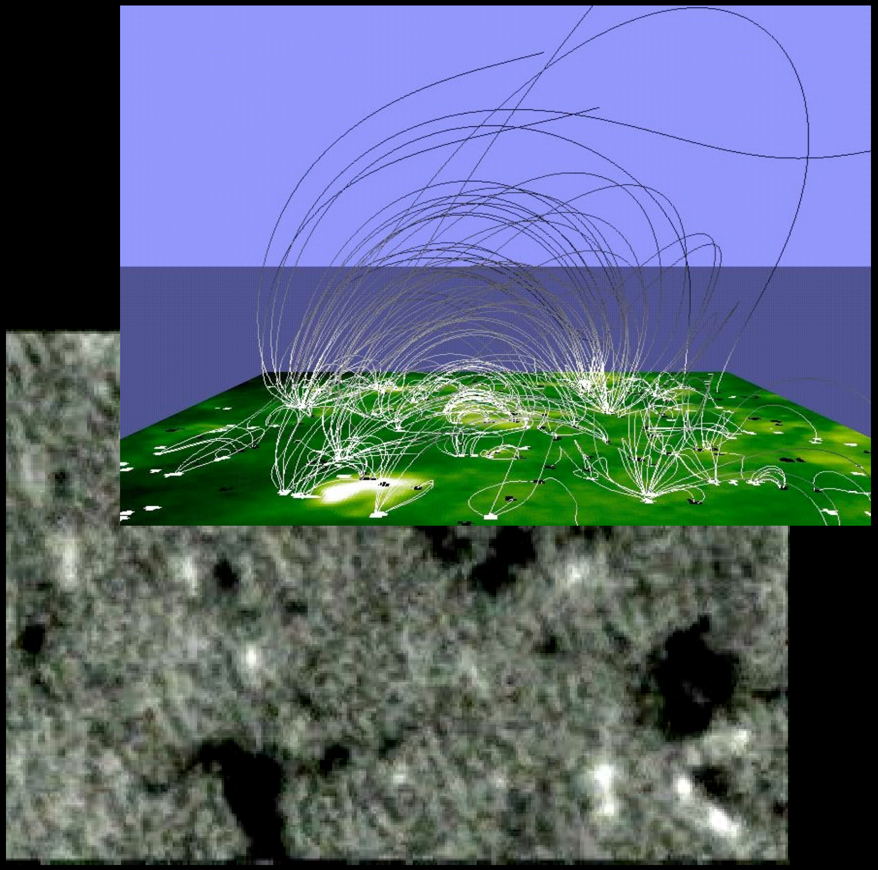
SUMER

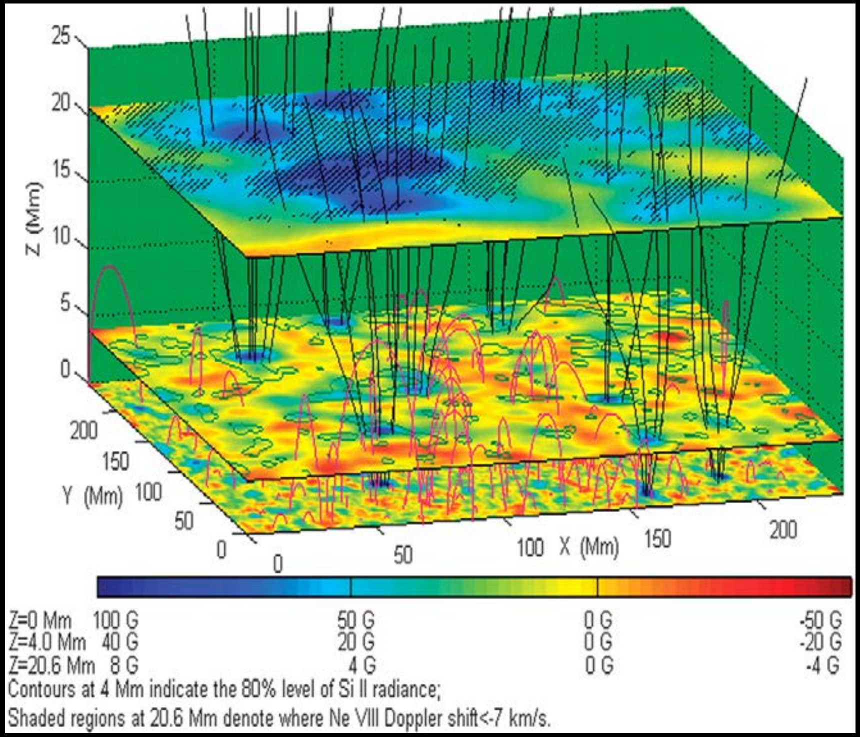




Constant magnetic flux emergence, fragmentation and disappearance on timescale of ~ 40 hours

Energy supply through “braiding” of large-scale coronal field sufficient to heat corona to >10^6 K

Nascent Solar Wind in Coronal Holes



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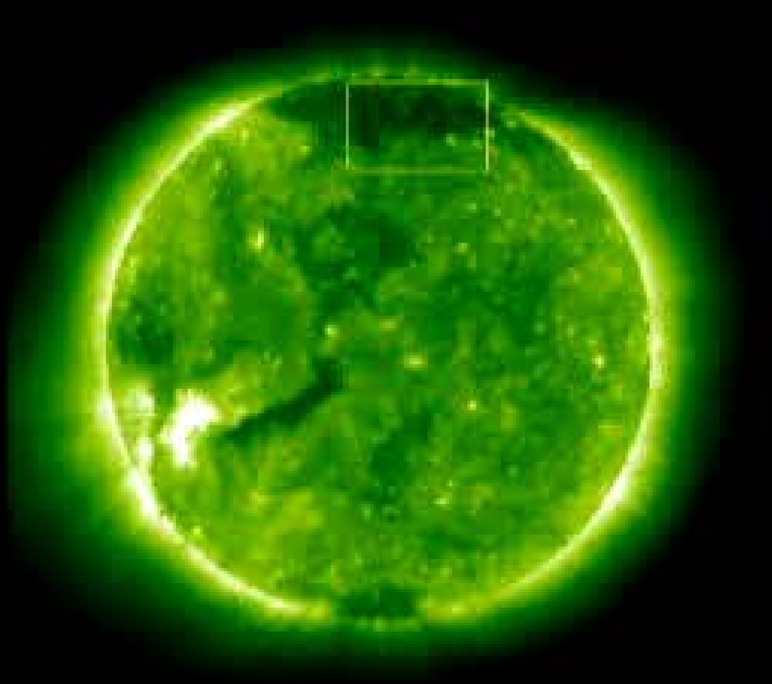


Fast solar wind originates along coronal funnels

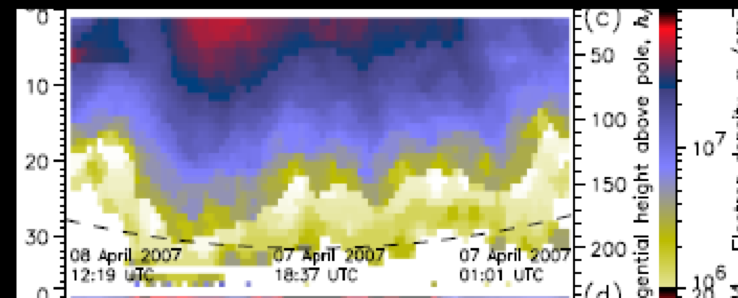
- *Blue-shifts of Ne VII (6 10^5 K) outline the outflow pattern in the transition region*
- *Acceleration starts at about 5.000 km above the photosphere*
- *Speeds of about 10 km s^{-1} reached at 20.000 km*

Anatomy of a Coronal Hole

Accurate spectroscopic measurements of physical conditions of coronal holes

CDS
SUMER

density

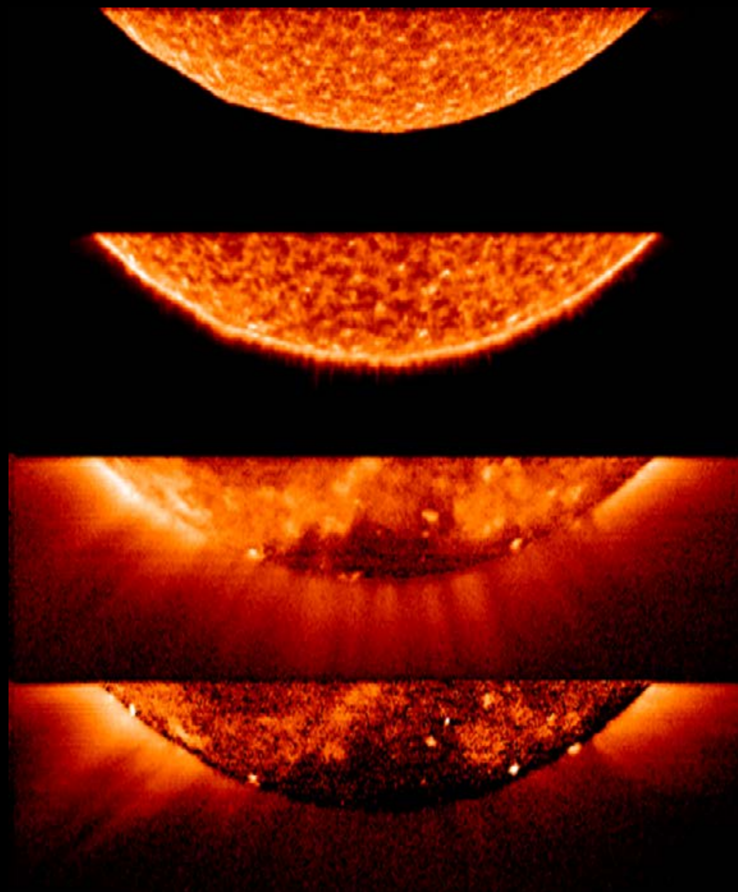


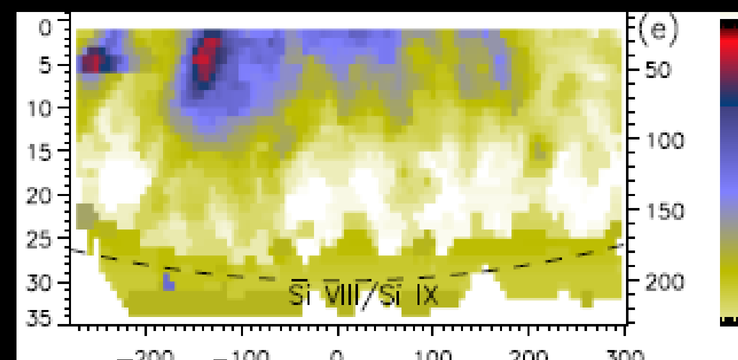
CI 124.9 nm
30 000 K
Network

NV 123.8 nm
190 000 K
Macro-spicules

Mg X 60.9 nm
1.1 10^6 K
Polar plumes

Fe XII 124.2 nm
1.4 10^6 K
Coronal hole





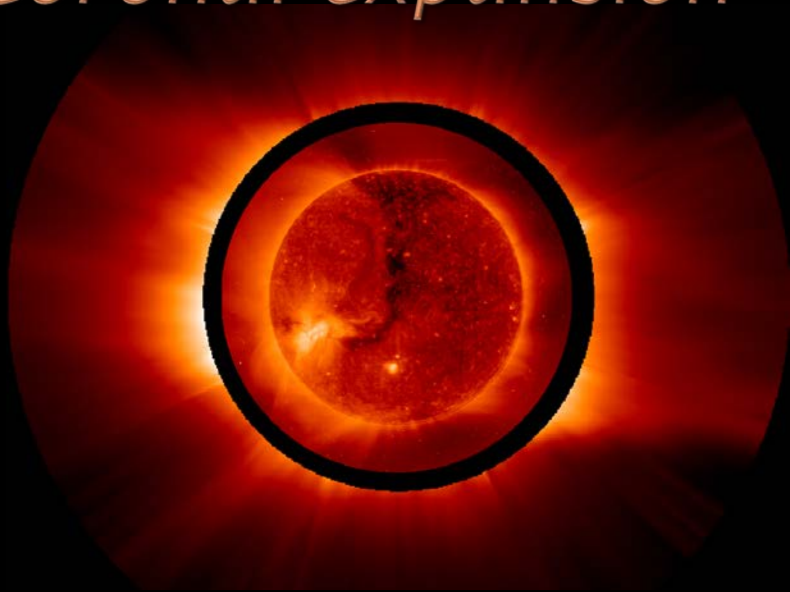
temperature

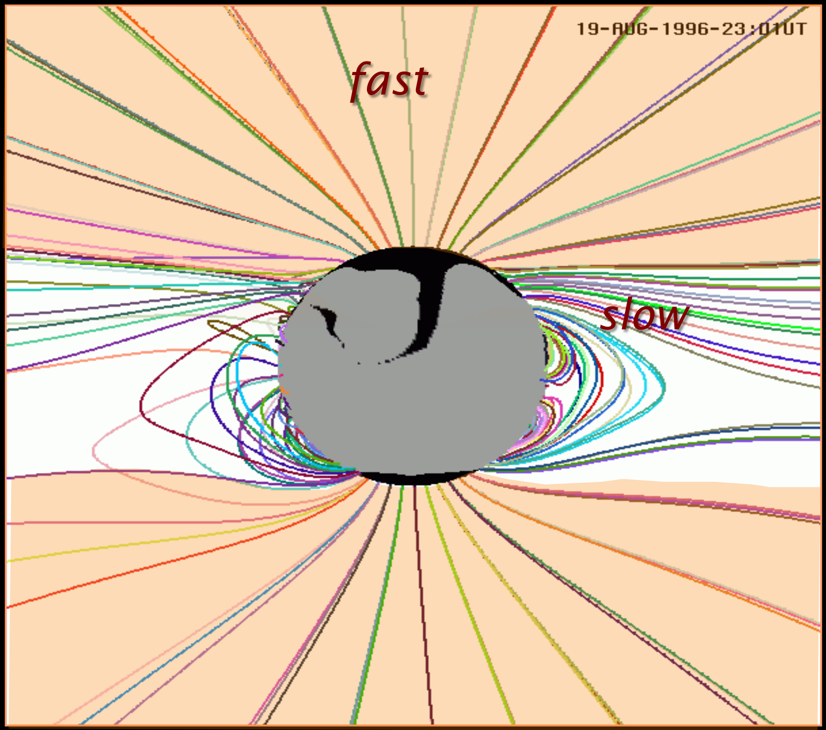
Physical parameters needed to derive the wind outflow speed in the outer corona via Doppler dimming

Density and temperature of coronal holes accurately measured close to the limb

Coronal expansion

UVCS





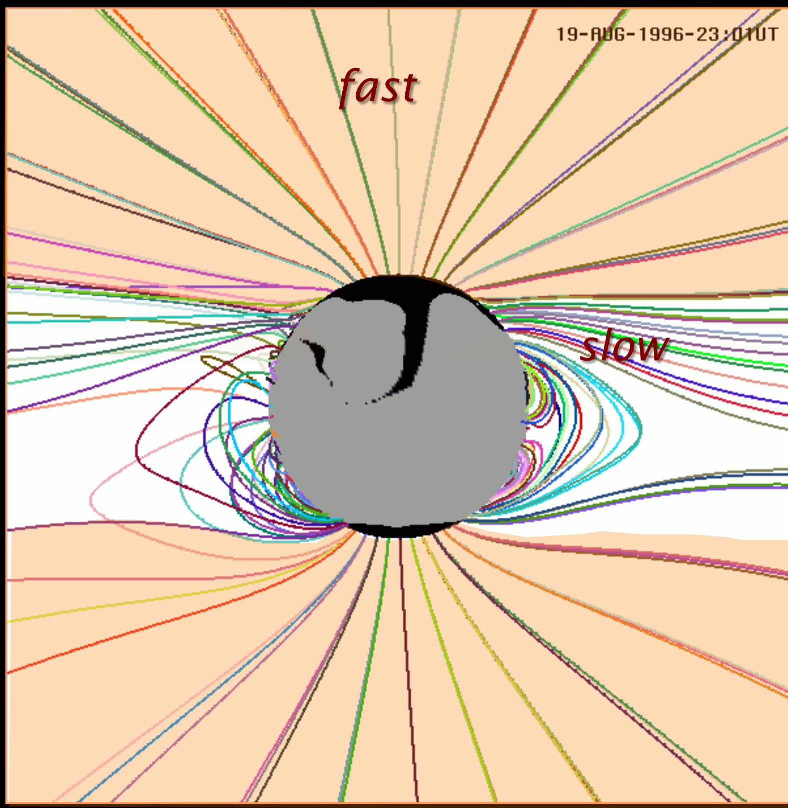
First application of spectroscopy of UV resonantly scattered emission to measure coronal outflows on the plane of the sky

Doppler dimming technique applied to HI Lyman alpha and OVI corona

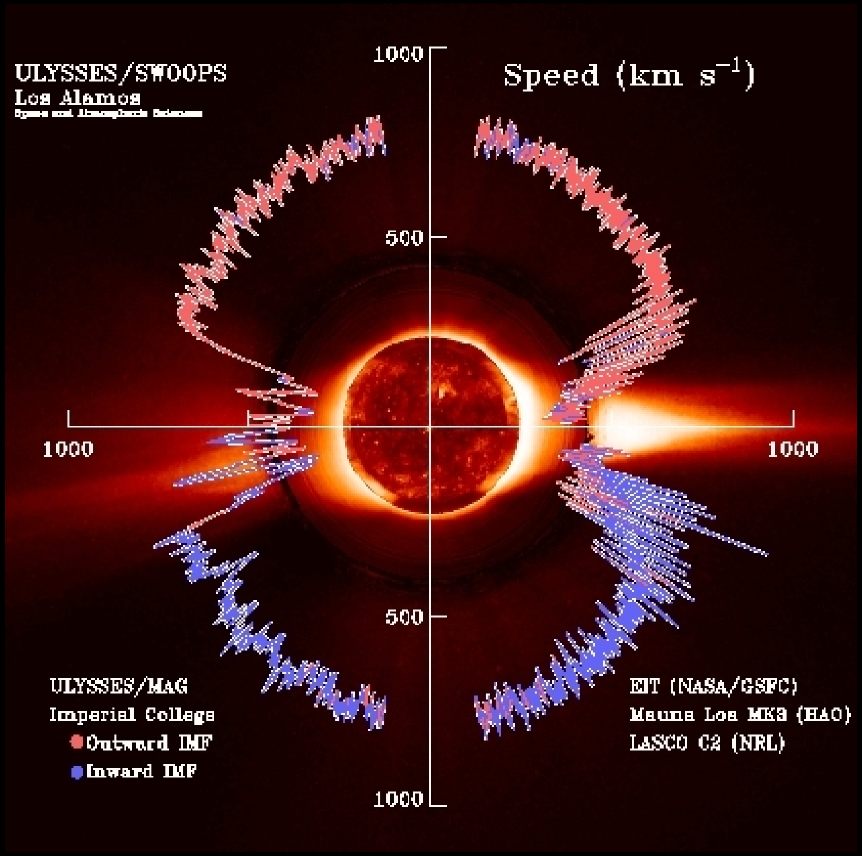
The open field lines emerging from solar minimum polar coronal holes channel the solar wind toward the heliosphere:

- *fast wind (≈800 km s^{-1}) from the core of polar coronal holes*
- *slow wind (≈400 km s^{-1}) along the flanks of polar coronal holes depending on the flux tube expansion factor*

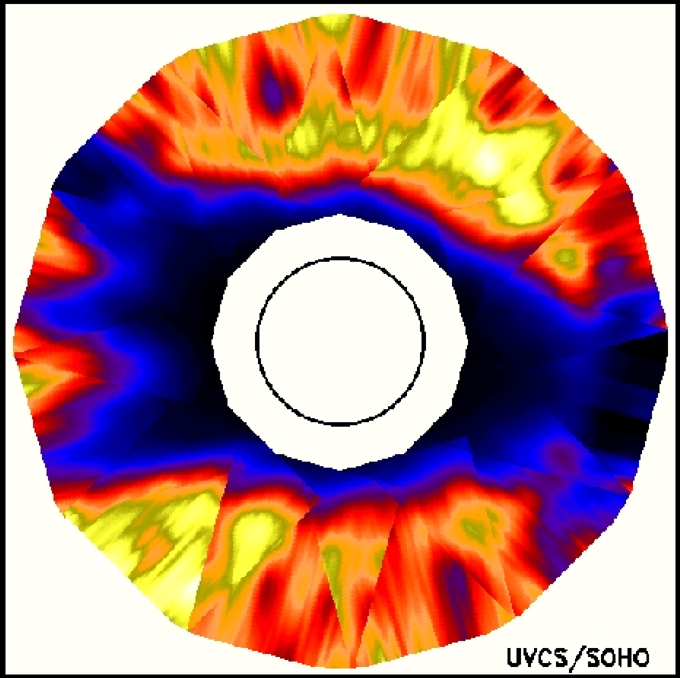
Coronal wind
SOHO



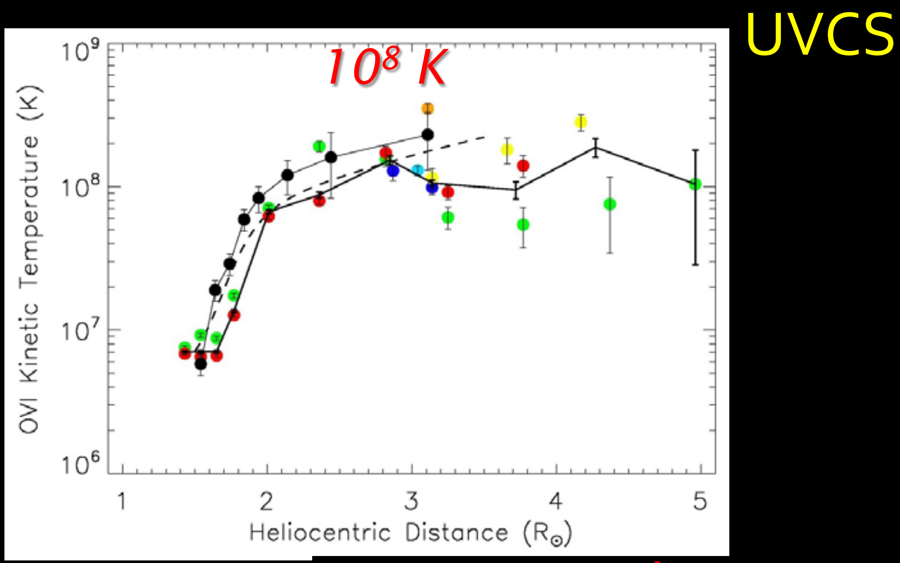
Heliospheric wind
Ulysses



Energy Deposition – Solar Wind Ion Component

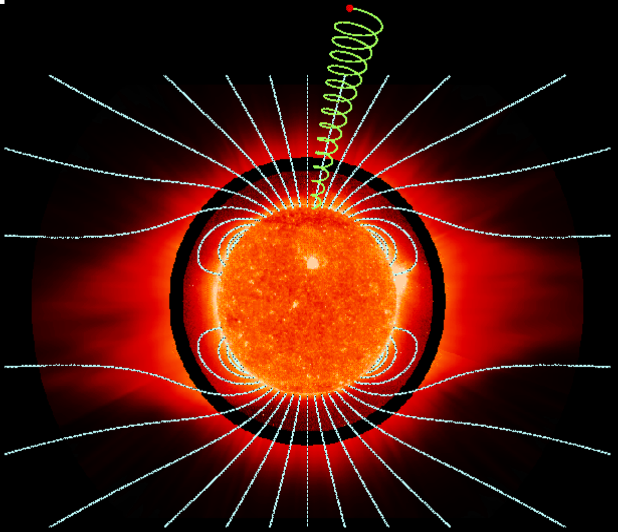


O VI ions kinetic temperature



Discovery of extremely high kinetic temperatures of OVI ions, $\geq 10^8$ K, measuring the ion velocity-distribution across the coronal magnetic field.

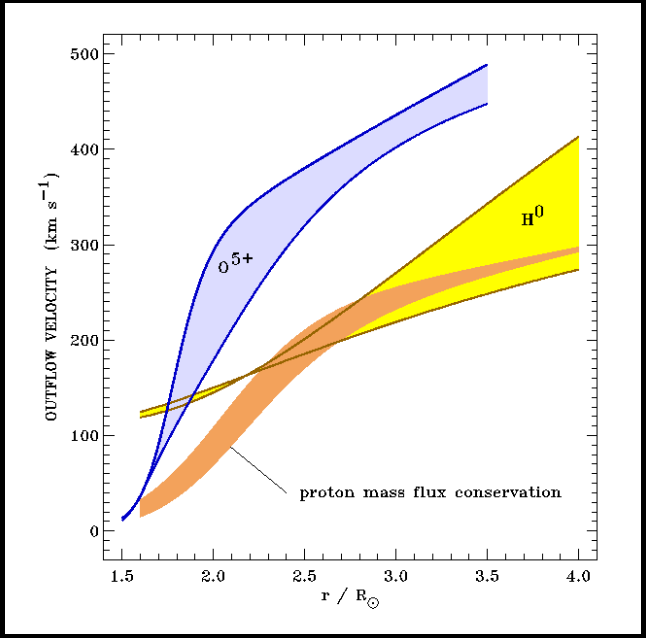
Signature of dissipation of high frequency Alfvén waves via ion cyclotron resonance

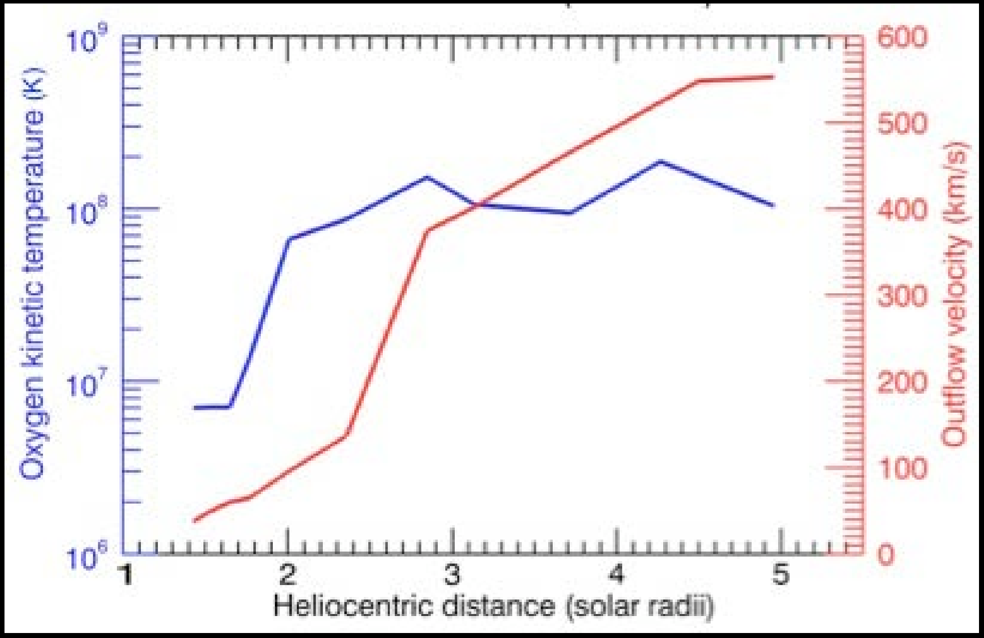


Wave particle-interaction

Fast Wind in Coronal Holes

UVCS



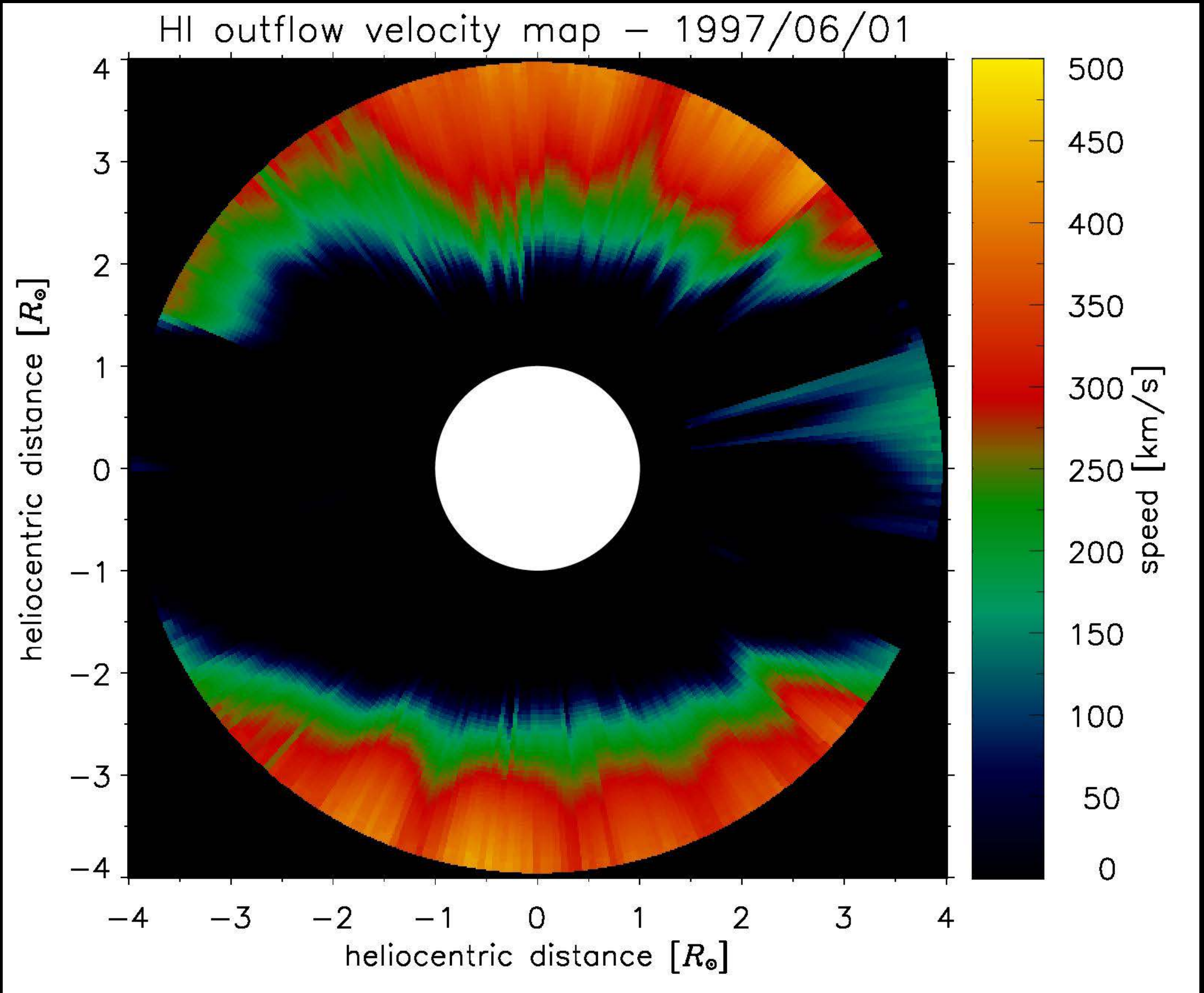


- *Outflow velocities of protons and minor ions solar wind components are different, preferential heating of protons (neutral H) and OVI ions at different heights (dependence on ion to mass charge, f(Z/A))*

- *Maximum energy deposition (ion component) in the range 2.0-3.7 $R_\odot$ in the supersonic region (≥ 1.7 $R_\odot$) co-spatial with maximum gradient of outflow speed*

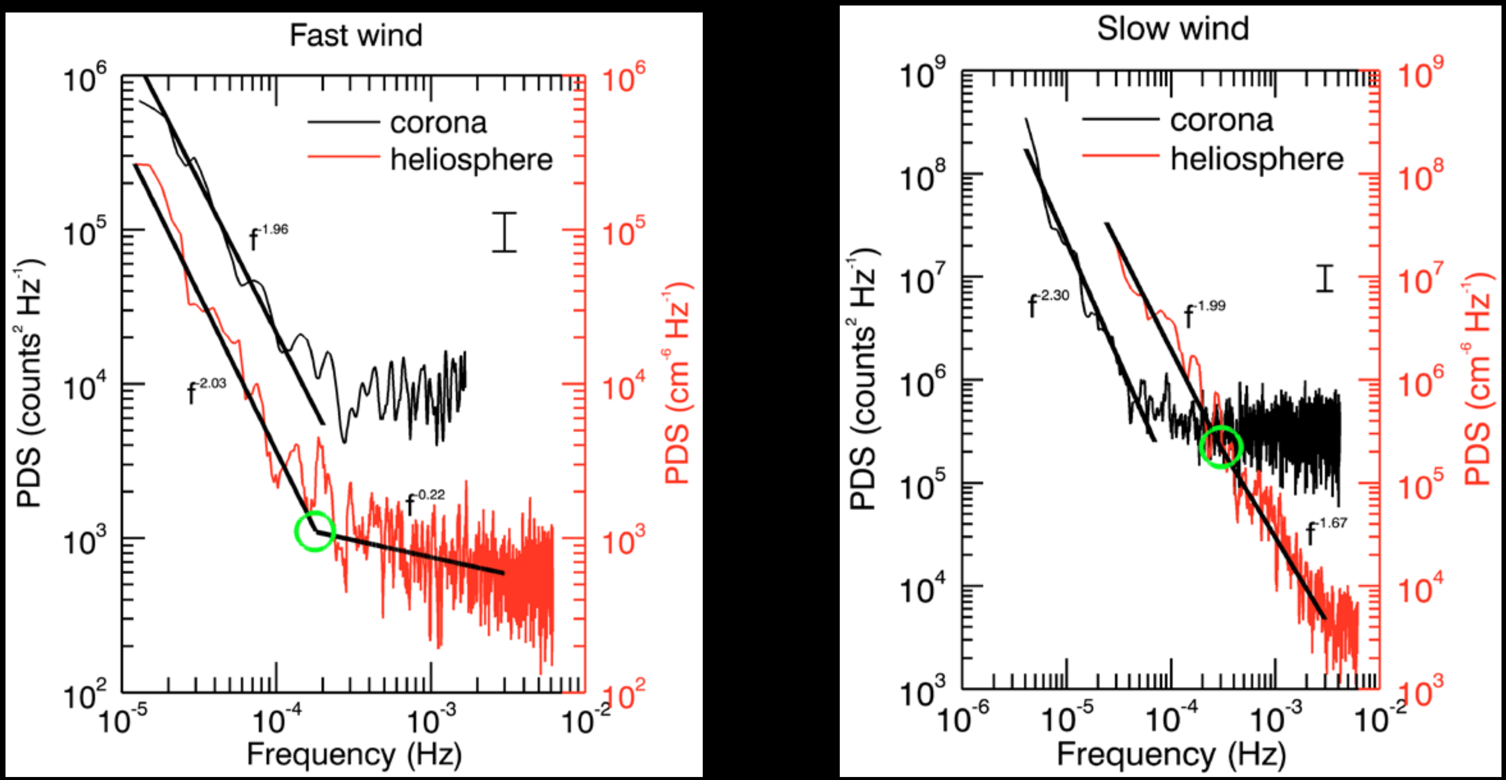
- *Asymptotic outflow speed of OVI wind component reached at ≥ 5 $R_\odot$*

Expansion of the Solar Wind Proton Component



Wind Fluctuations in Corona & Heliosphere

UVCS

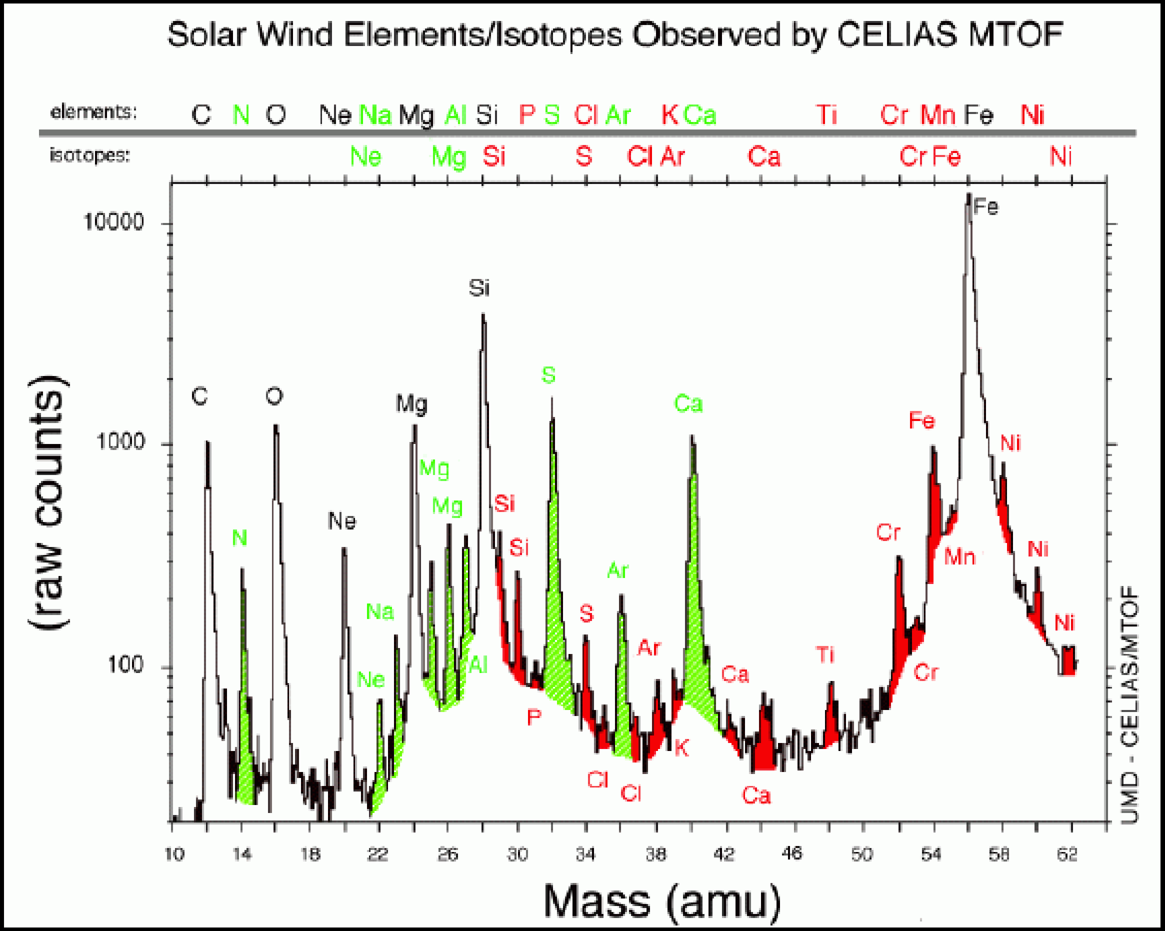


First observations of fluctuations in the outer corona

- *Fast wind - coronal origin of interplanetary low-frequency fluctuations, weak evolution at high-frequency*
- *Slow wind - evident evolution of the spectrum in the transition to heliosphere (0.3 AU)*

Composition of the Solar Wind

CELIAS



SOHO has doubled the number of elements and isotopes previously recorded in the solar wind

Red: new elements/isotopes

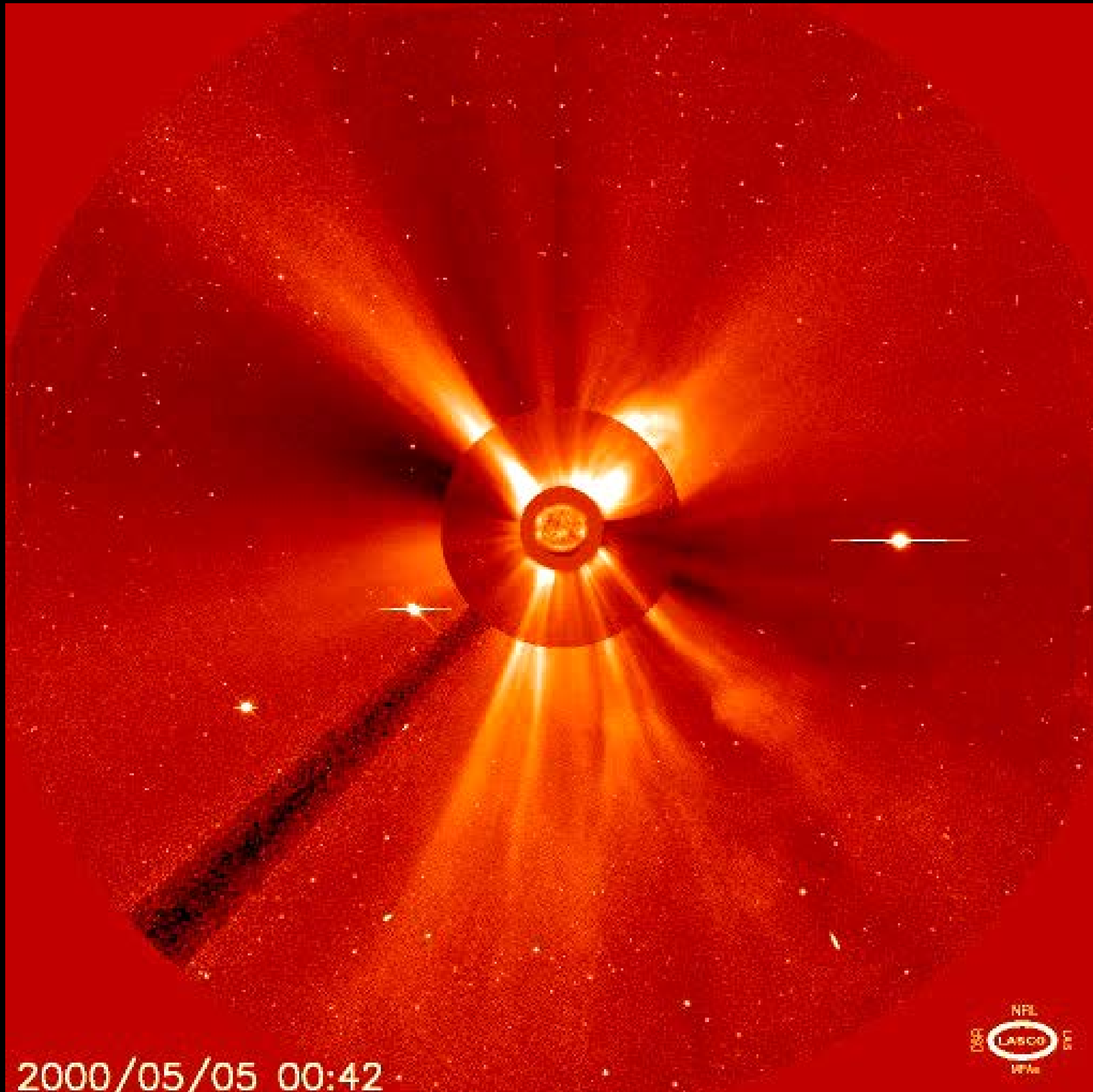
Green: rarely observed elements/isotopes

Sun Earth Connection

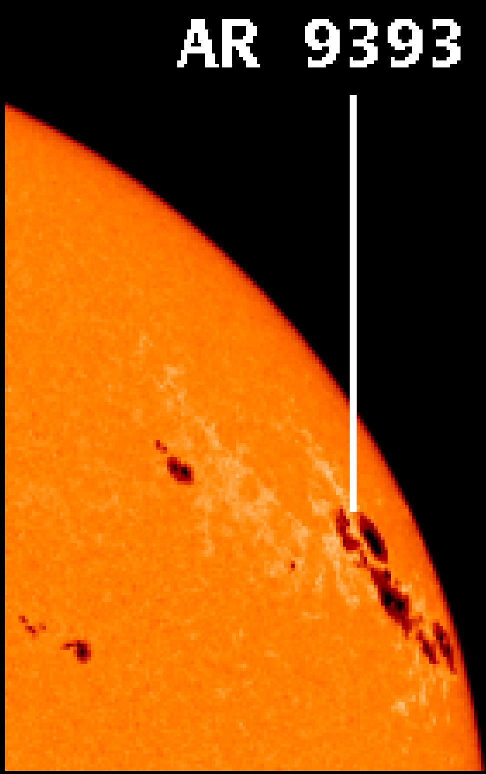
Solar Wind and Coronal Mass Ejections

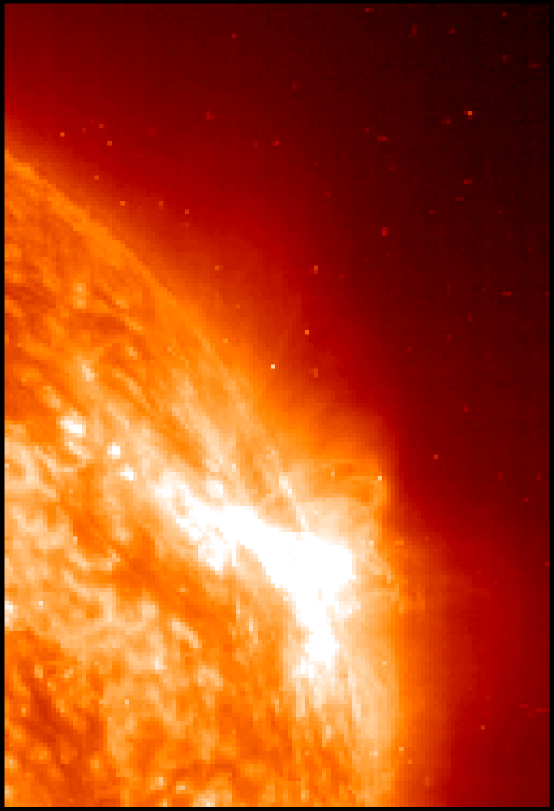
Mass Ejections
Solar Wind and Coronal

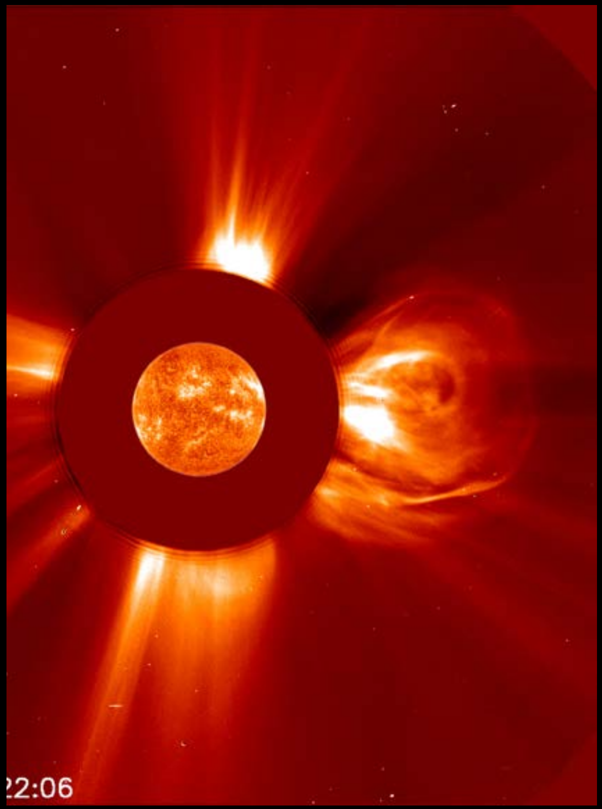
LASCO



Magnetic Activity







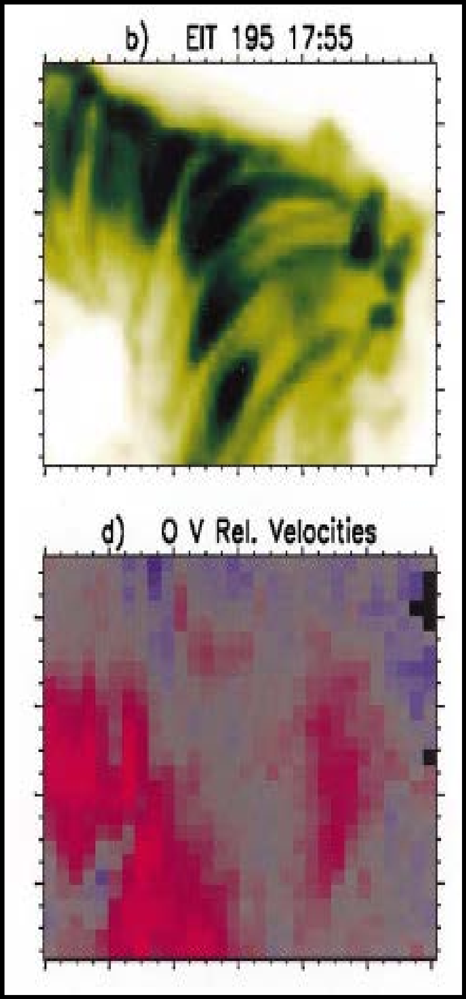
Explosive reconnection of intense magnetic fields in active regions and associated coronal mass ejections (CMEs)

- *Flares - 1-3 10^{32} ergs, T ≈ 20 10^{6} K*
- *CME - mass of ejected plasma up to 1 10^{16} g, speed up to 3200 km s^{-1}*
- *Solar Energetic Particles (SEP) - acceleration of ions up to 10 GeV, electrons up to 100 MeV*

On-going Magnetic Reconnection in Flares

CDS -EIT

TRACE



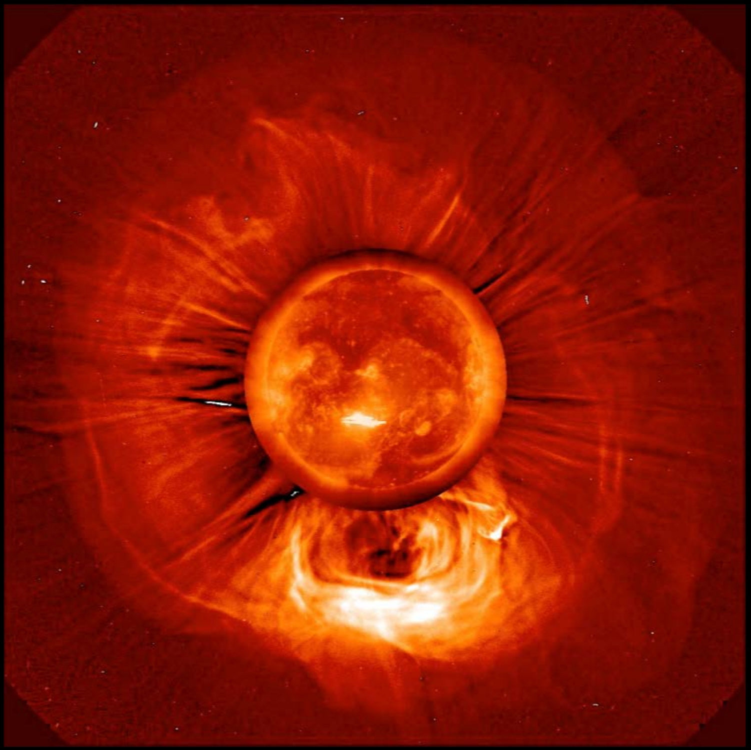
Chromospheric evaporation observed in the late gradual phase of flares highlights the continuous formation of loops due to ongoing reconnection

SOHO Coronal Mass Ejections CME Statistics

LASCO

SOHO has continuously (24 h a day) monitored the Sun at L1

Largest statistics on CMEs and halo CMEs, hitting directly the Earth, due to the high sensitivity of the onboard coronagraphs

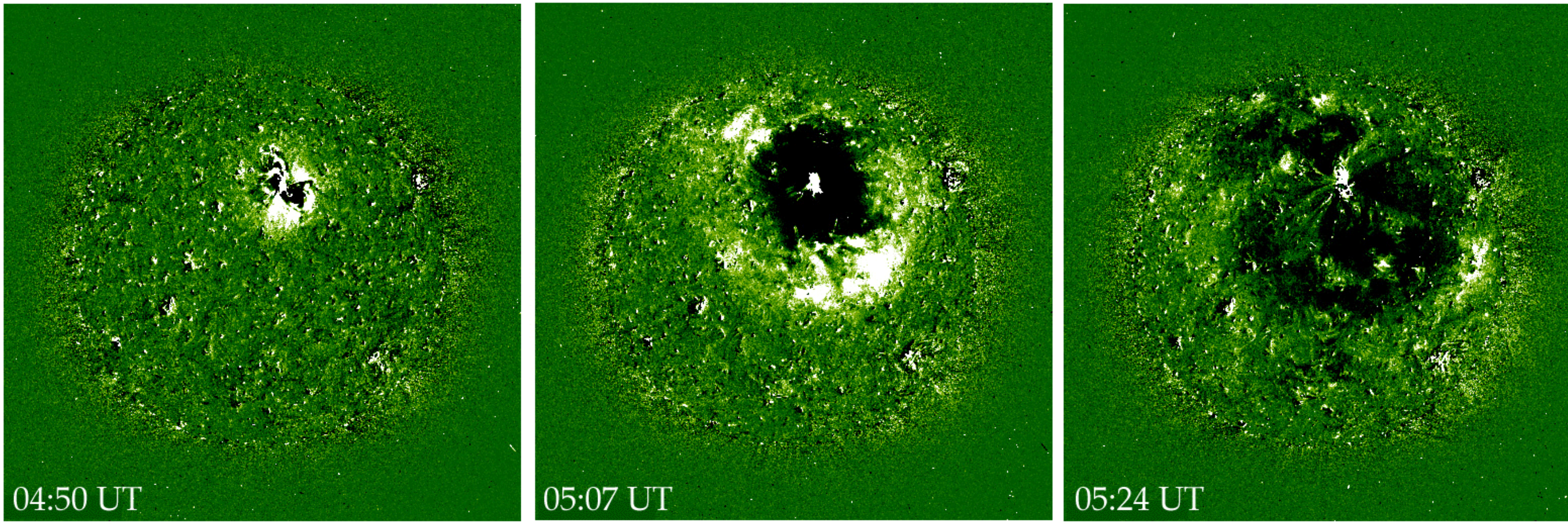


LASCO Coronagraphs

Number of events	
18.863	Coronal mass ejections
388	Full halo CMEs
358	Partial halo CMEs

Initiation of Coronal Mass Ejections

EIT



SOHO-Extreme ultraviolet Imaging Telescope (EIT)
observations of Moreton wave expanding from coronal mass ejection (CME) initiation site
1997 May 12
First differences in Fe XII 195 Å (1.5 MK)

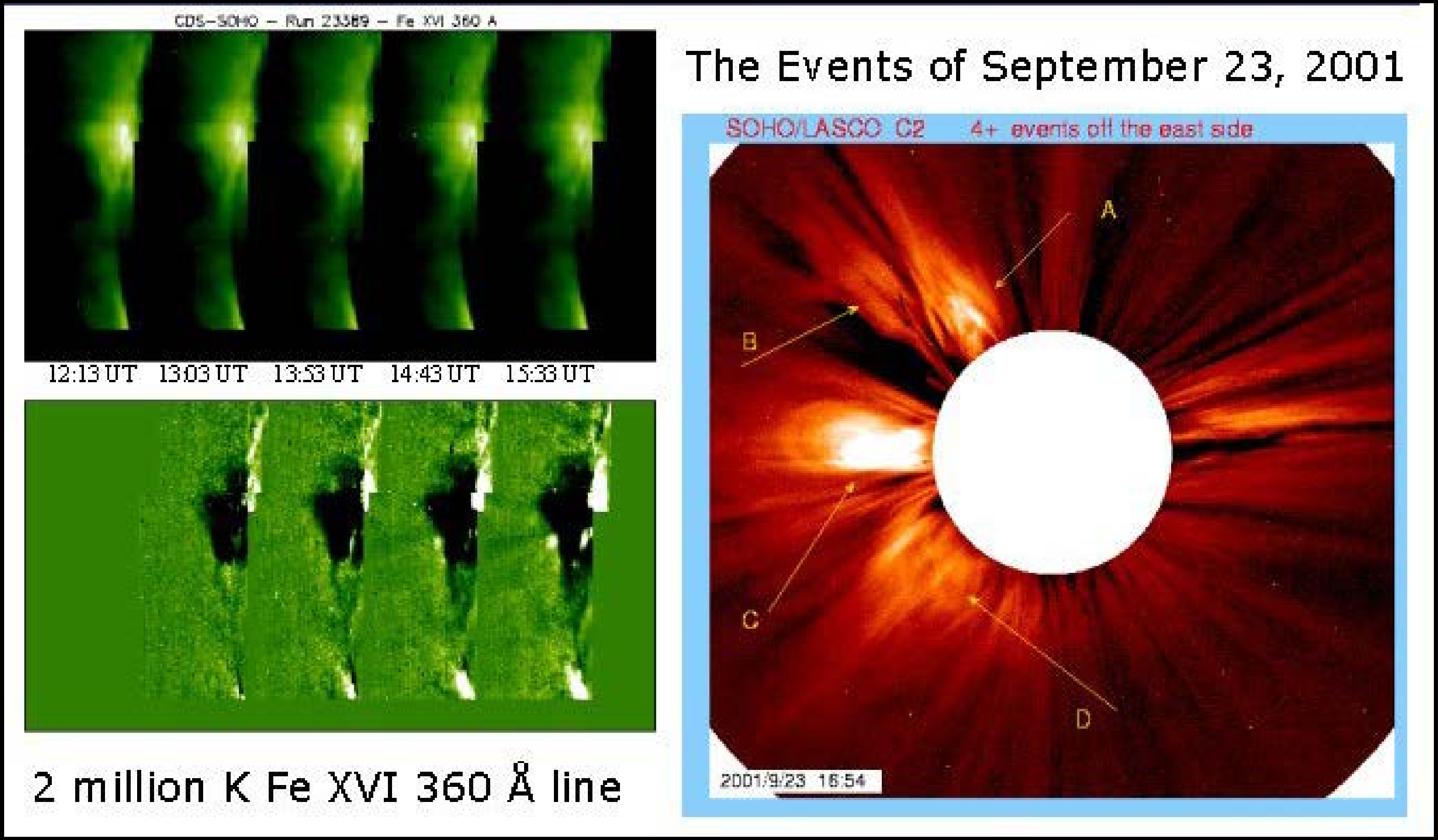
First identification of the ejection in the lower corona on EUV solar disk images

The signature of the expansion of coronal mass is a dimming with propagation at 200-600 km s^{-1}

The dimming was discovered by applying a Fe XII Image differences technique

Coronal Dimming

CDS



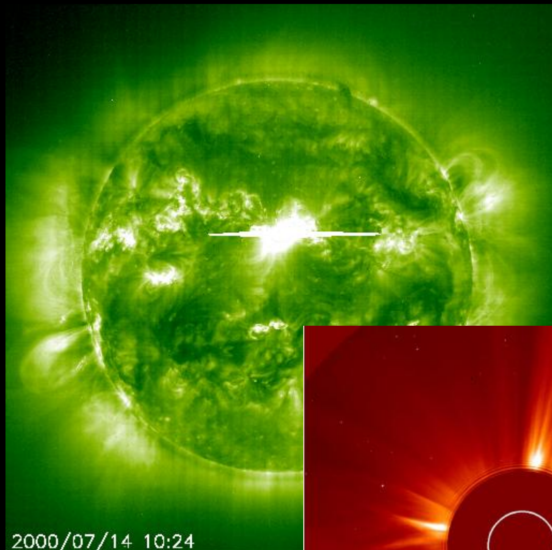
Coronal dimming, associated with the CME onset process, can be traced in solar EUV spectral data observed at the limb

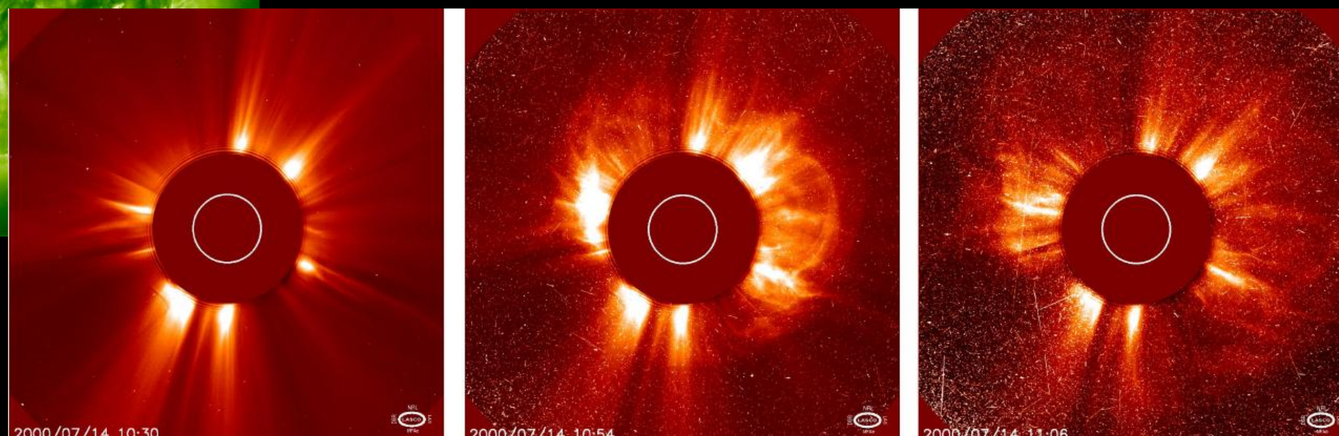
Spectral analysis shows that the EUV dimming is due to a mass loss which is consistent with overlying CME mass from coronagraph data

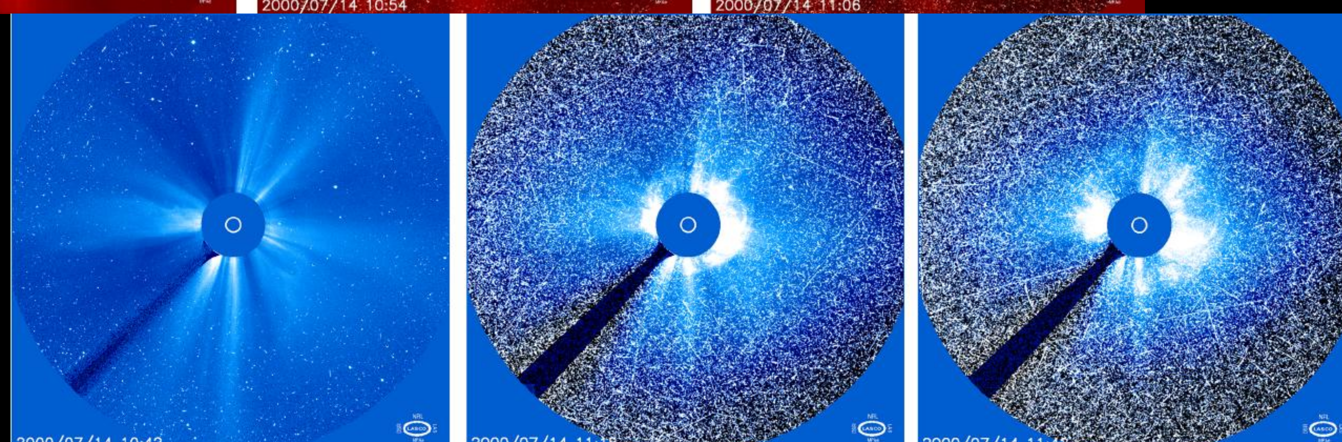
The 'Bastille' Event - 14 July 2000

EIT
LASCO

Halo coronal mass ejection directed toward the Earth
Solar energetic particles blur LASCO detectors



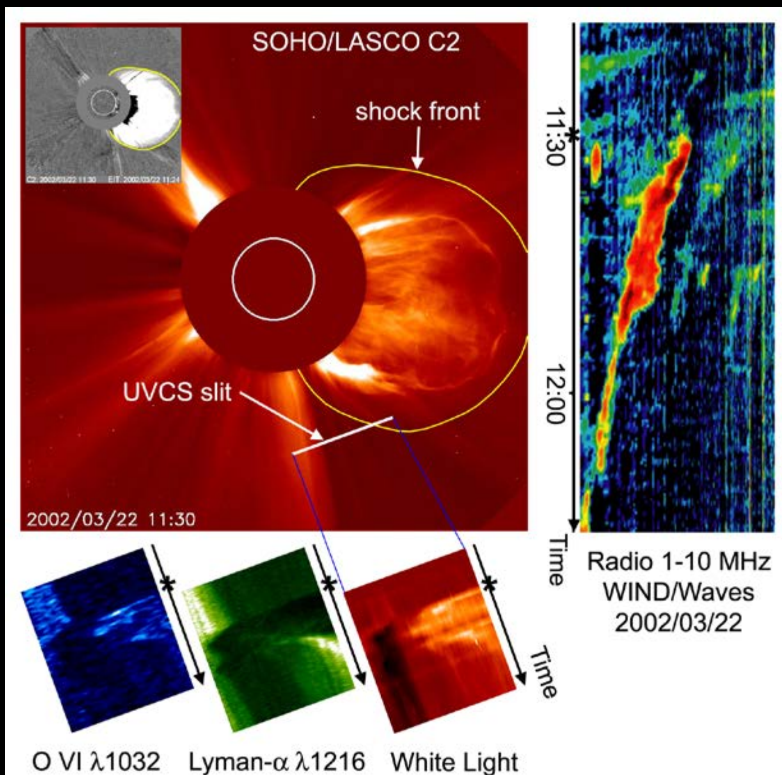


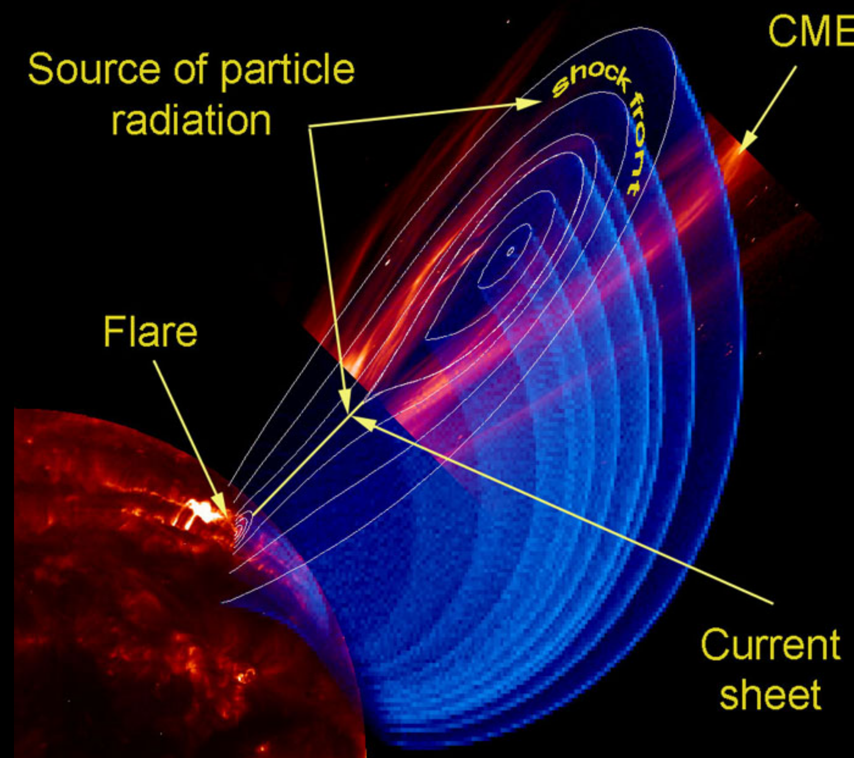


First coronal images out to 30 $R_\odot$

CME-driven Shocks & Solar Energetic Particle Acceleration

LASCO
UVCS

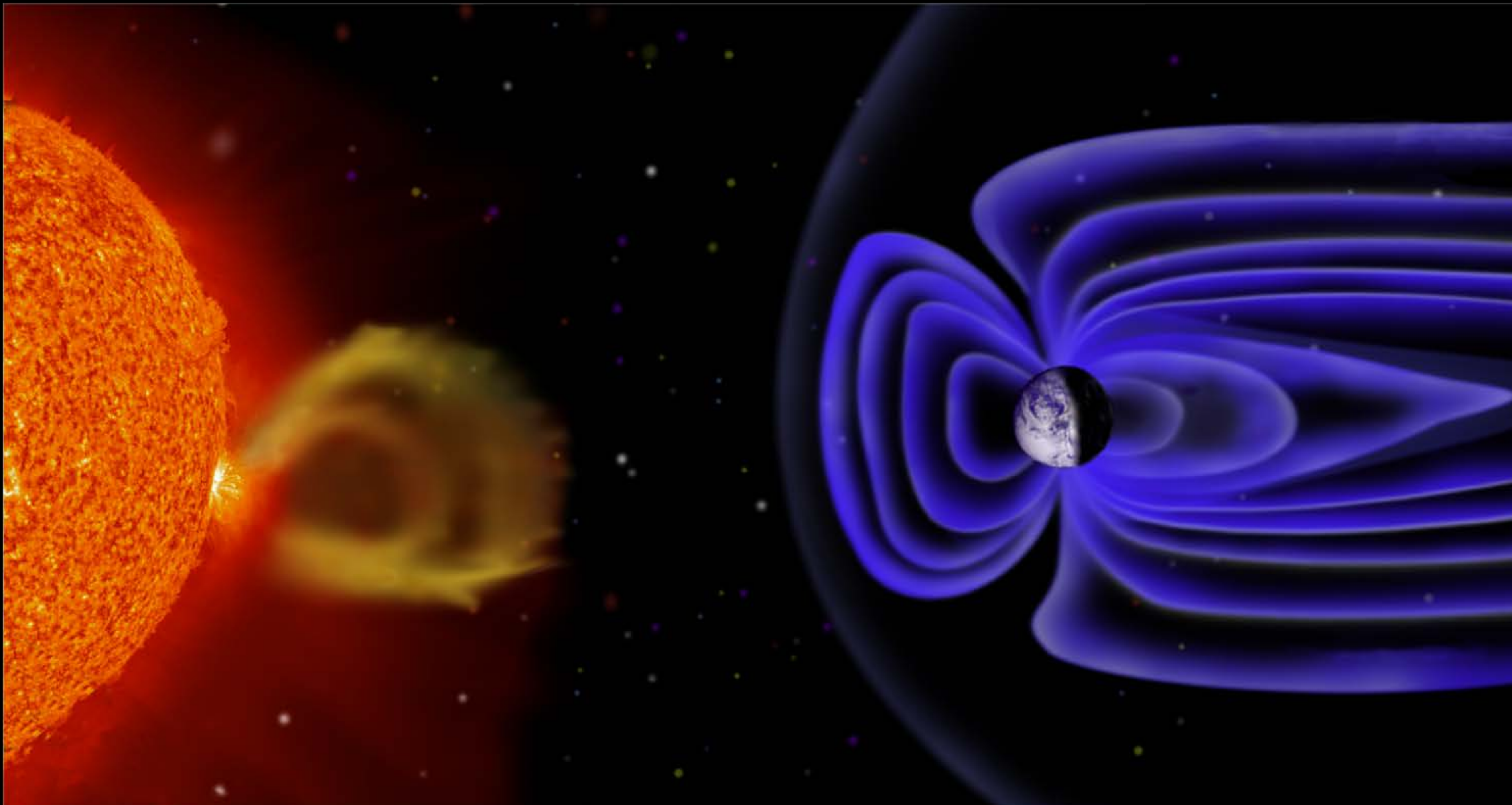




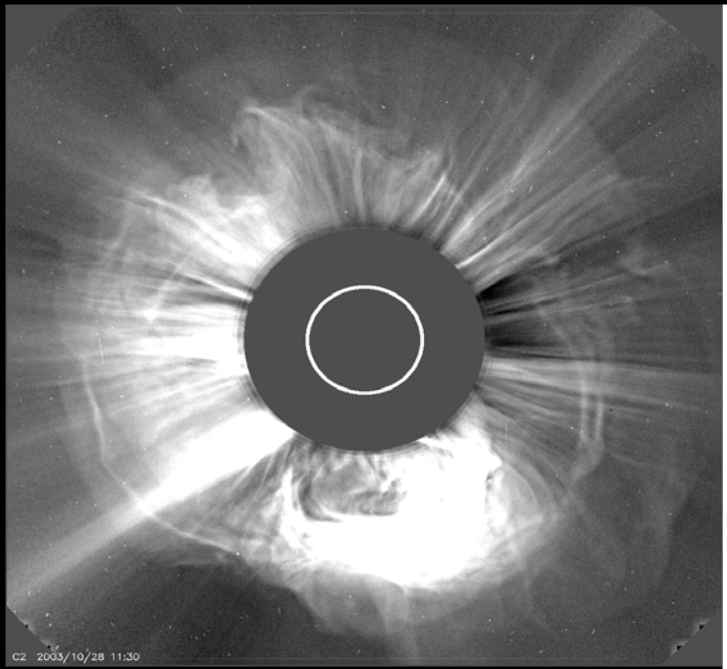
- *Identification of the CME shock front which accelerates the solar energetic particles, passing through the corona*
- *Shock front characterized by UV line broadening*
- *High temperature plasma observed in the current sheet (Fe XVIII line, 6.3 10^6 K)*

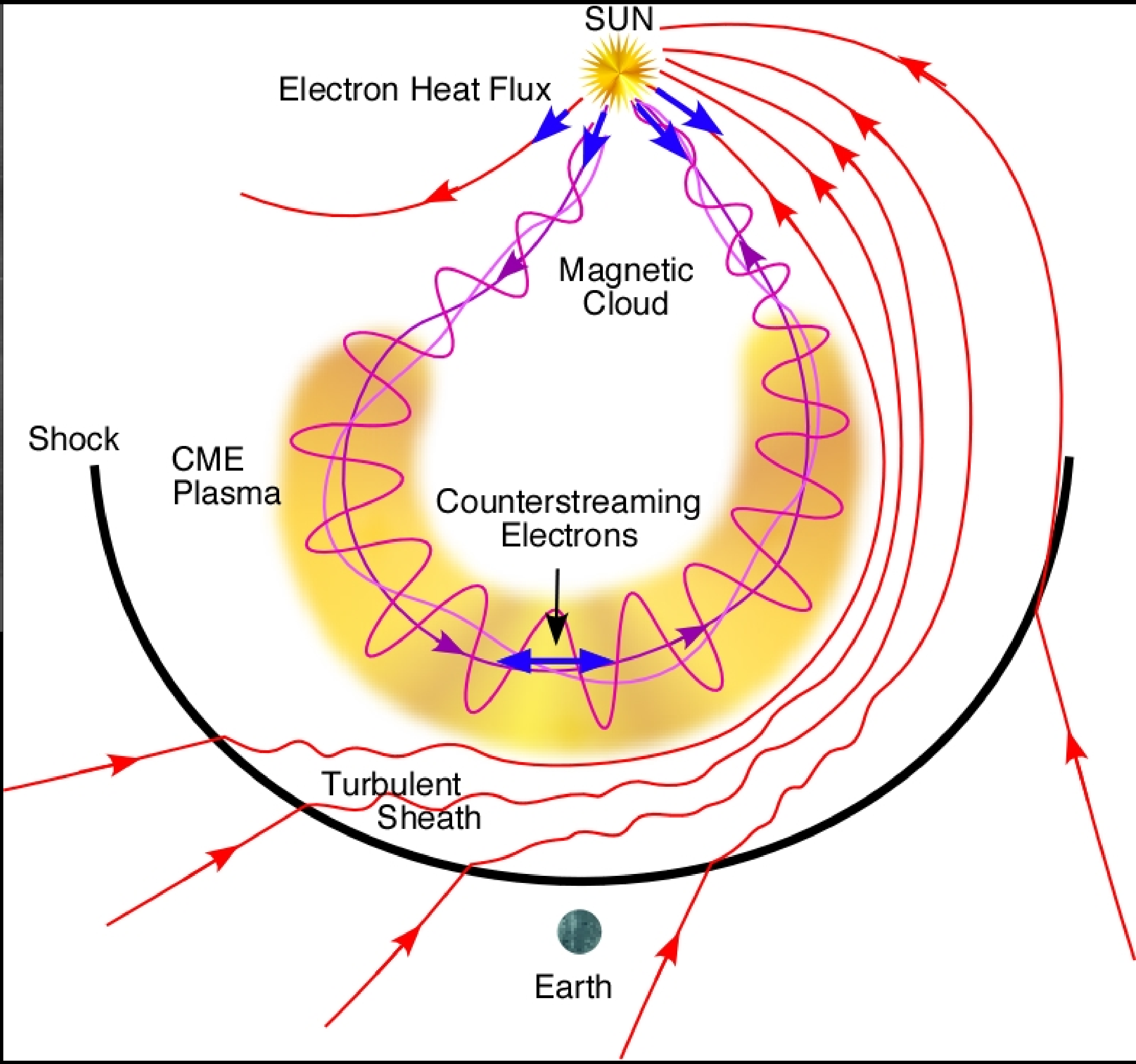
Sun Earth Connection

Effects on Earth and Heliosphere



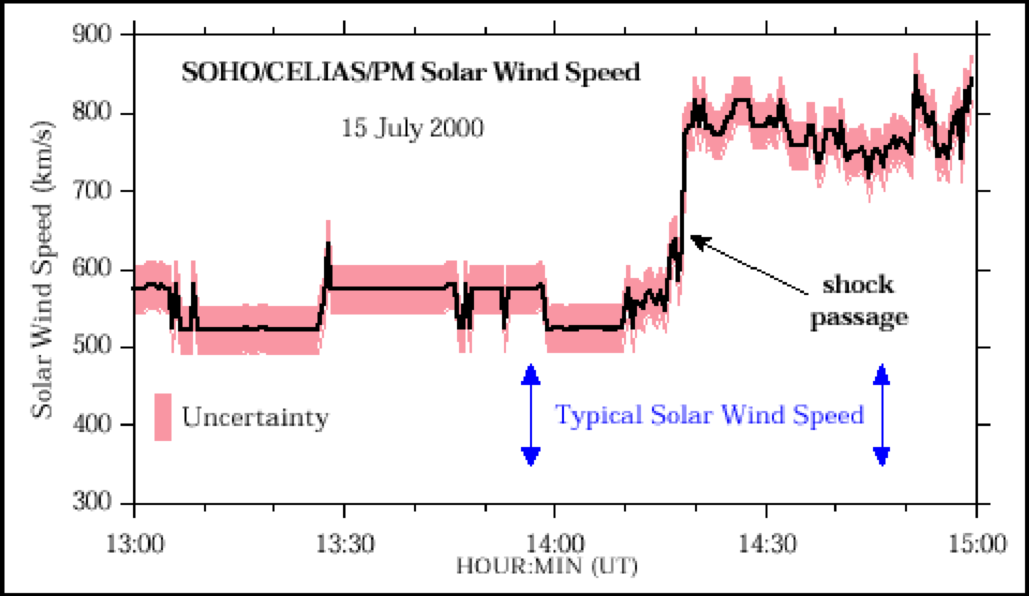
Halo CME Propagation to L1 and Earth

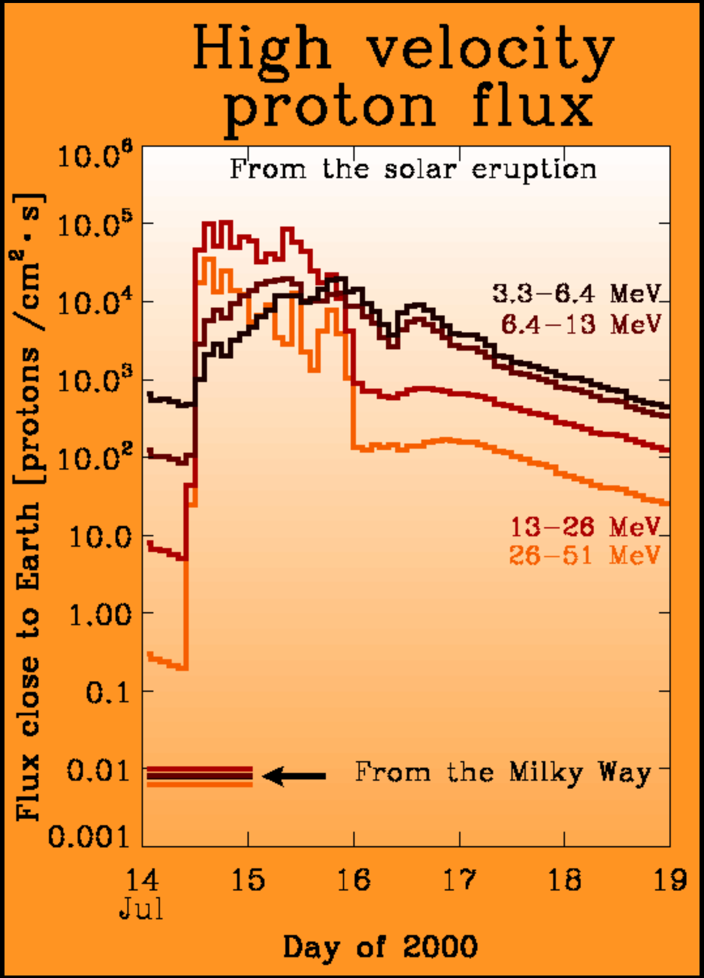


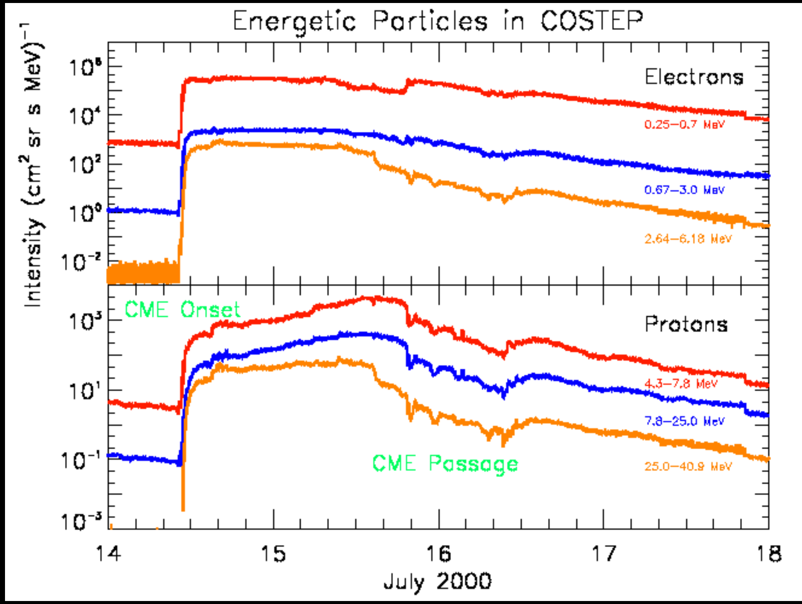


The 'Bastille' Event at L1

CELIAS
COSTEP

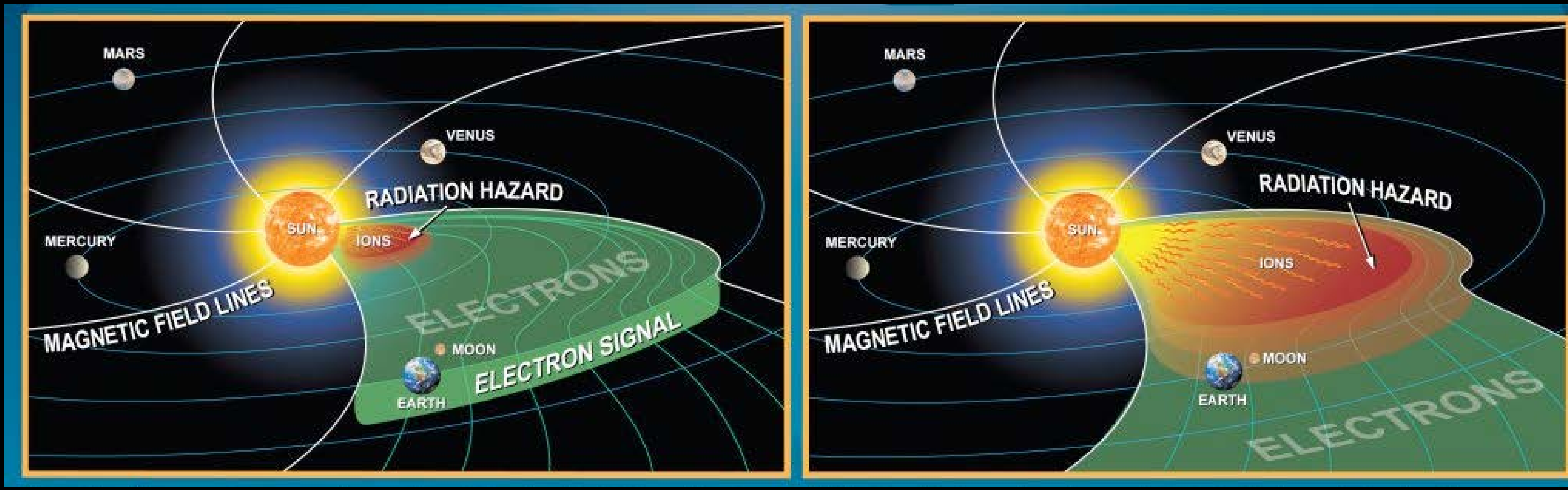






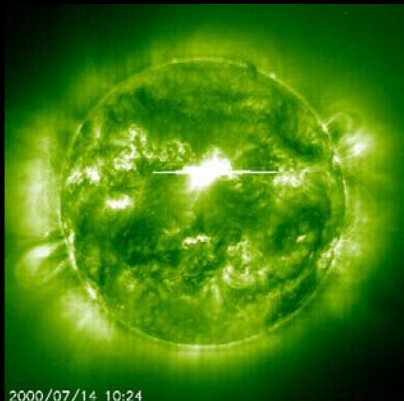
Solar Storm Forecasting

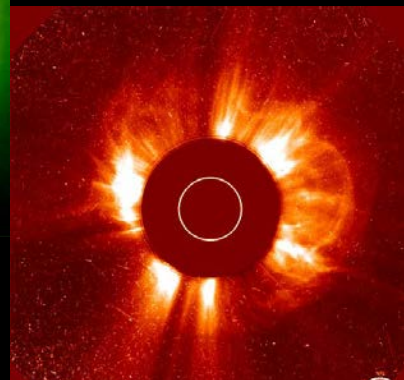
COSTEP

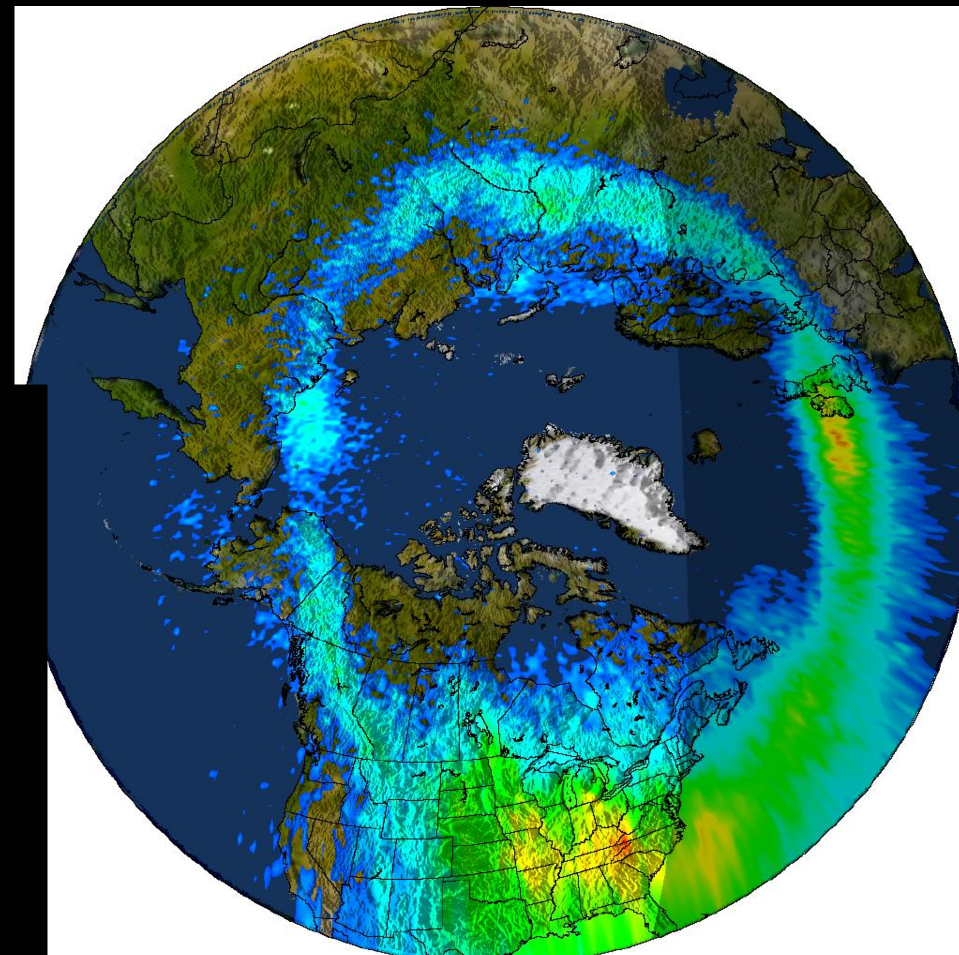


- *Particle storm consists of a mix of electrons, protons, ions*
- *Electrons travel faster than protons*
- *Electron data allow a forecast matrix with up to 1h advance warning, have been used by Johnson Space Center to ensure astronaut safety*

The 'Bastille' CME hits the Earth



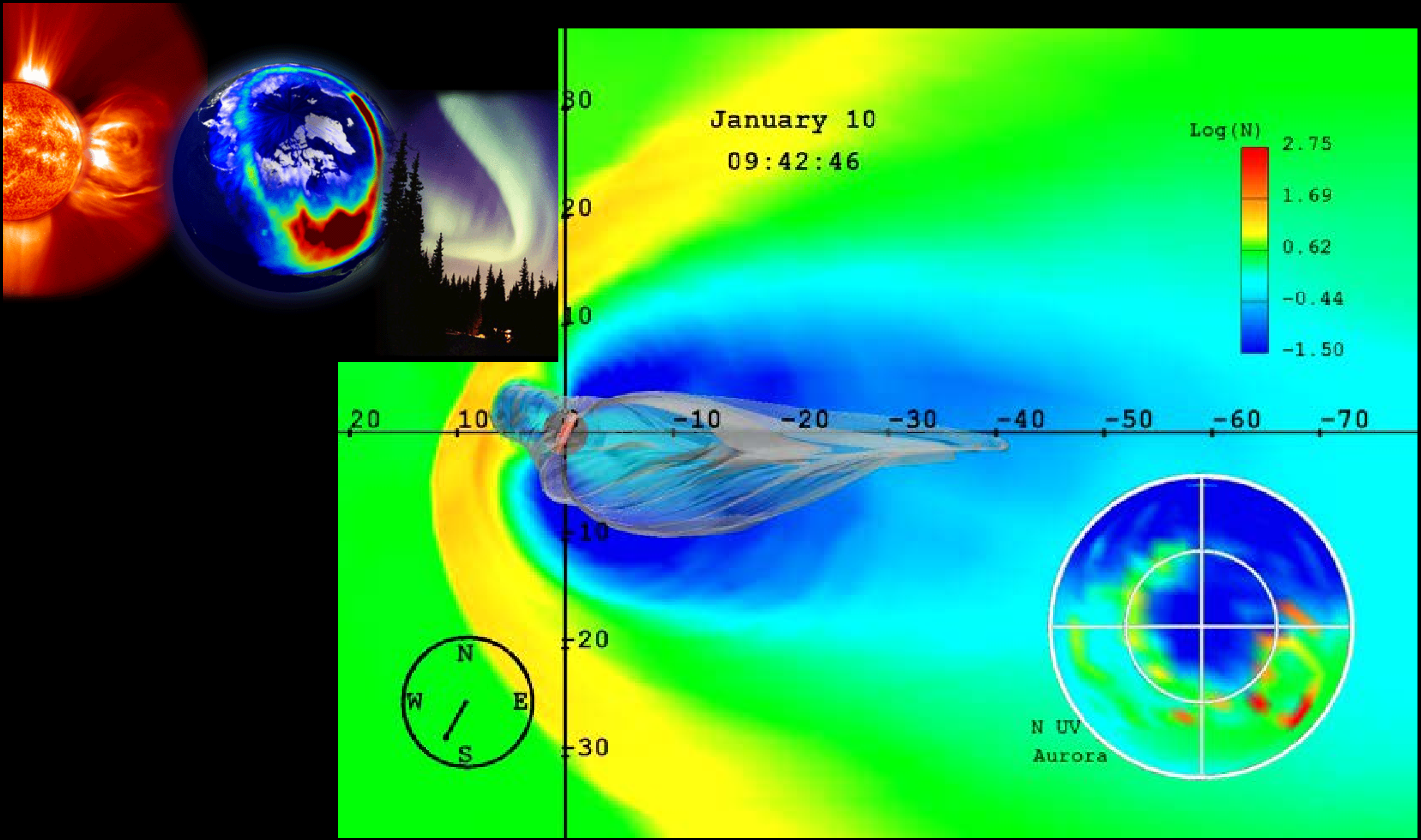




Auroras seen from ISS on 15 Sept. 2017

[Image ESA, P. Nespoli]

Magnetosphere Dynamics



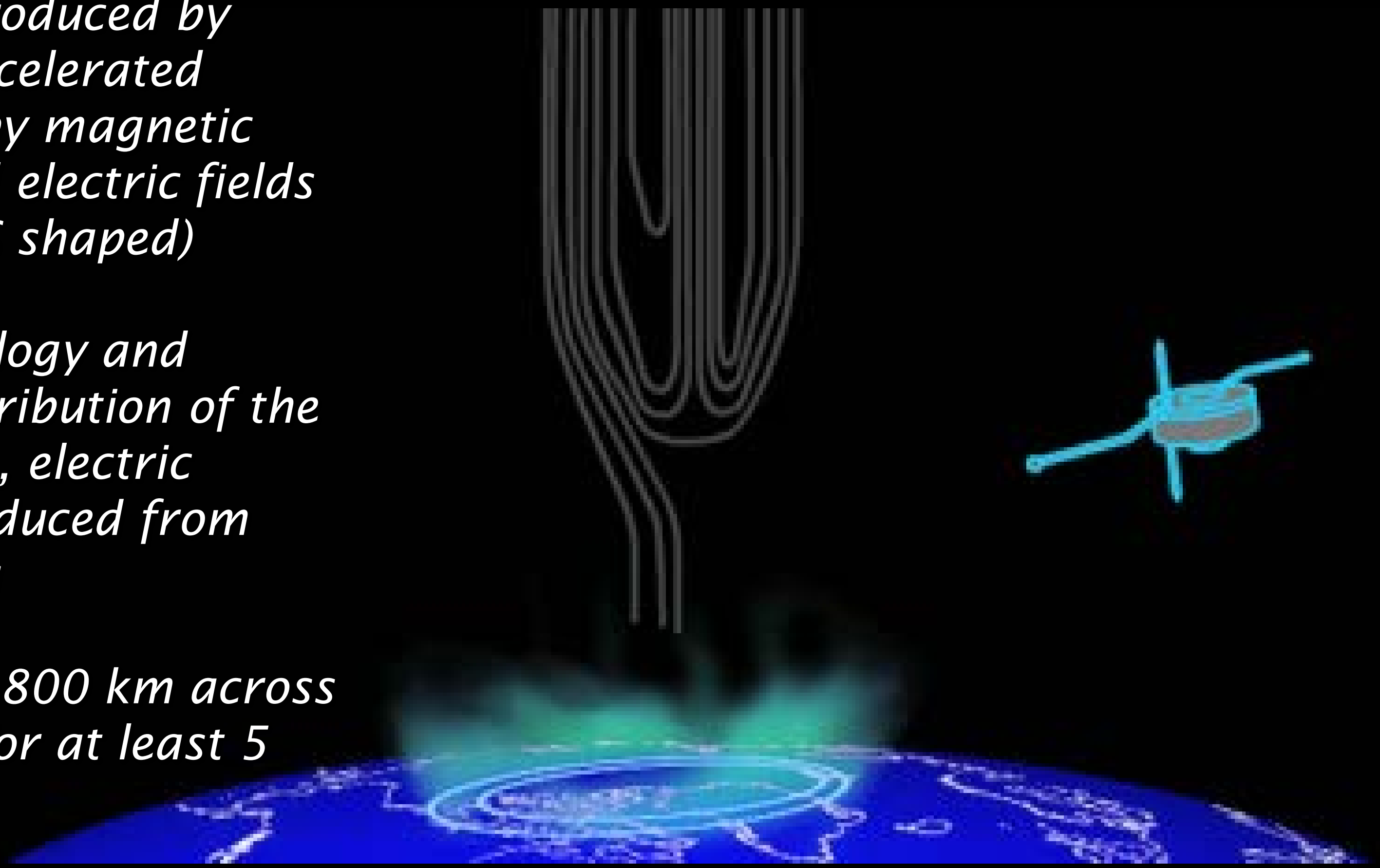
Response of the Earth magnetosphere to solar activity
Multi-point measurements needed to fully characterize the response of the magnetosphere

Auroras Electric Potential detected with Cluster

Aurora is produced by electrons accelerated downward by magnetic field-aligned electric fields (U-shaped, S shaped)

2-D morphology and altitude distribution of the acceleration, electric potential deduced from Cluster data

Auroral arc 800 km across and stable for at least 5 minutes



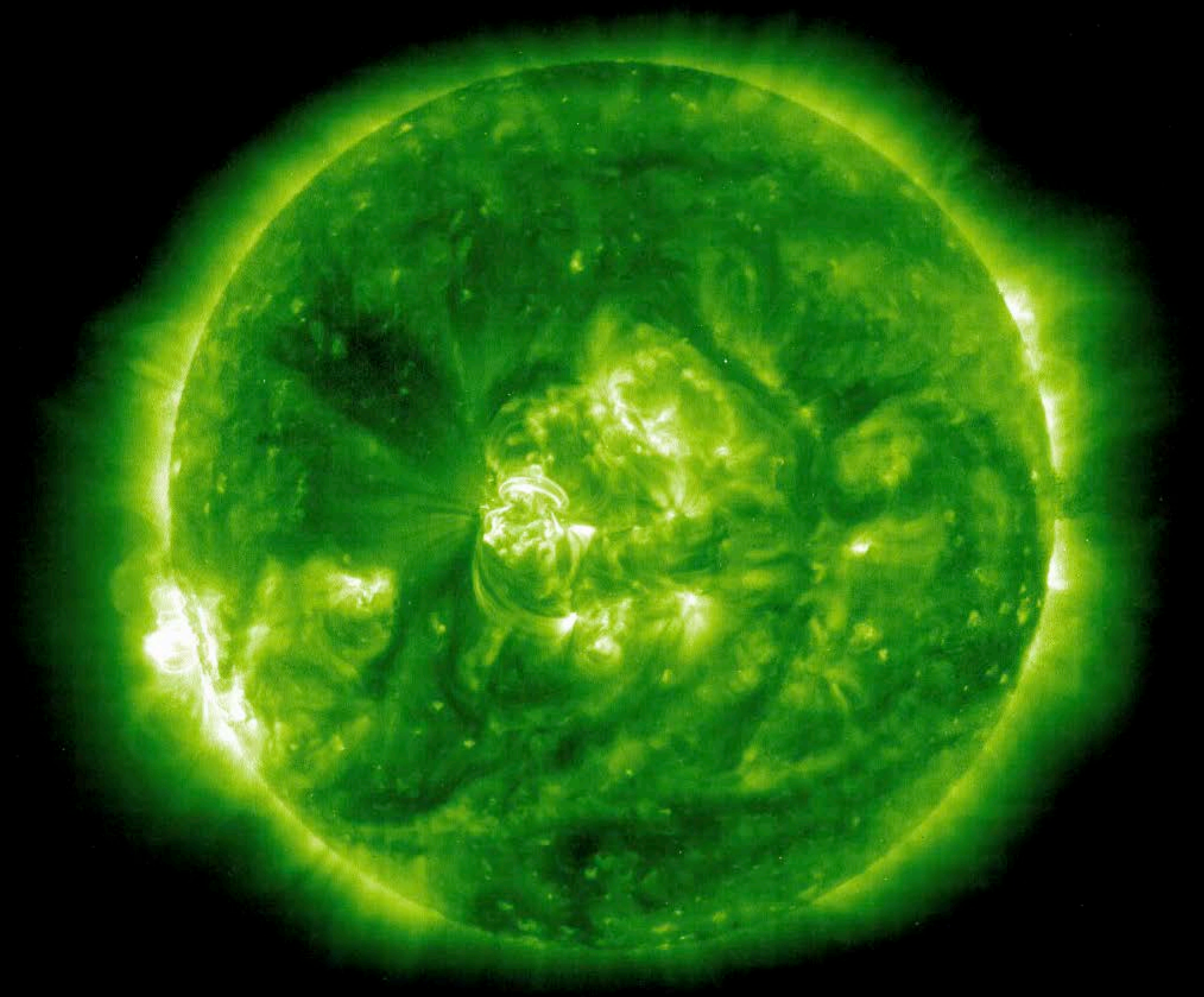
Halloween Storm

Halloween Storm: Oct-Nov 2003

First large storm observed with SOHO

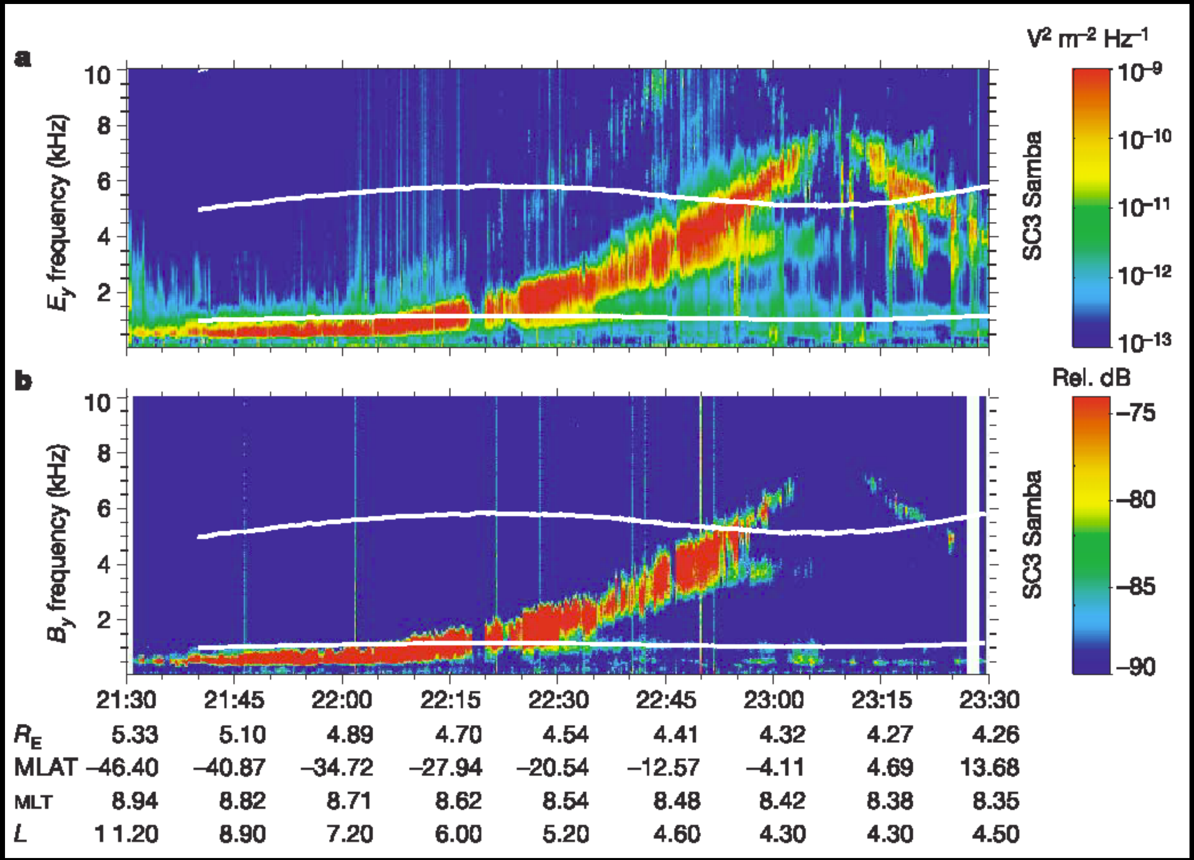
- *80 Coronal Mass Ejections*
- *Two fast transit events: less than 1 day from Sun to Earth (above 2000 km/s) (last such event 4 August 1972)*
- *50.000 people without electricity in South Sweeden*
- *GPS signal degraded and outage*
- *Many spacecraft anomalies*

Flare Activity during the Halloween Storm



Fe IX/X 195 Å (1-1.5 10^6 K)

Halloween Storm - Cluster

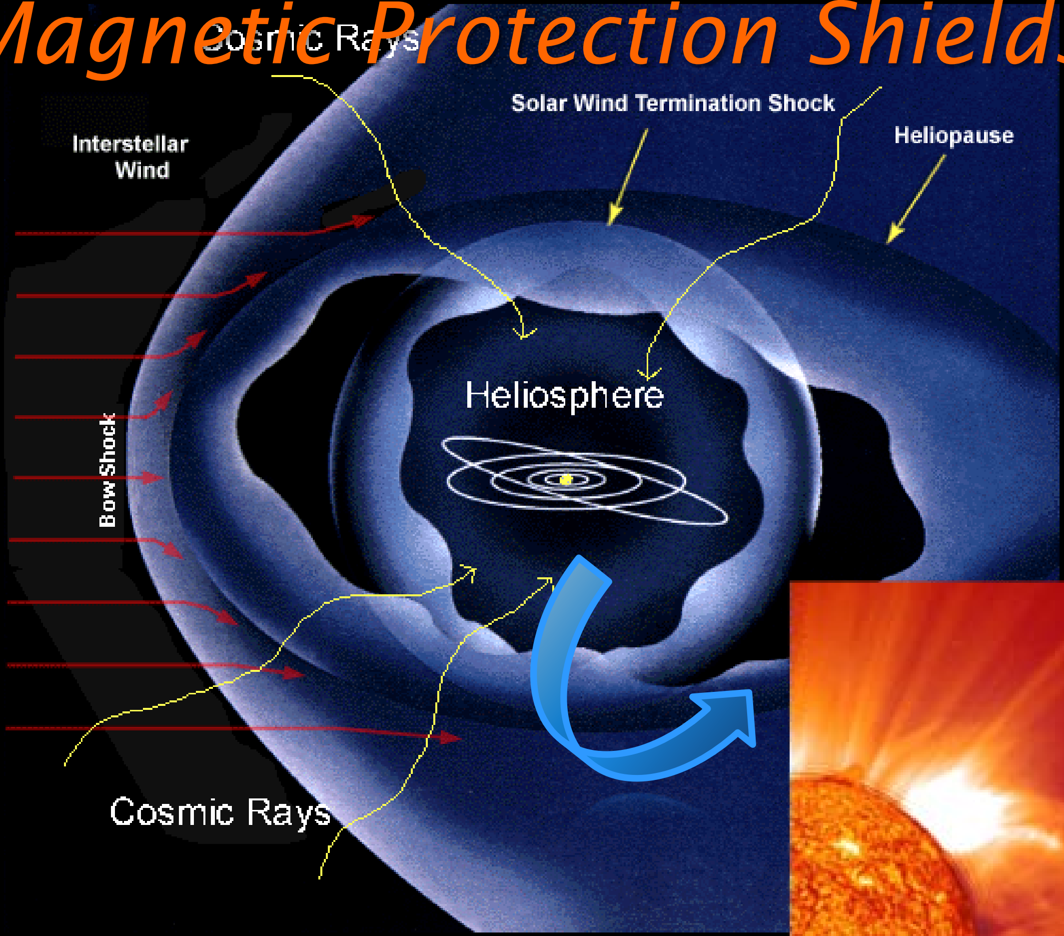


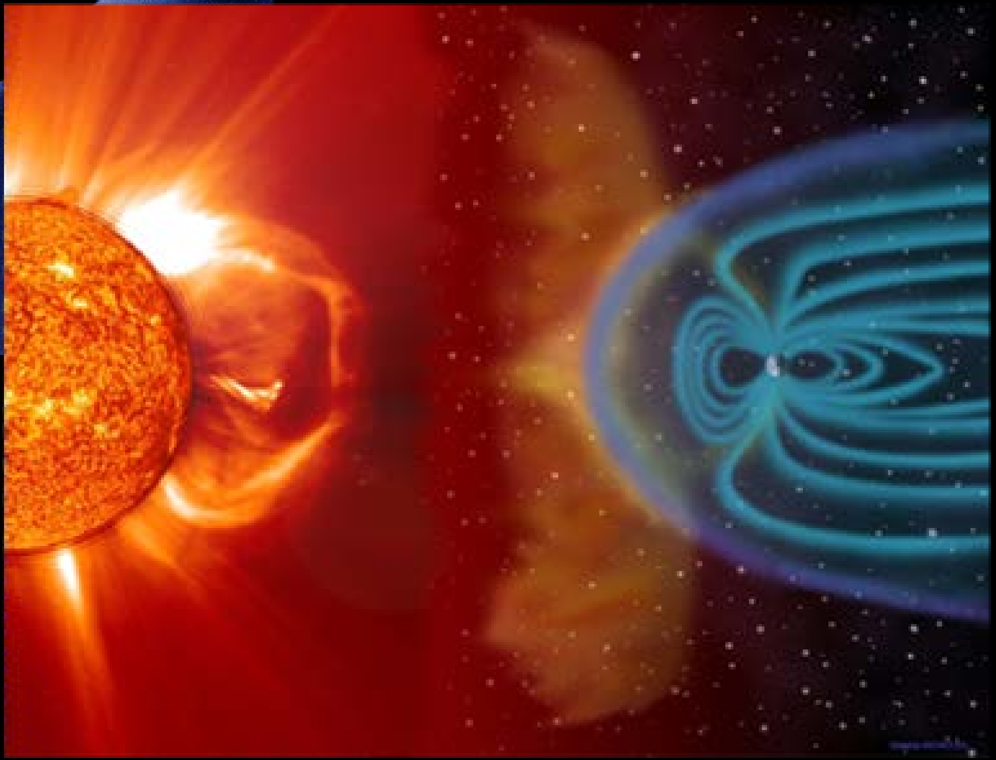
Rare event- the outer radiation belt (L=3.5) was depleted and reformed close to the Earth (L=2.5)

- *Electrons are accelerated by electromagnetic waves of a few kHz*
- *Very strong chorus emission associated with electrons accelerated to MeV (Cluster Wideband plasma instrument on 31 10 2003)*

Heliosphere during the Halloween Storm

Magnetic Protection Shields





Sun Earth Connection

The magnetosphere observed with Cluster

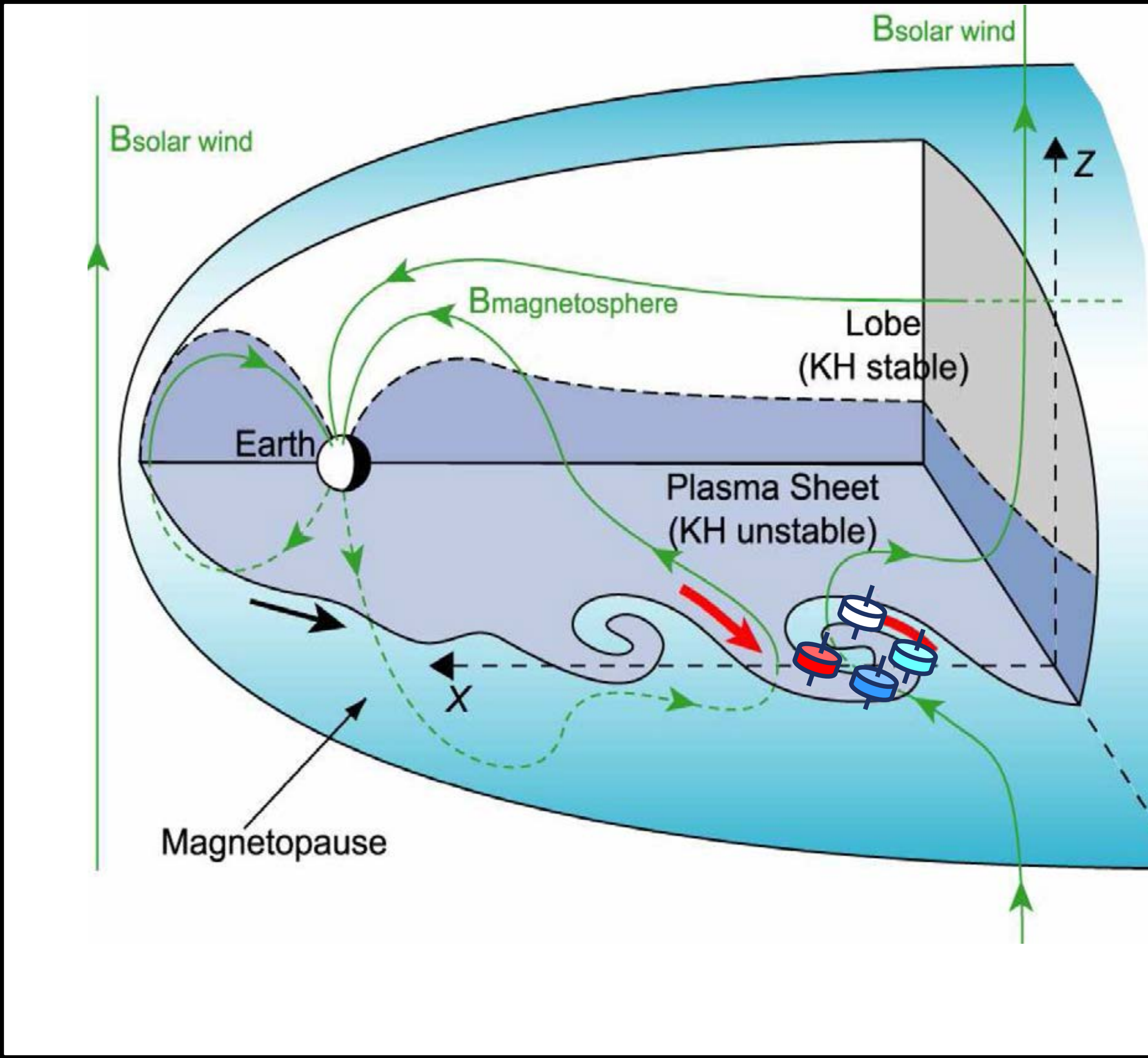
Discovery of Giant Vortices

First evidence of Kelvin-Helmholtz vortices.

Rolled-up vortices allow plasma transfer through magnetopause

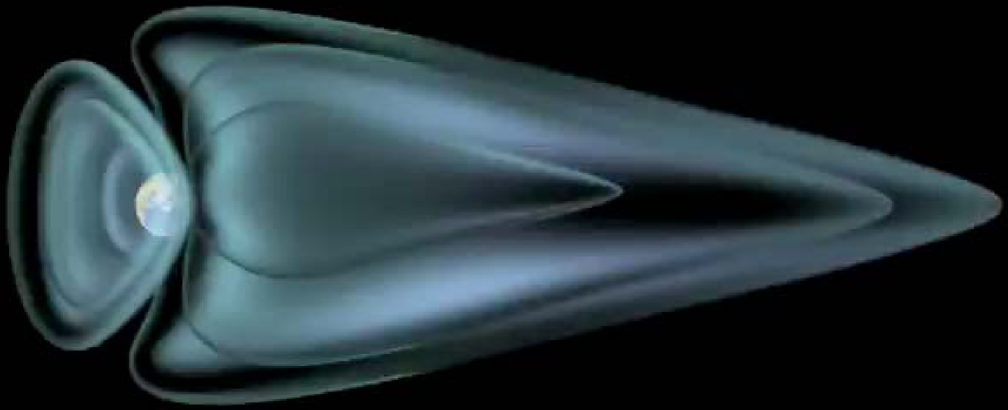
Establishing the mechanism by which the solar wind enters the Earth's magnetosphere

K-H instability occur along the flanks of the magnetosphere where the shocked solar wind if flowing fast relatively to the stagnant magnetosphere



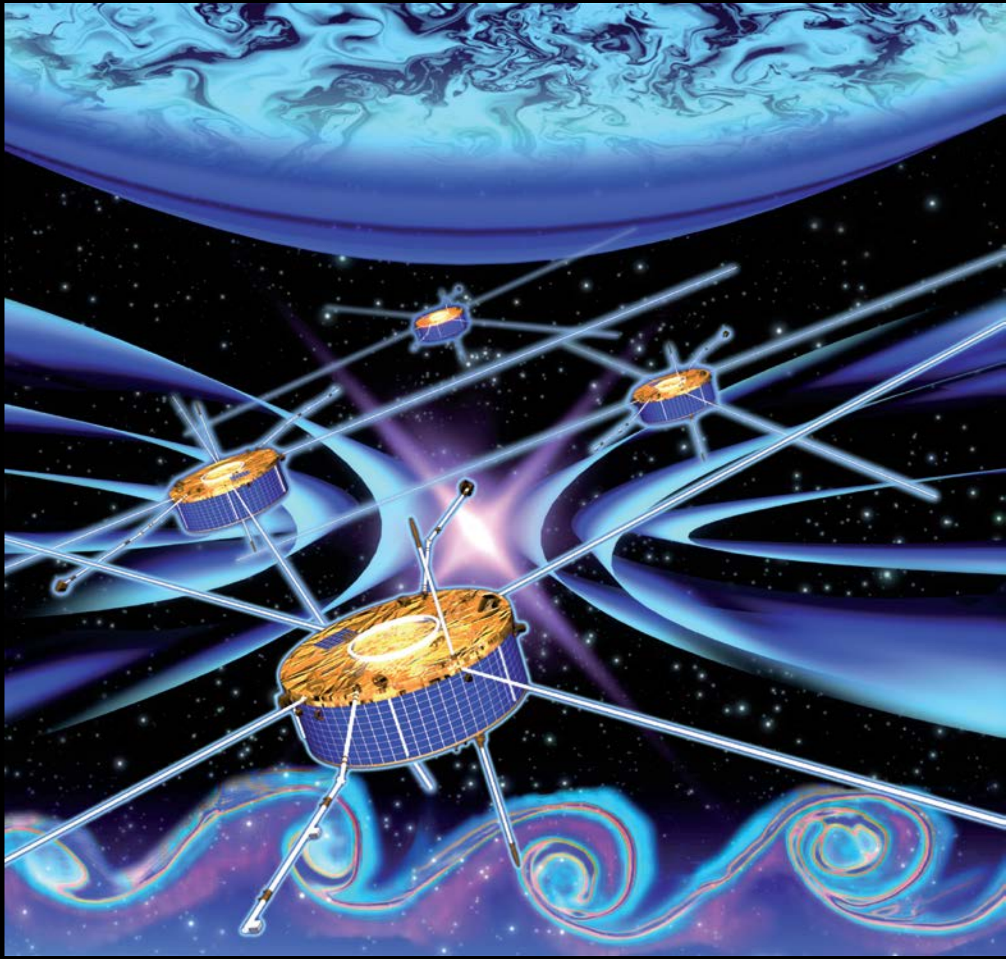
Discovery of Giant Waves in the Magnetotail

Cluster and Double Star working in tandem show for the first time that giant waves (>25.000 km) form in the magnetotail

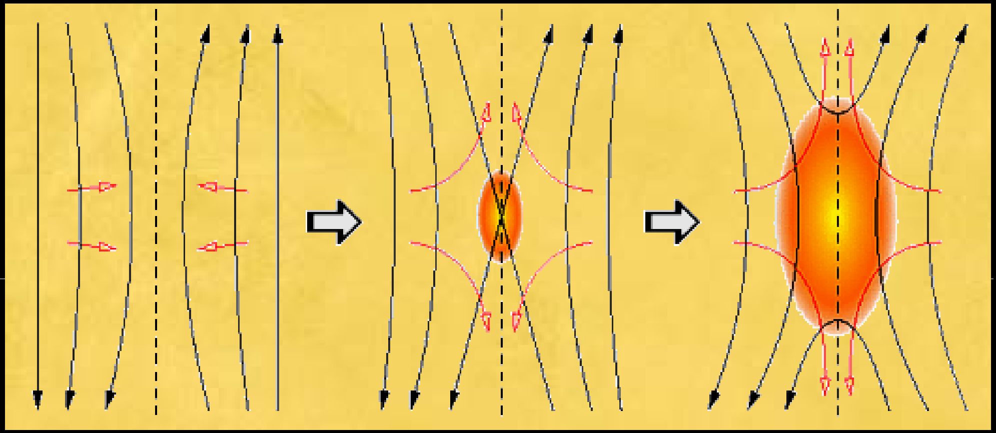


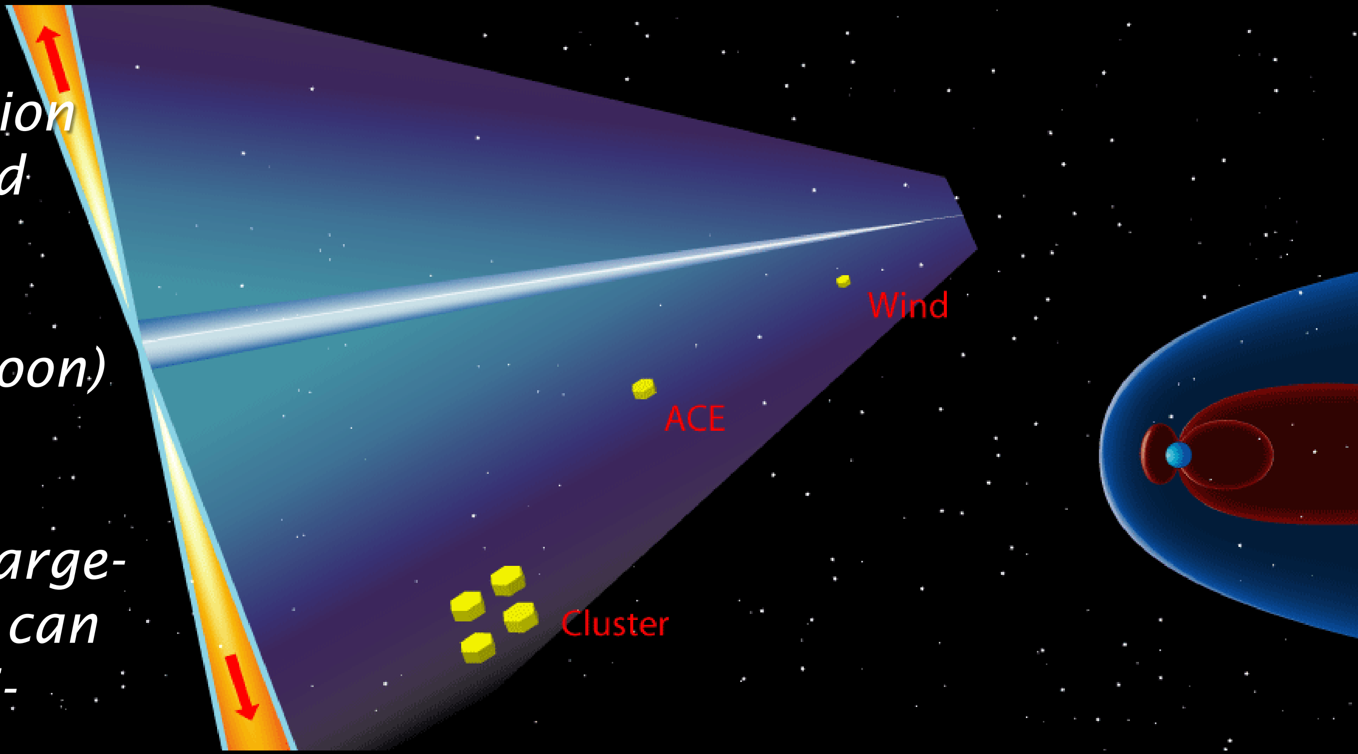
Magnetic Reconnection

- First direct observation of magnetic reconnection in 3D (2004)
- Largest reconnection line in the solar wind (2006)
- Magnetic null observed at the heart of reconnection (2006)
- Magnetic reconnection in the turbulent magnetosheath (2007)
- Electron trapping around a magnetic null (2008)
- Asymmetry of the ion diffusion region (2010)
- Acceleration of electrons in variable magnetic reconnection (2013)



Magnetic Reconnection





Largest reconnection line ever measured

2.5 Millions km (10 times Earth-Moon)

Reconnection is fundamentally a large-scale process and can operate in a quasi-steady-manner

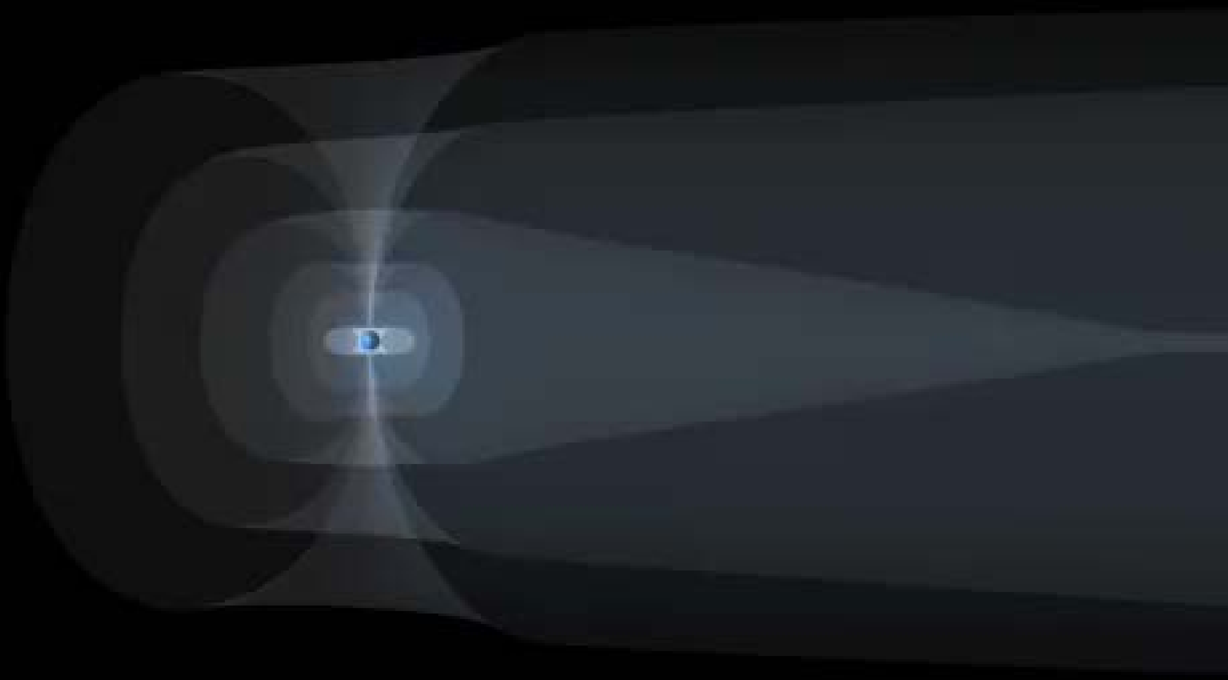
Atmosphere Escape

First observation of plasmaspheric wind

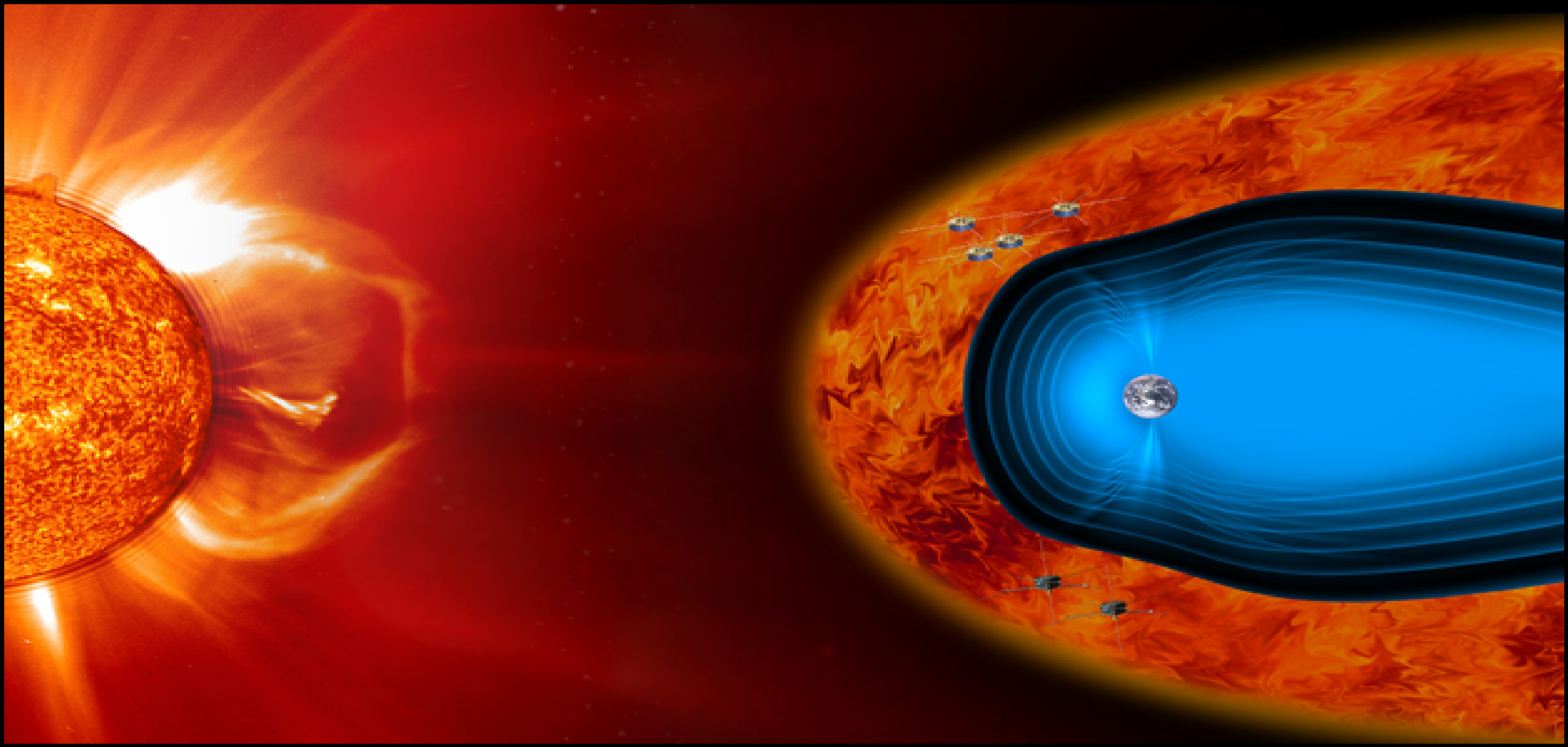
Constant leakage of material from the plasmasphere outwards to the magnetosphere, across the magnetic field lines

5×10^{26} ions s^{-1}
(90 tons/day)

Dominant during quiet and moderately active conditions



Turbulence in Earth Magnetic Environment
Cluster and THEMIS

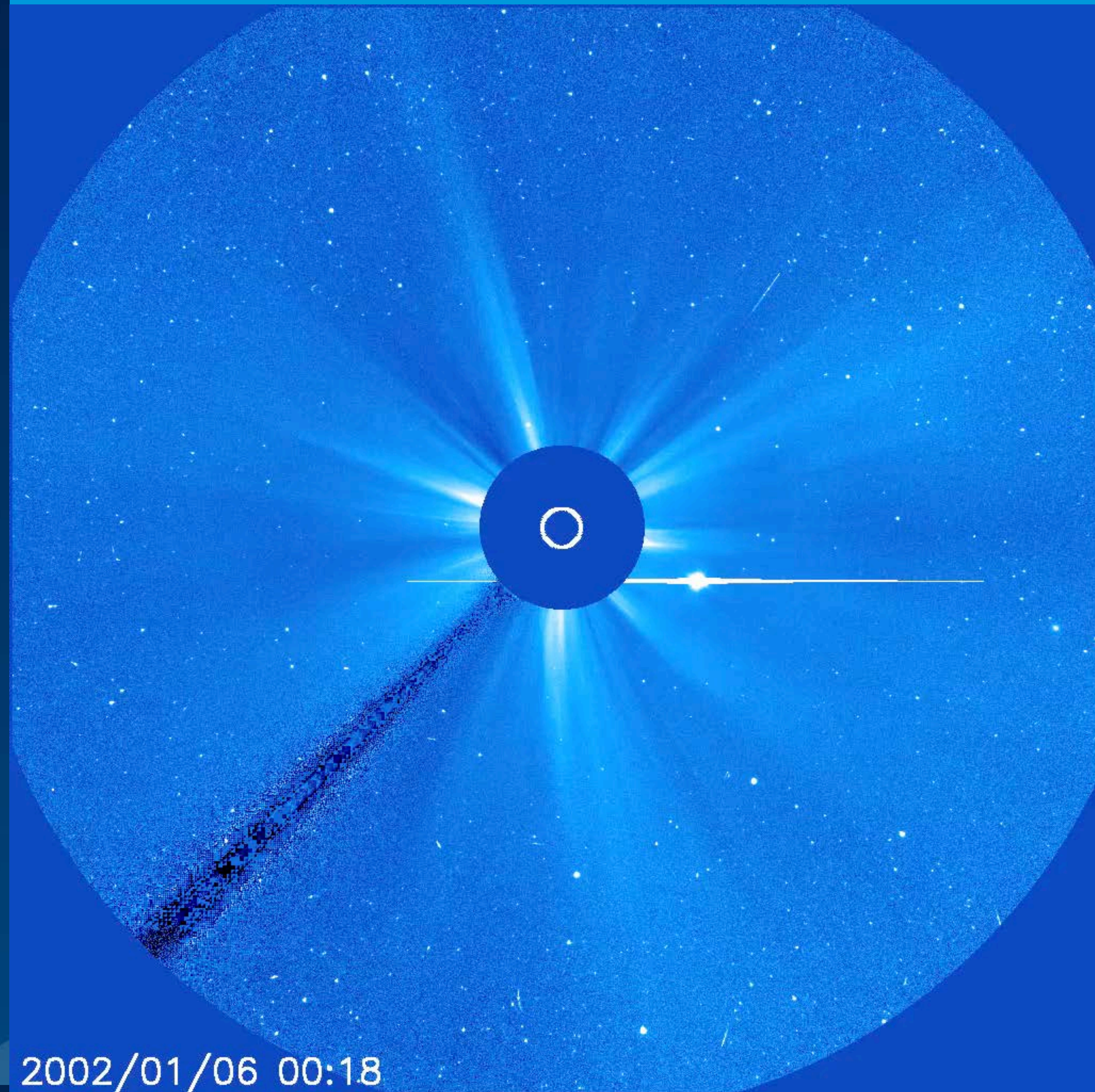


First estimate of how much magnetic energy is transferred from large (order of 10^3 km) to small scale (1 km), where particles are heated and accelerated, within the magneto-sheath, the solar wind/magnetosphere boundary region.

Density and magnetic fluctuations caused by turbulence in the magneto sheath amplify the rate at which energy cascades from large to small scale.

Comets

SOHO the Comet Hunter



Thanks to:
P. Escoubet, B. Fleck, D. Mueller, T. Duvall, F. Marcucci, R. Howard
Image credit: ESA, NASA &
SOHO, Cluster, TRACE, THEMIS teams