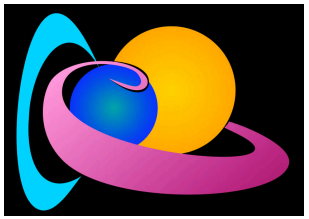
SOLI INVICTO

Solar-Terrestrial Research and Modeling at the STCE

Andrei N. Zhukov

Solar–Terrestrial Center of Excellence



RMI

Motivation and goals

- Our Earth is situated in the atmosphere of a variable magnetic star!
- The goal of the solar-terrestrial research at the STCE is therefore to understand the complex structure and dynamics of the solar-terrestrial system, including space weather.
- Solar-terrestrial research is a synergetic science requiring expertise in multiple domains: astronomy, astrophysics, plasma physics, geophysics, atmospheric physics and chemistry, aeronomy, meteorology, etc.

A chain of Solar-Terrestrial connections

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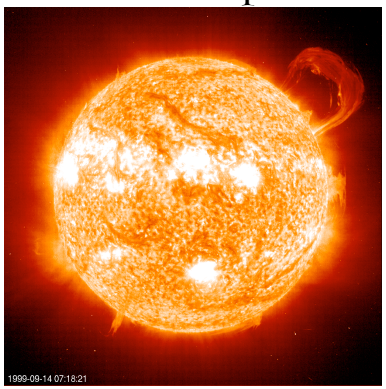
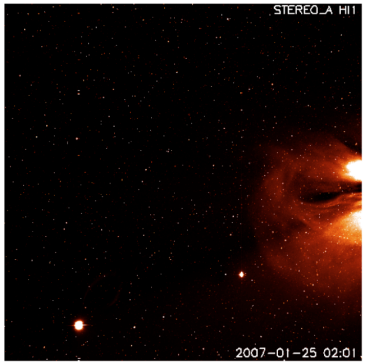
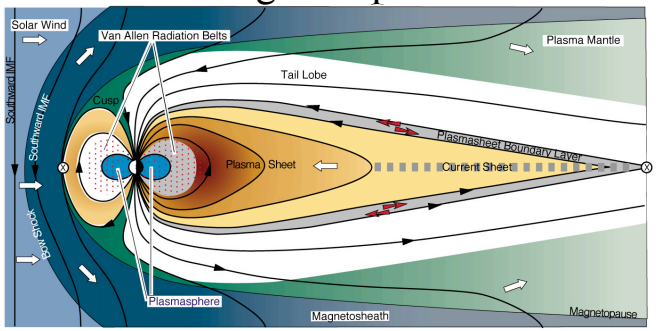
solar atmosphere



solar wind

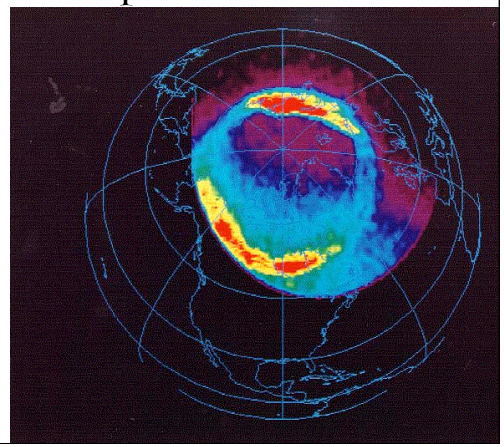


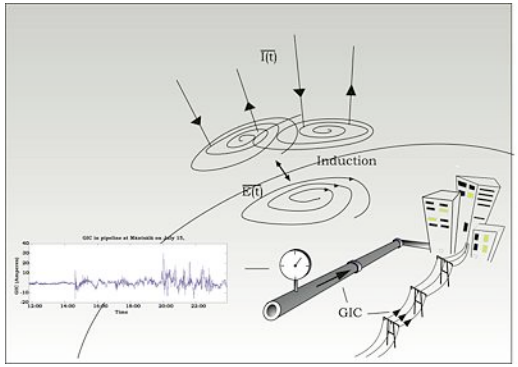
magnetosphere



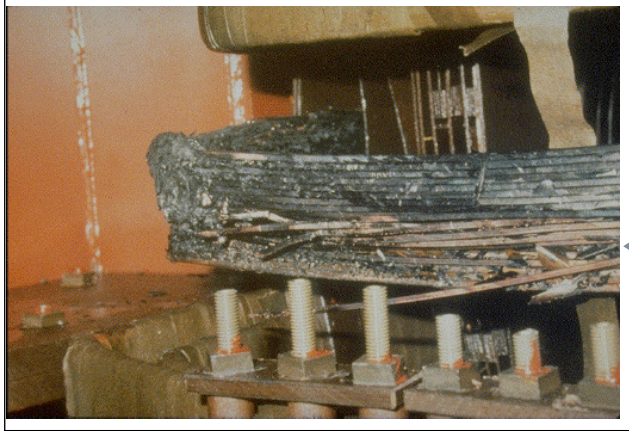
There is more than one chain!

ionosphere



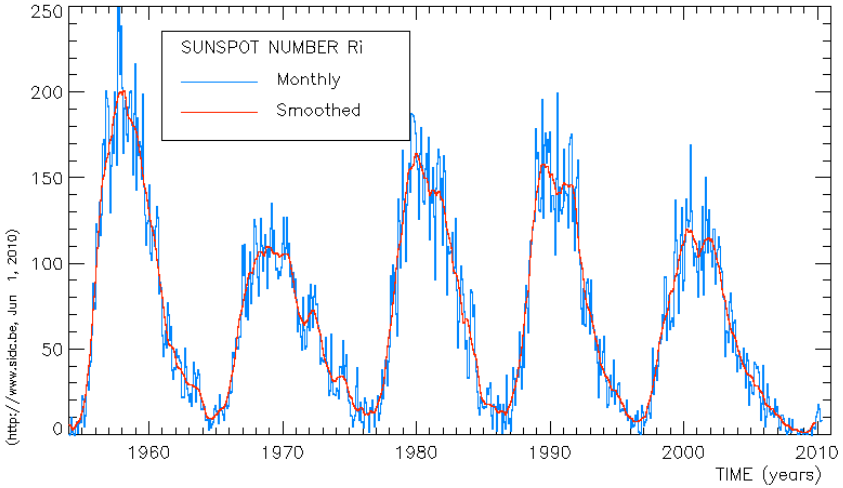


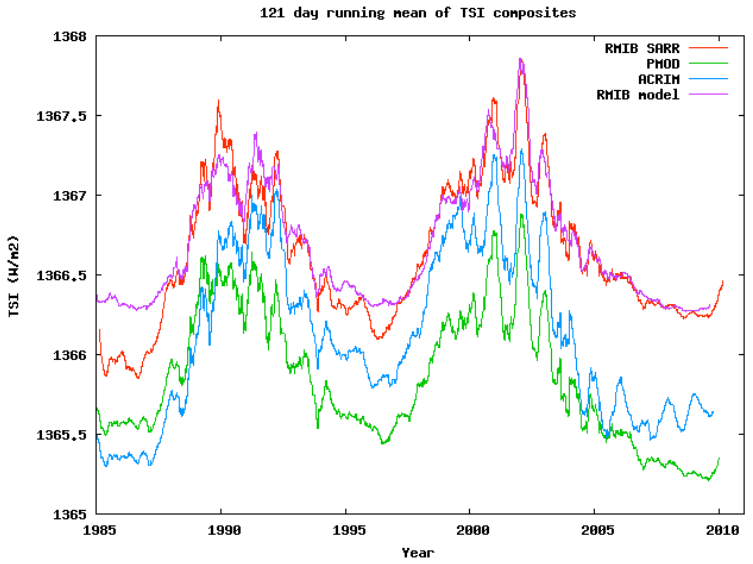
geomagnetically induced currents



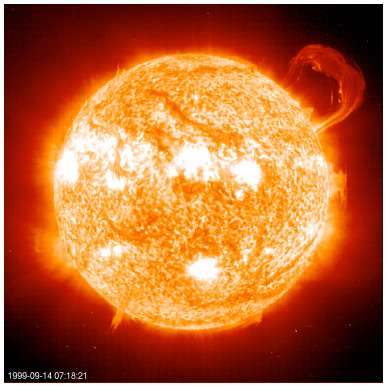
Long-term processes

- The solar-terrestrial connection chain for long-term processes (including the influence on the Earth's climate) is still not clear.

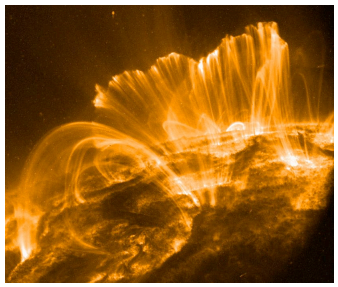


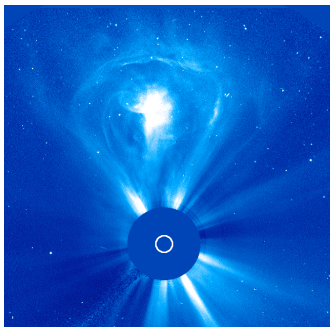


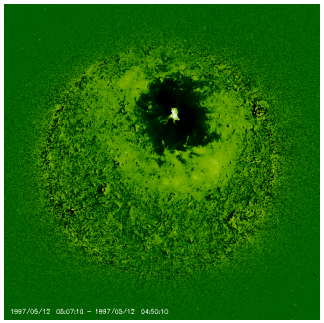
Solar atmosphere



- Observational research of the photosphere and chromosphere.
- 3D structure of the quiescent solar corona: active region loops.
- Spectroscopic diagnostics of the nascent solar wind.
- 3D structure of coronal mass ejections (CMEs).
- Plasma dynamics in the low corona during CMEs: “EIT waves”, coronal dimmings, shock waves.

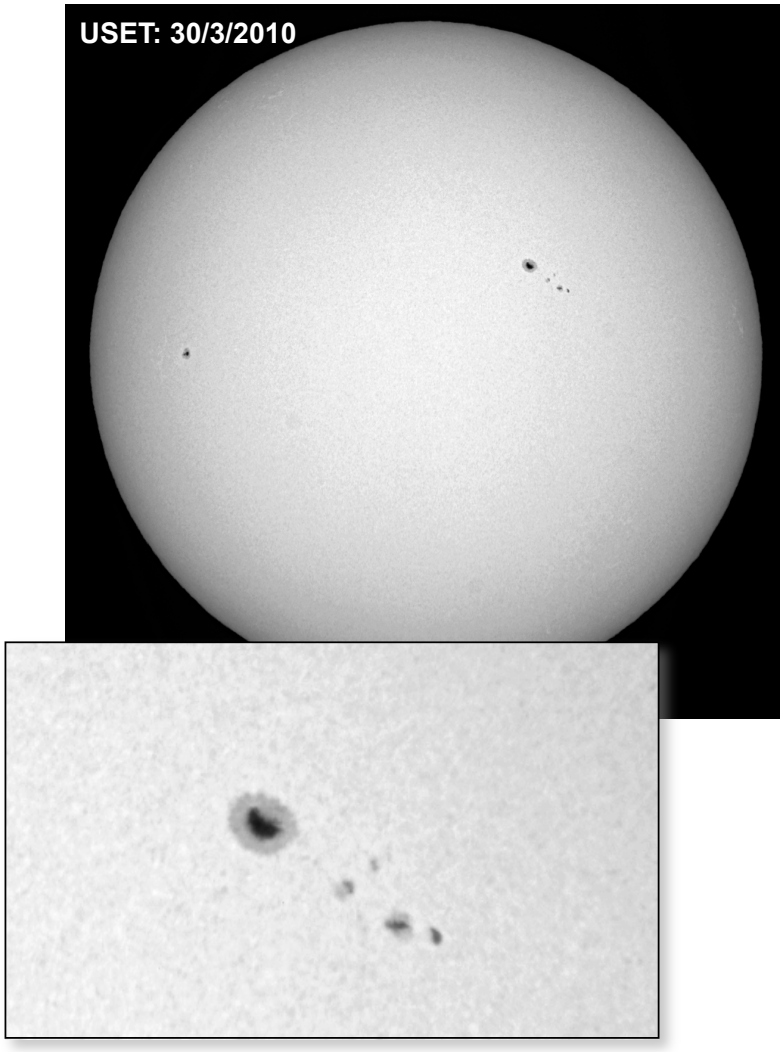






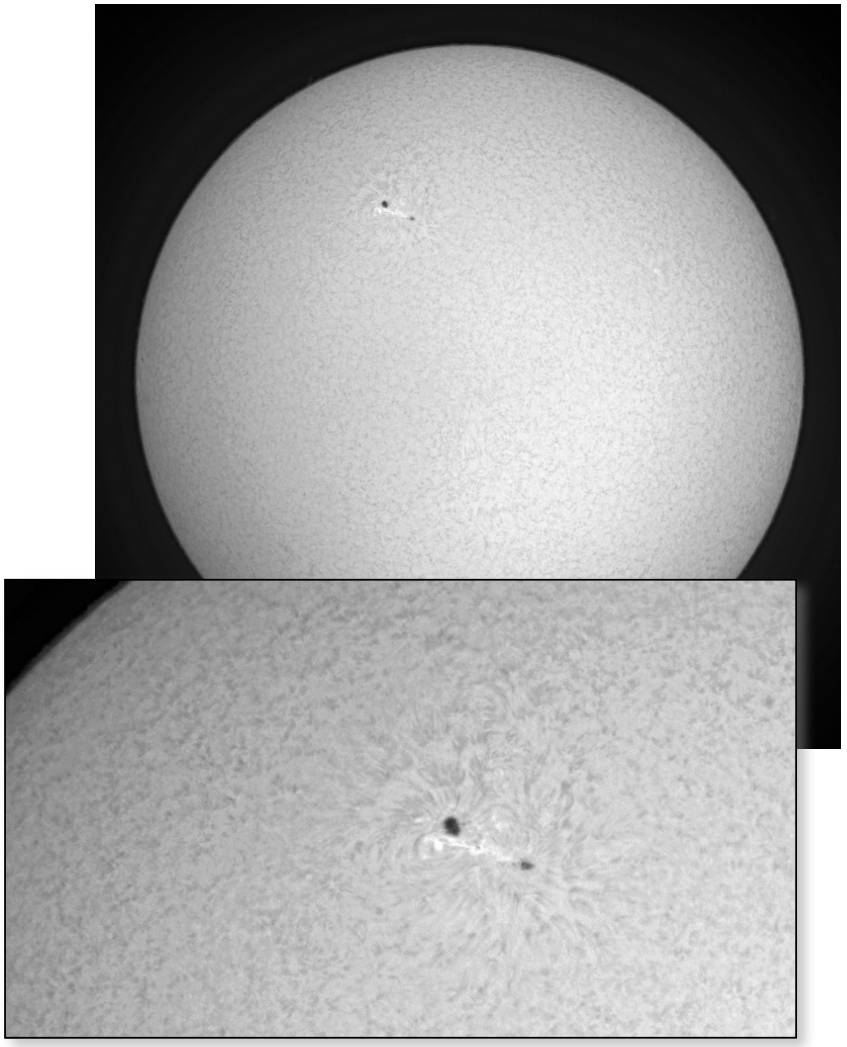
Solar photospheric observations by USET

- Construction of sunspot catalogs from multiple image sources (Uccle, Debrecen).
- Investigation of image-based solar activity indices.
- Extension of the historical visual sunpot index.
- Long-term backward proxies for irradiance, particle fluxes.



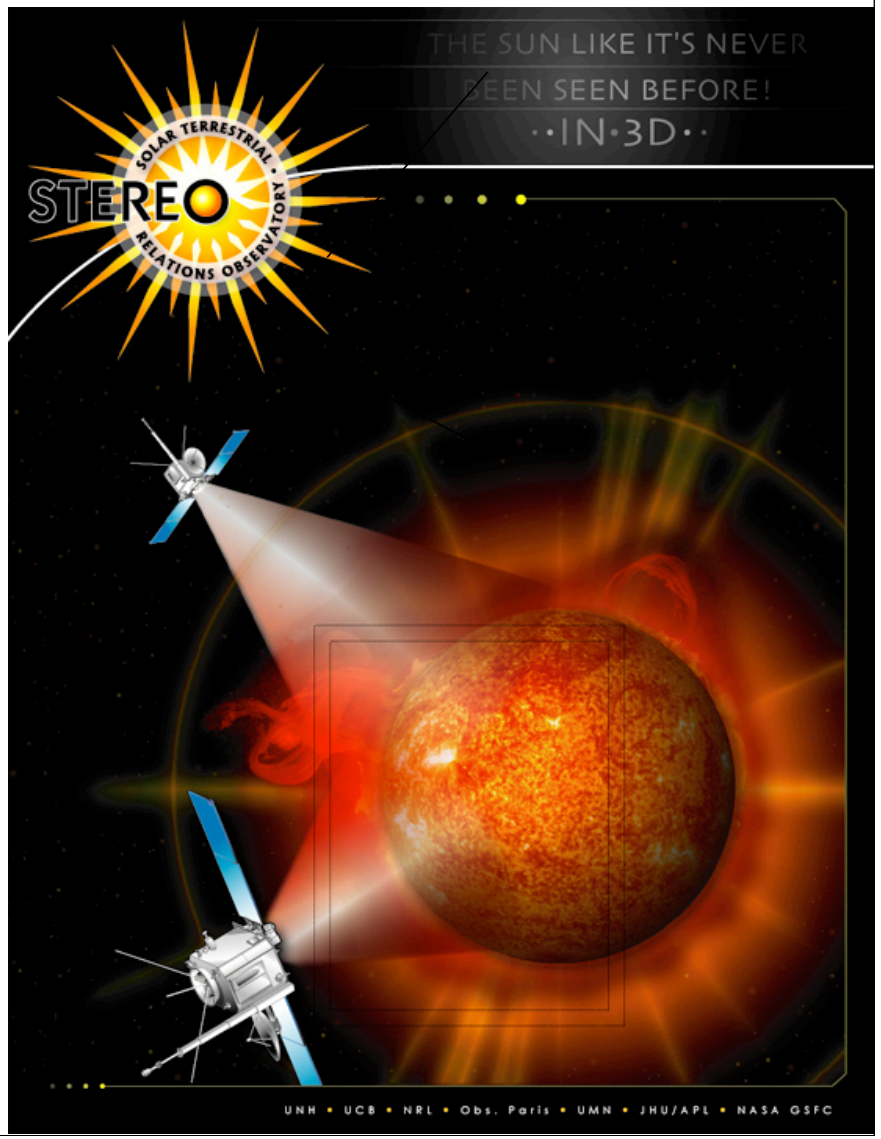
Solar chromospheric observations by USET

- Flares: onset, energy release, sympathetic flares.
- Moreton waves.
- Filaments: eruptions, disparition brusque, bulk flows, magnetic topology.



3D STRUCTURE OF ACTIVE REGION LOOPS IN THE SOLAR CORONA

- Automatic identification of the "same" pixels in SECCHI/EUVI images taken from two STEREO spacecraft by means of local correlation tracking.
- Triangulation of matched points to determine loop hights.
- Some loops that look co-spatial in two bandpasses have in fact different heights and thus occupy different volumes *(Rodriguez, Zhukov, Gissot, Mierla, 2009)*.
- Torsional Alfvén waves in small-scale threads inside the loops may contribute to the coronal heating *(Copil, Voitenko & Goossens, 2010)*.



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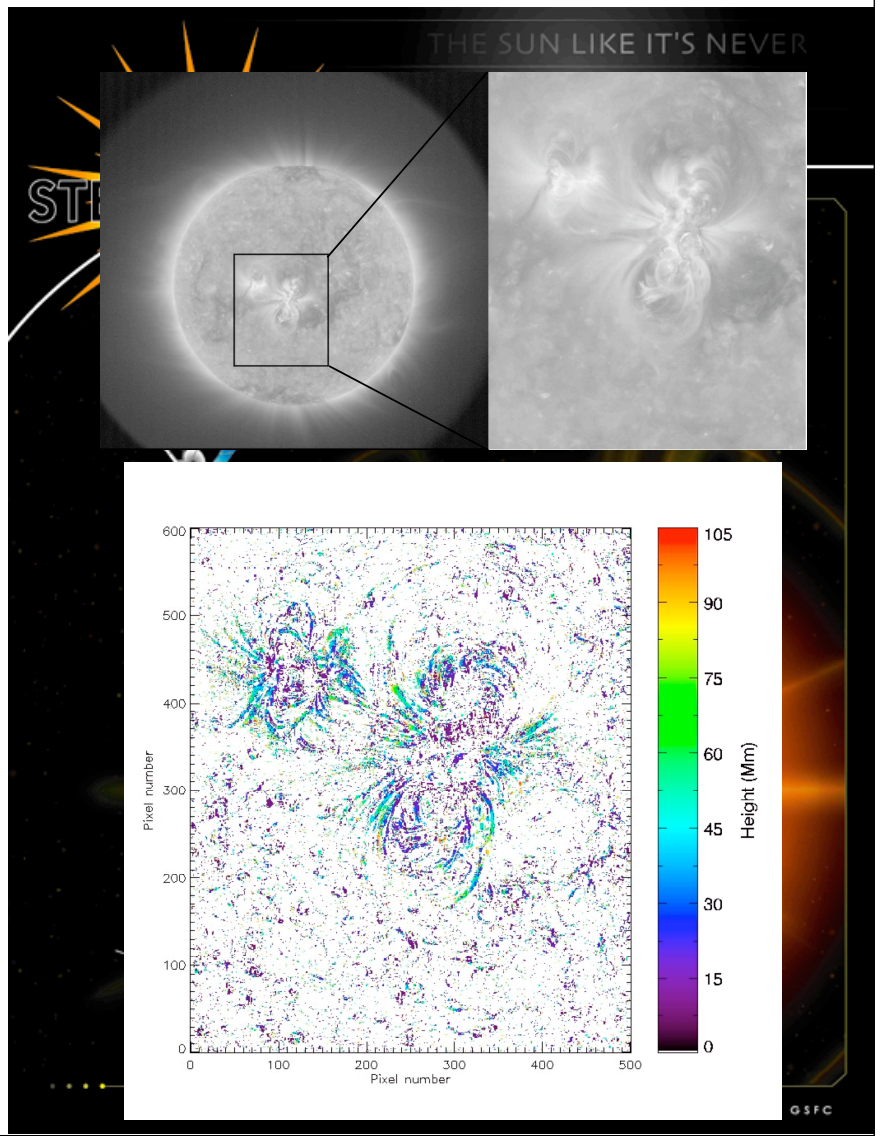

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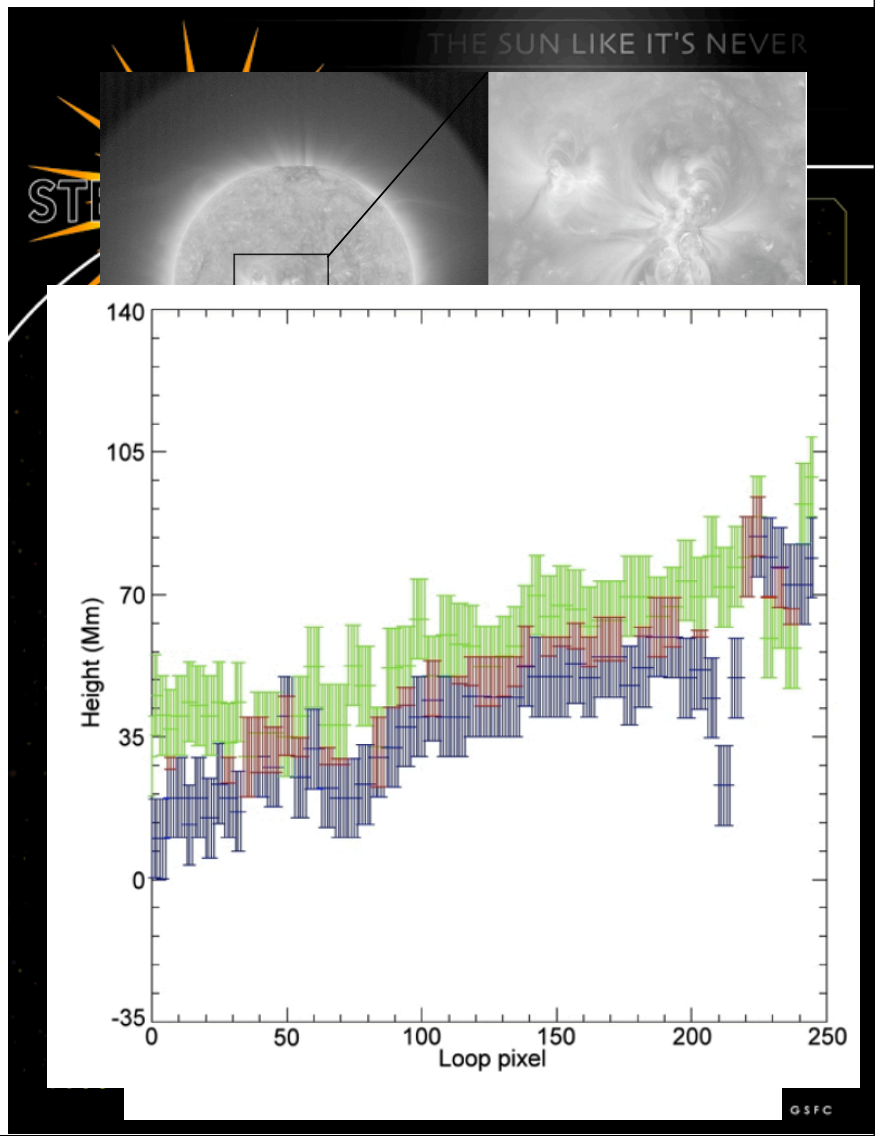

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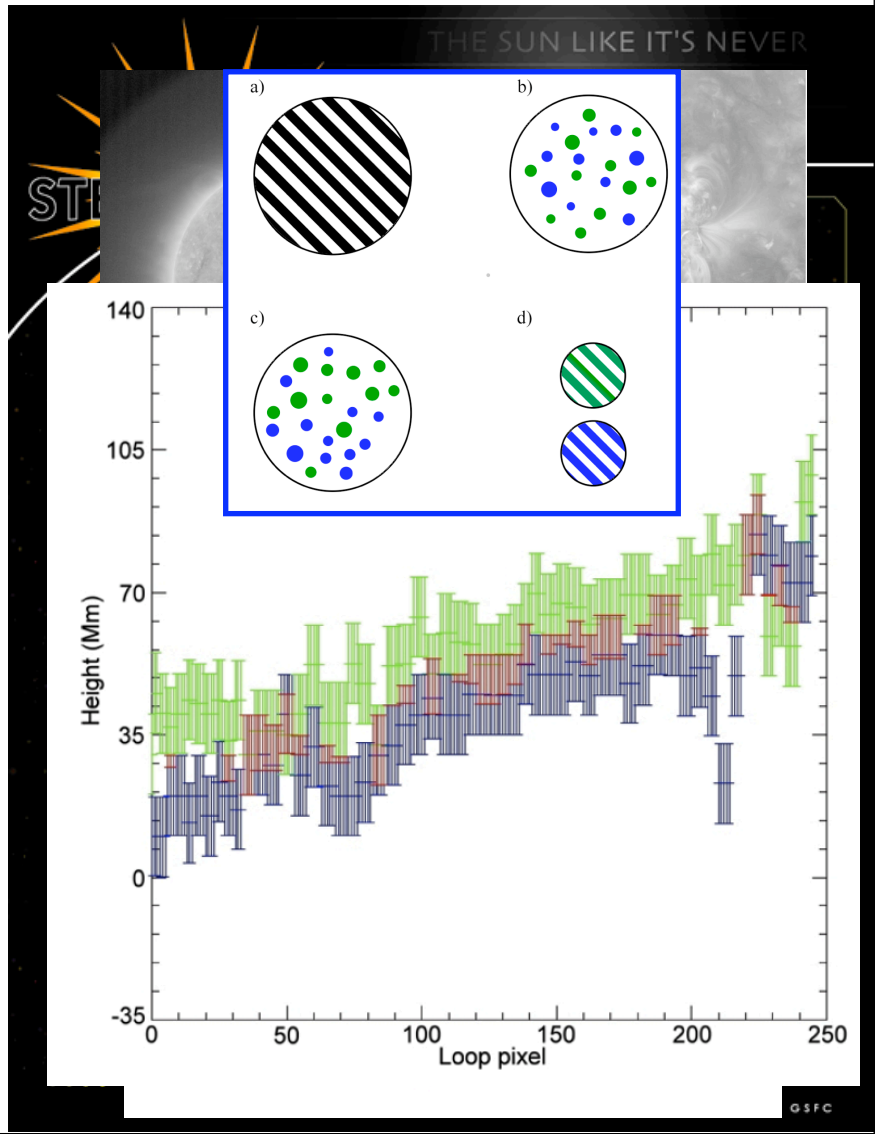

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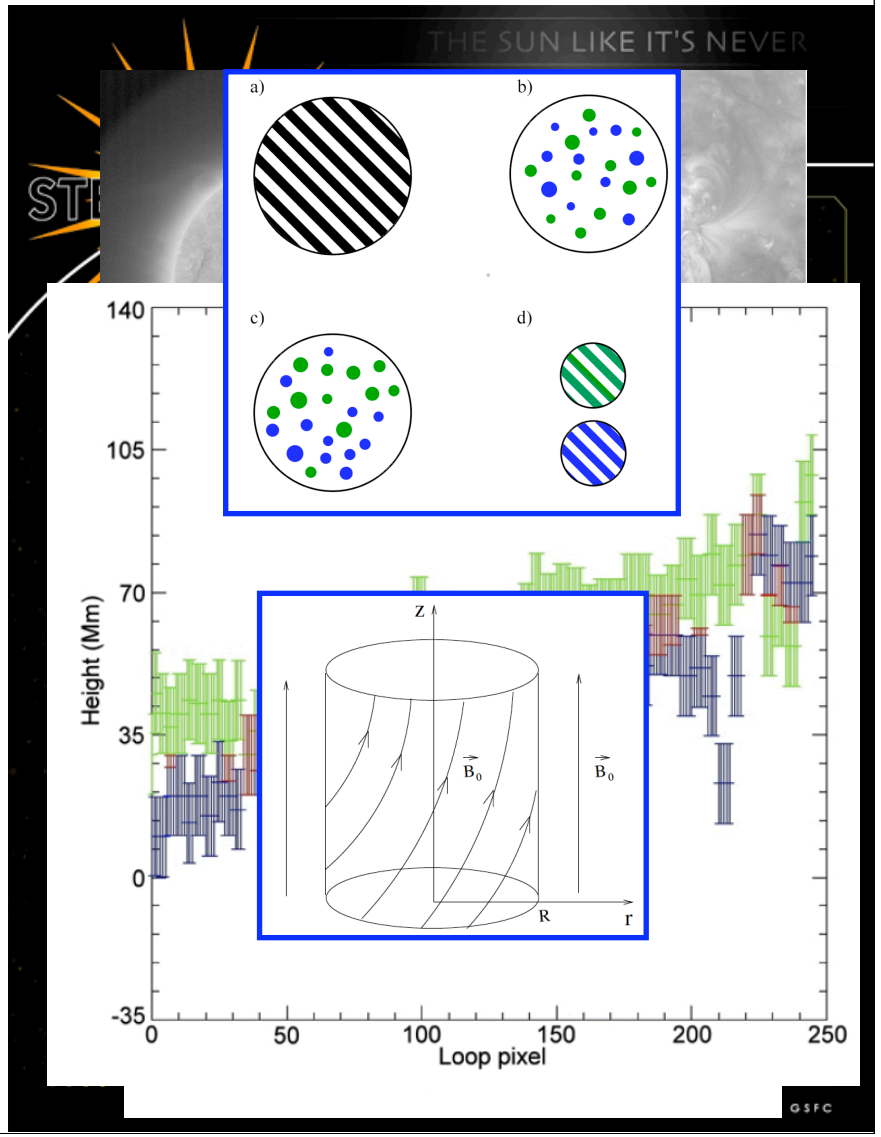
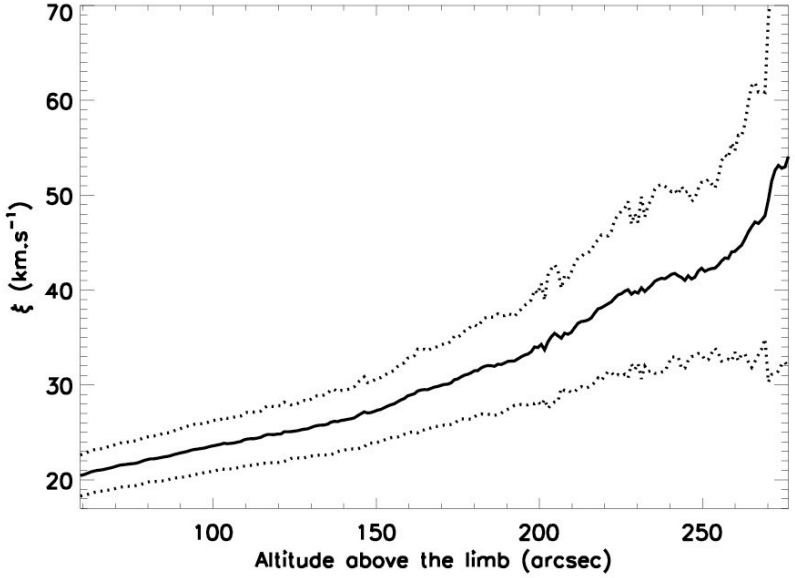
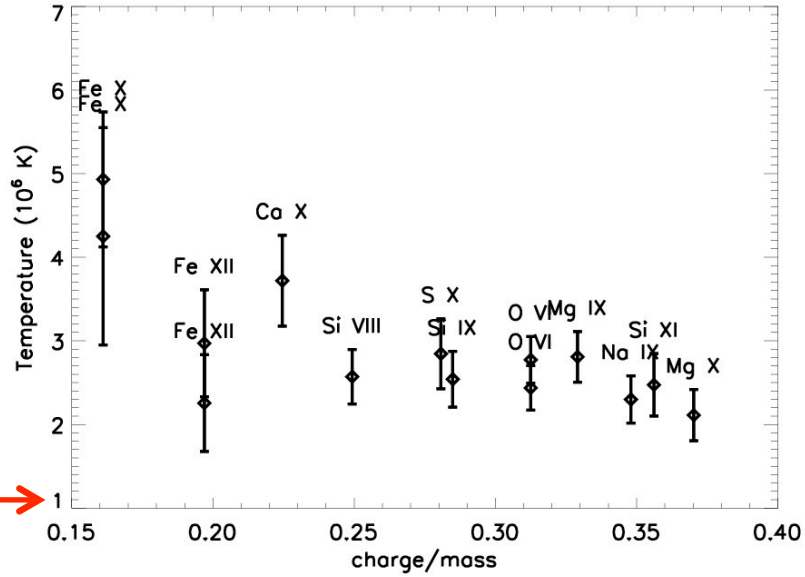


Spectroscopic diagnostics of the nascent solar wind in coronal holes

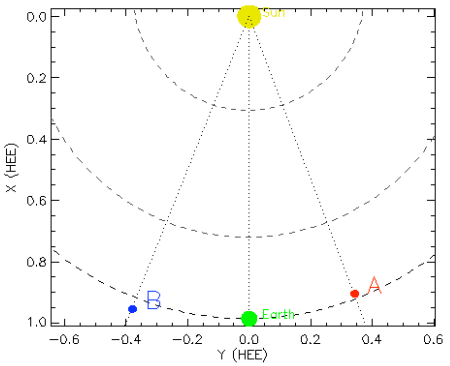
- Coronal lines are broadened by thermal and "non-thermal" (integrated bulk motions along the line-of-sight) Doppler effects, which are difficult to disentangle.
- It was found that ions are hotter than electrons and exhibit some signature of preferential heating of species with low charge-to-mass ratio.
- This may be a signature of ion-cyclotron resonance – a possible source of energy for the solar wind *(Dolla & Solomon, 2009)*.

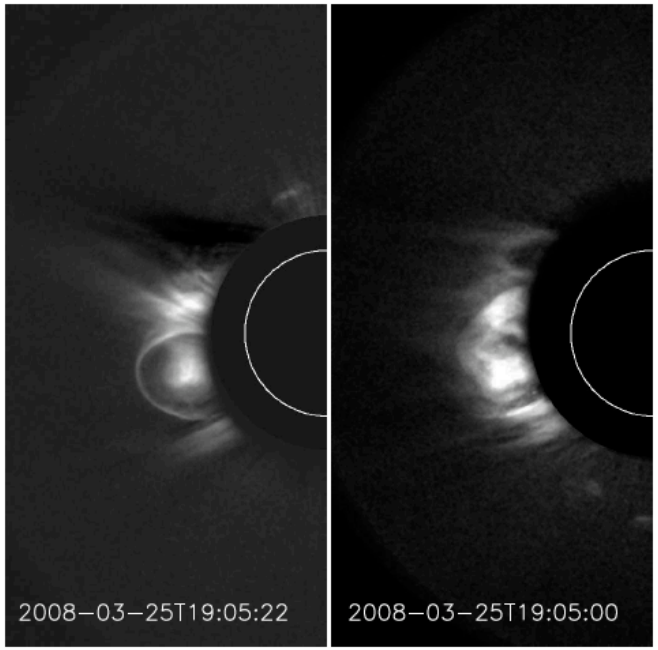




Electron temperature →

3D structure of CMEs





- Comparison of different techniques used to reconstruct the 3D structure of CMEs on the base of STEREO/SECCHI data
  (Mierla, Inhester, Marqué, Rodriguez, Gissot, Zhukov, Berghmans, Davila 2009).

- A review of different reconstruction techniques was compiled in the framework of the international collaboration
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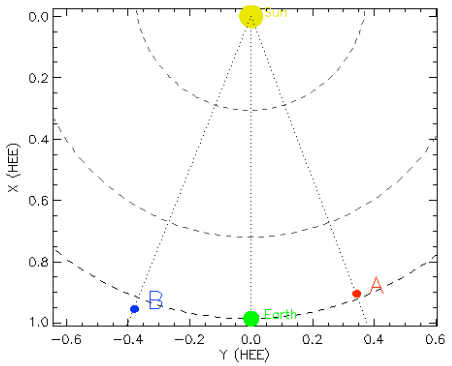
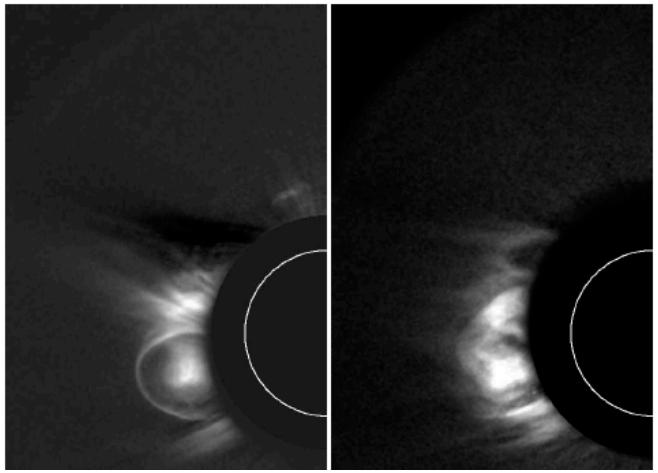
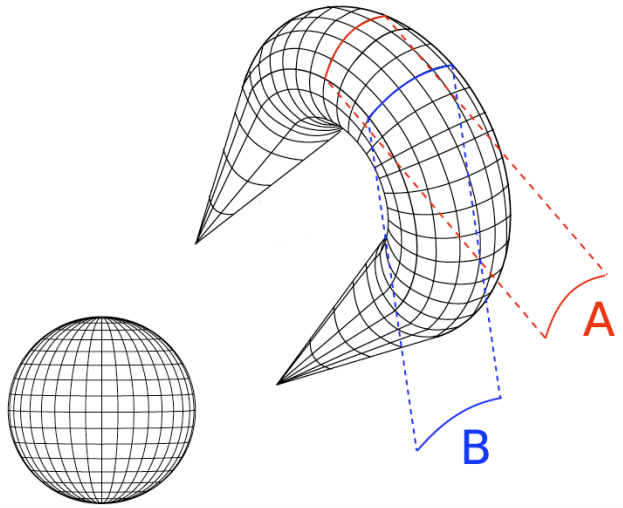


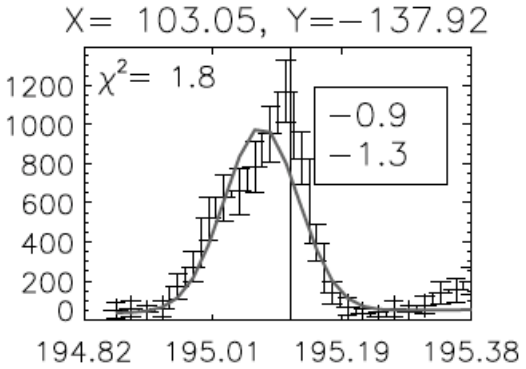


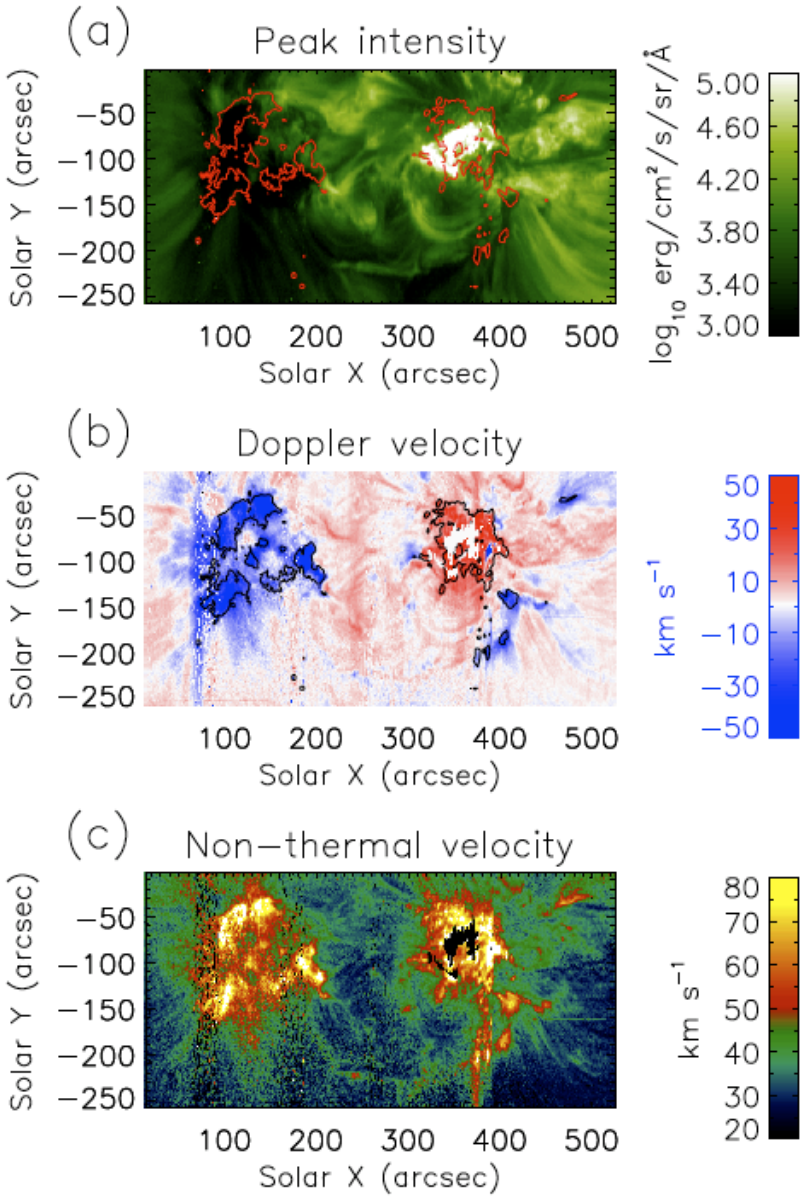


Plasma dynamics in the low corona during CMEs: dimmings

- Coronal dimmings exhibit blue-shifted line profiles due to the outflow of the coronal mass during a CME.

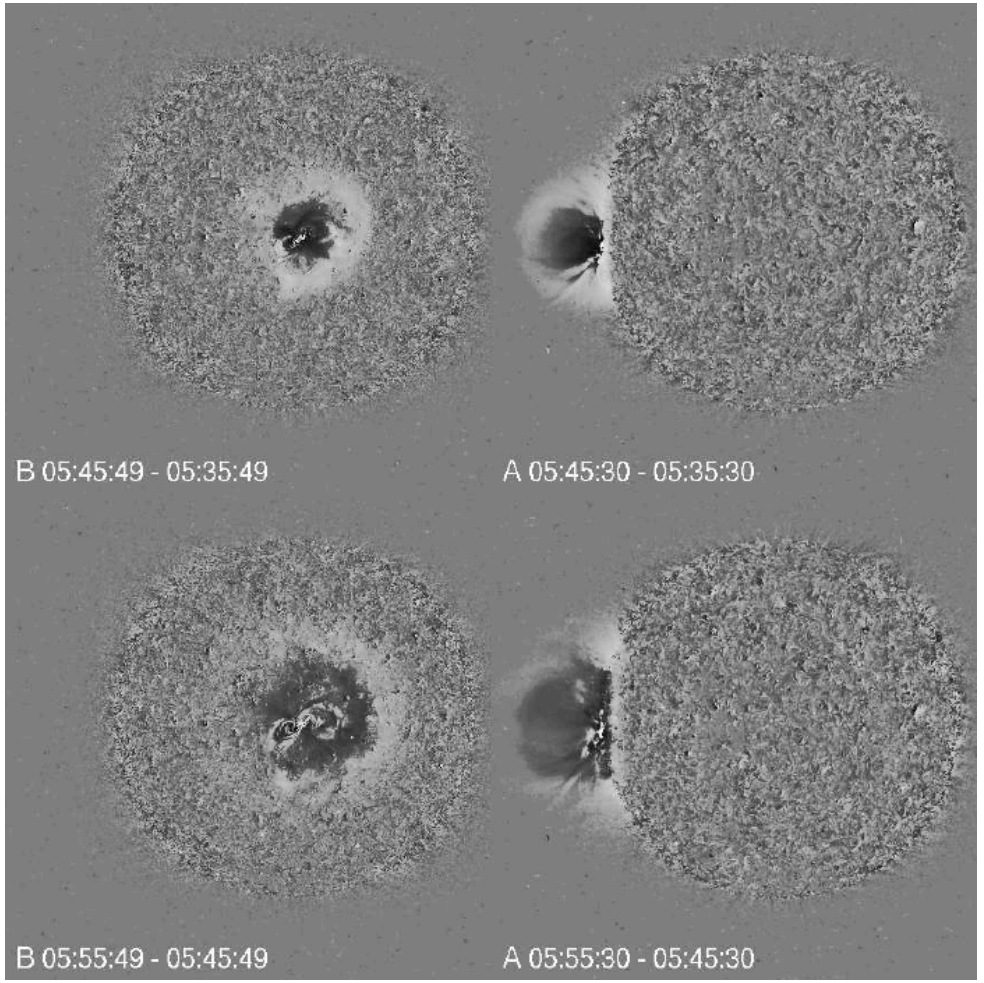
- These line profiles are often asymmetric! The asymmetry is produced by outflows with different speeds *(Dolla & Zhukov, 2010, submitted)*.



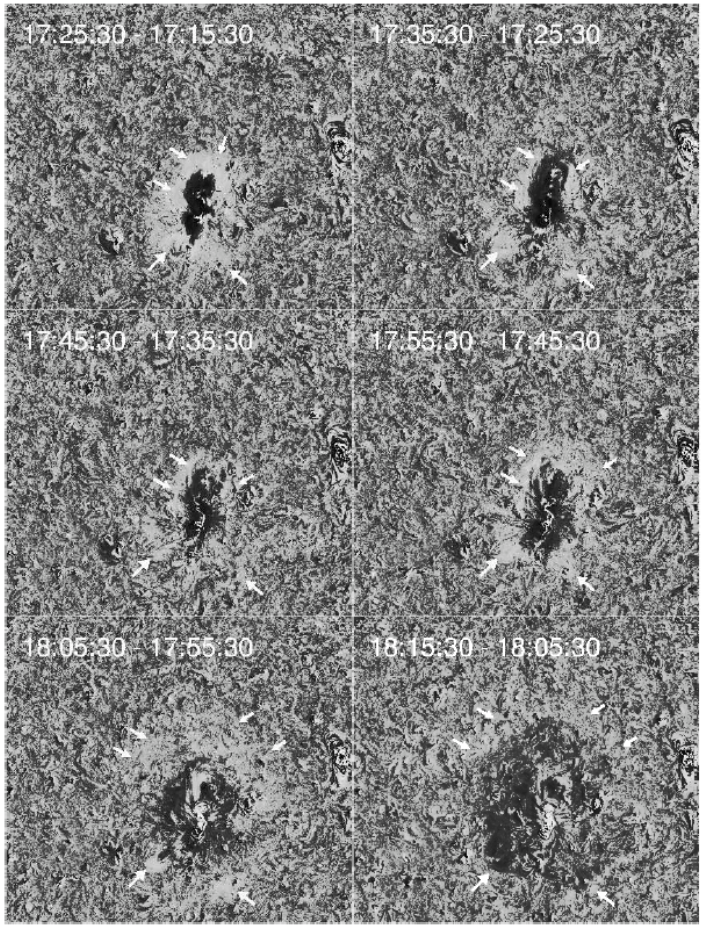


Plasma dynamics in the low corona during CMEs: "EIT waves"

- What is the physical nature of "EIT waves"?
  - Fast mode MHD waves
  - Successive "opening" of magnetic field lines (with plasma compression and/or heating) during the CME lift-off
  - Expanding electric current sheets at the boundary between the erupting flux rope and the ambient field
- A review on the physics of the "EIT wave" phenomenon was written *(Zhukov 2010, submitted)*.



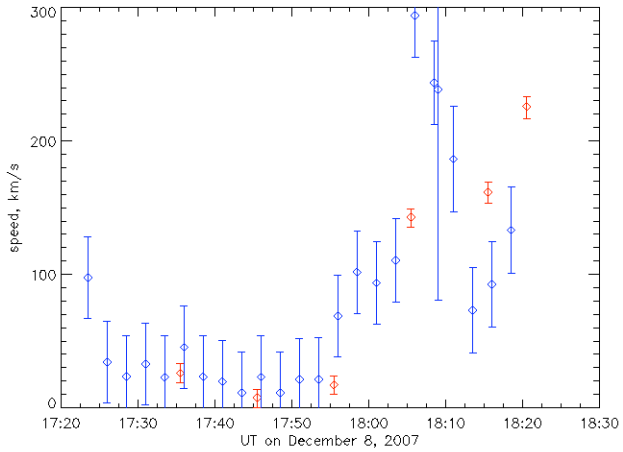
Physical mechanism of EIT waves



(Zhukov, Rodriguez, de Patoul, 2009)

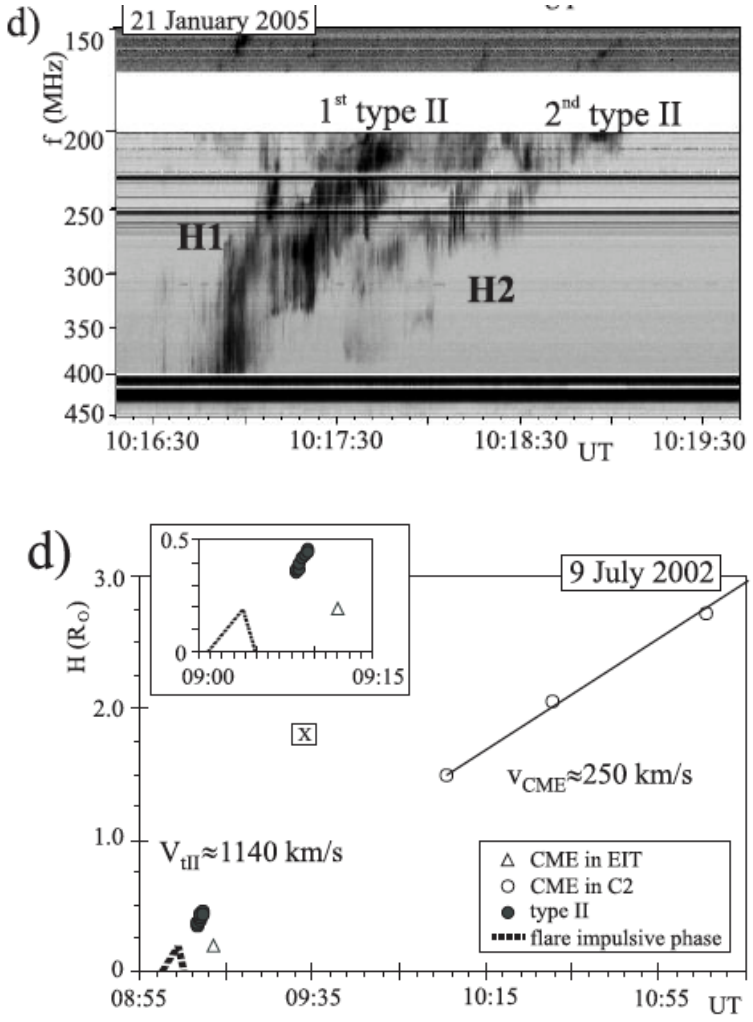
- An EIT wave with a peculiar velocity profile was found. Such a velocity profile is difficult to envisage for a true propagating MHD wave.

- This event presents an observational evidence that even EIT waves with a symmetric front can be produced by a magnetic field restructuring during the CME eruption.

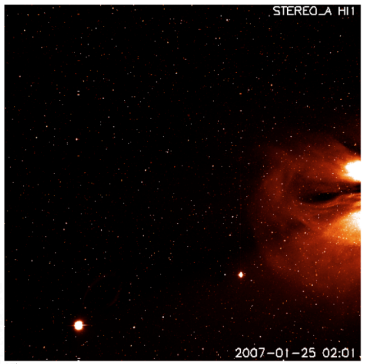


Plasma dynamics in the low corona during CMEs: coronal shock waves

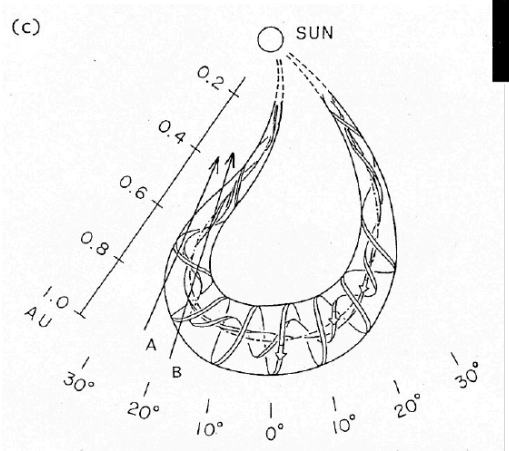
- The origin of coronal shock waves (observed as type II radio bursts) is still not clear.
- A detailed investigation of the kinematics of several shocks and associated CMEs shows up to a factor 4 difference between their speeds.
- Coronal shock waves can be produced by flares!
  (Magdalenić, Marqué, Zhukov et al., 2010, in press).

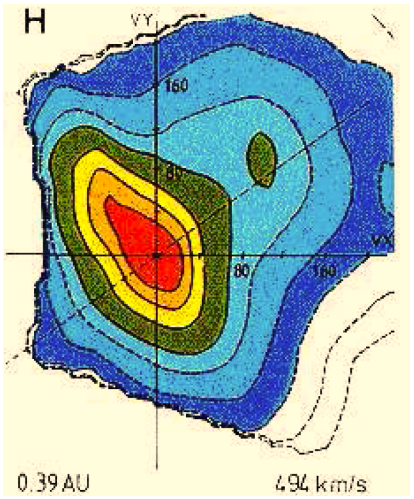


Solar Wind



- Macro-physics of the solar wind and the origin of its large-scale disturbances - interplanetary CMEs (ICMEs).
  - Linking CMEs with their counterparts in the solar wind and conditions for the CME geoeffectiveness.
- Micro-physics of the solar wind: field-aligned proton beams.



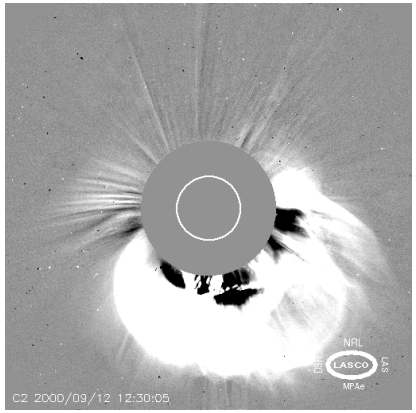


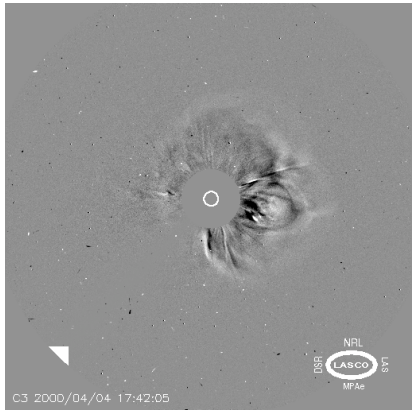
Connecting CMEs on the Sun with their counterparts in the solar wind

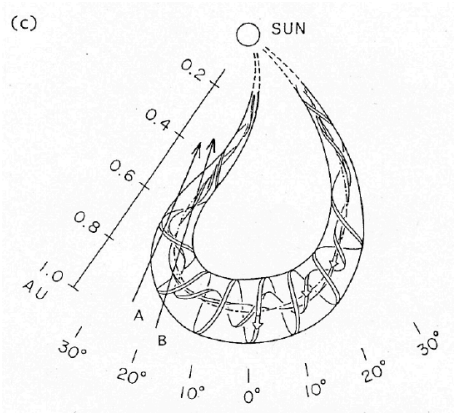
- Fast frontside full halo CMEs (presumably directed to the Earth) were investigated together with their geomagnetic response *(Rodriguez, Zhukov et al., 2009; Dasso et al., 2009)*.

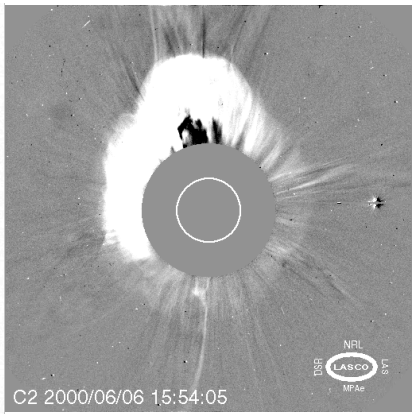
- The geomagnetic response of these CMEs may be very different: from no storm to major storm.

- Geometry of the ICME encounter with the Earth is the key! *(Rodriguez, Zhukov et al., 2009)*.





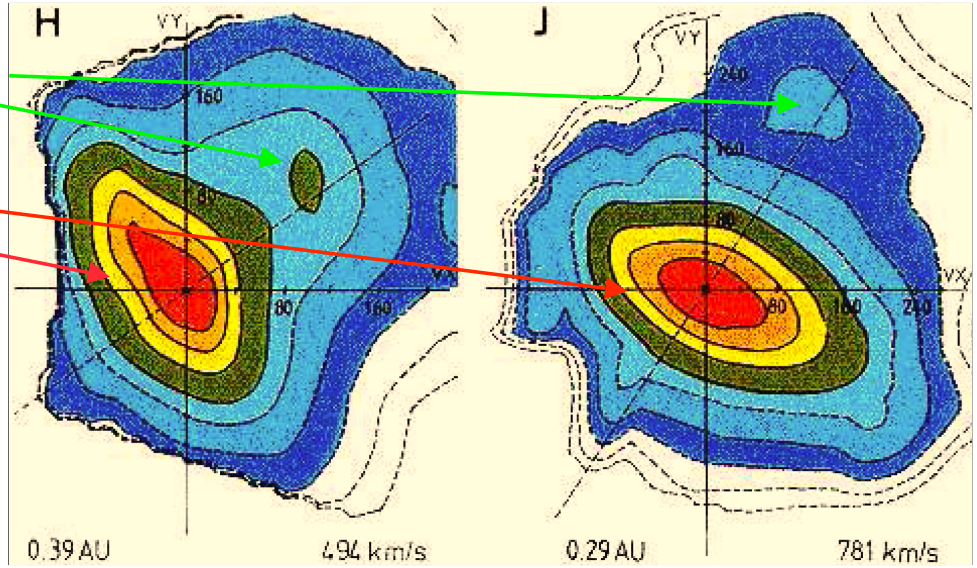




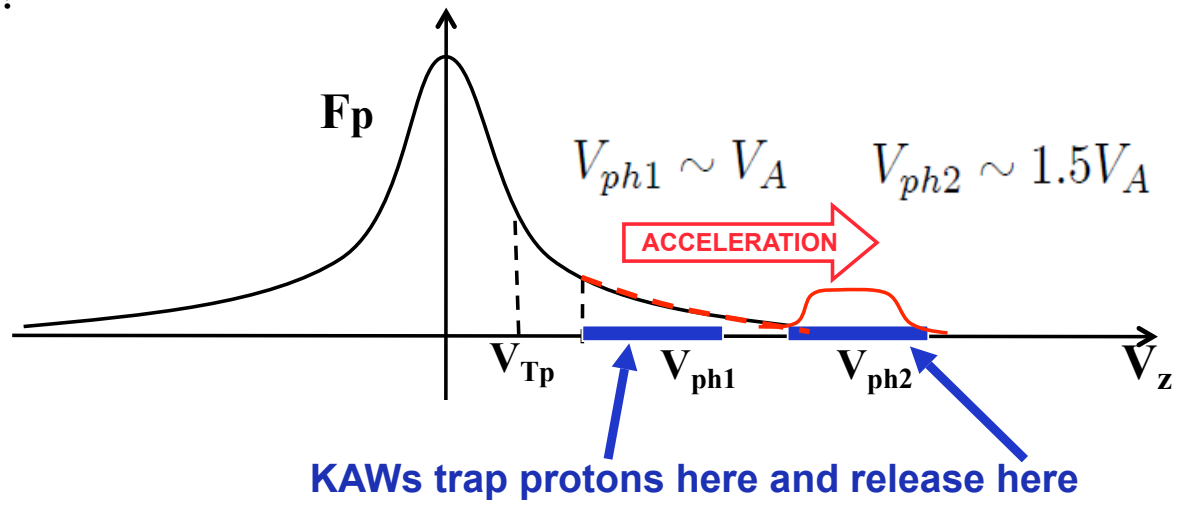
SOLAR WIND MICROPHYSICS

proton beams

anisotropic proton cores

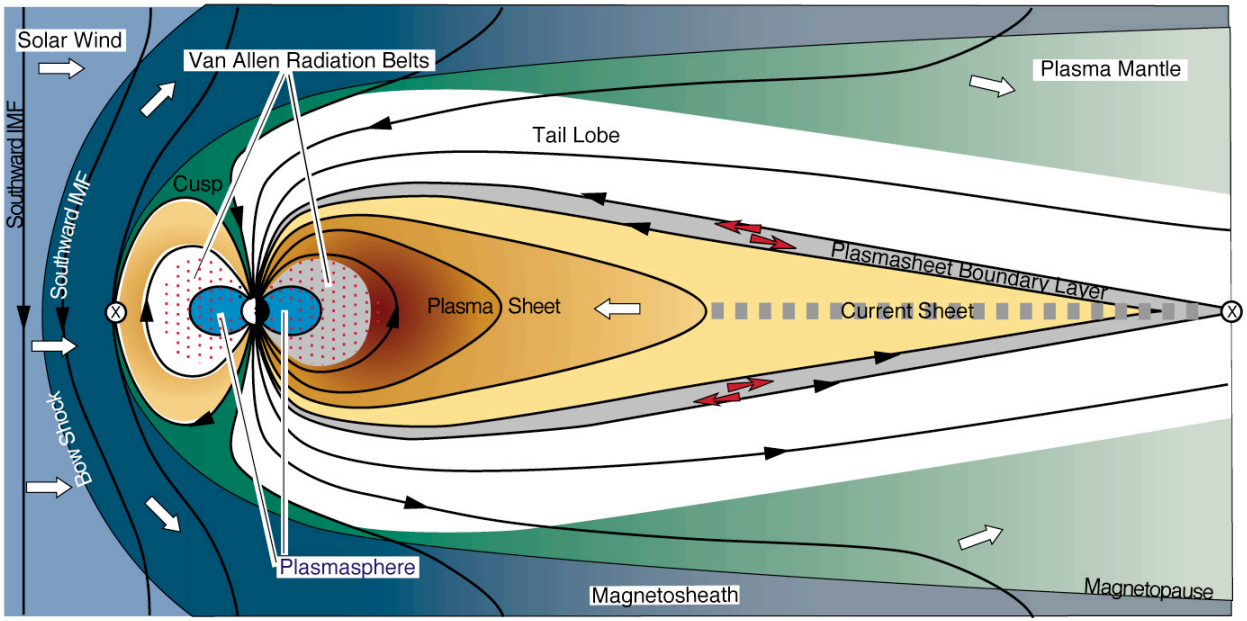


- What is the origin of field-aligned proton beams in the solar wind?
- Beams are driven by kinetic Alfven waves! *(Pierrard and Voitenko 2010).*



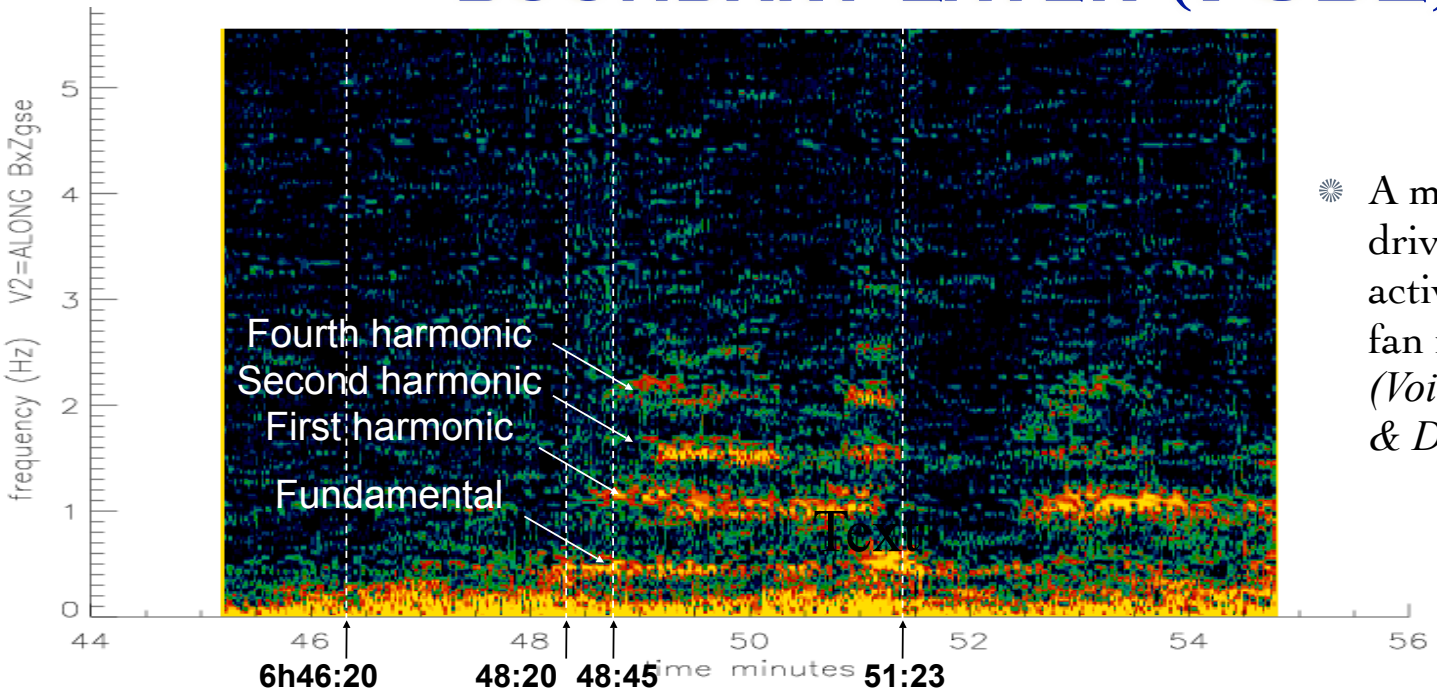
Formation of a super-Alfvenic proton beam

Magnetosphere



- Plasma sheet in the magnetotail
- Plasmasphere
- Acceleration of auroral electrons

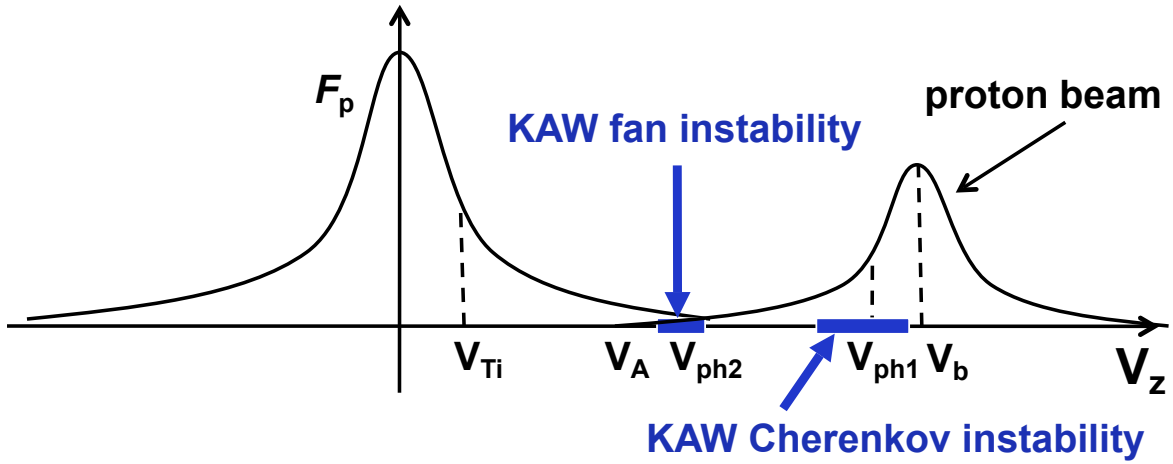
Wave activity in the plasma sheet boundary layer (PSBL)



- A model of beams driving the wave activity in PSBL by fan instability *(Voitenko, Maggiolo & De Keyser, 2009).*

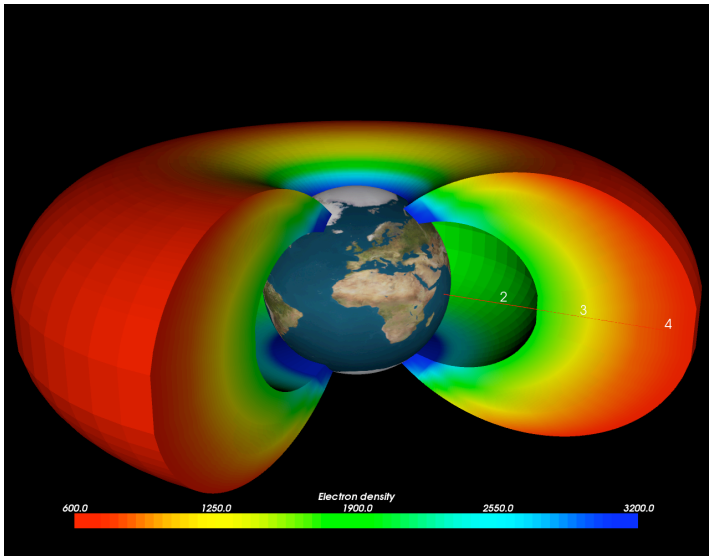
- Fundamental harmonic is identified as kinetic Alfven wave (KAW).

- Energy source is provided by proton beams that are observed by Cluster simultaneously with KAWs.



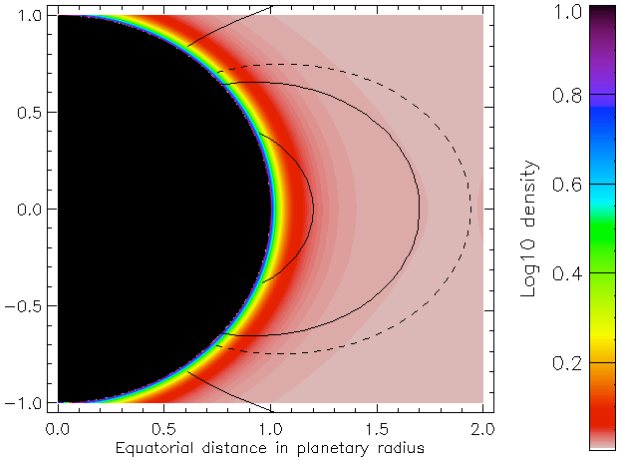
Advanced modeling of planets' exospheres

- Plasmasphere - ionosphere model *(Pierrard 2009a)*.
  - Development of a 3D dynamic model of the plasmasphere and its extension in the ionosphere.
  - Study of plasmasphere-radiation belts interactions.
  - Comparisons with observed TEC in the ionosphere are possible.

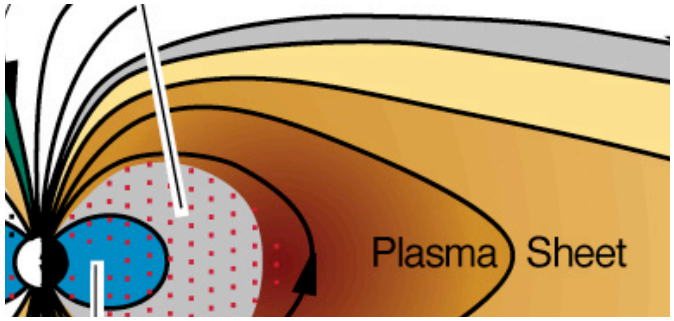


- Development of kinetic exospheric models for the exospheres (plasmasphere and polar wind) of Jupiter and Saturn *(Pierrard, 2009b)*.

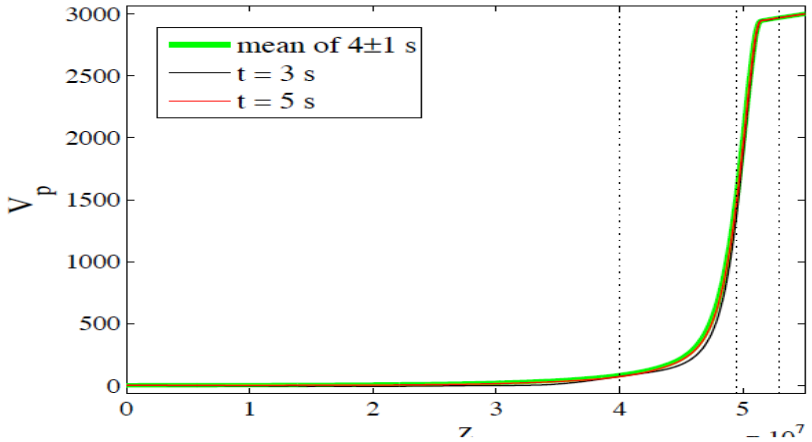
- A book for students was published *(Pierrard 2010)*.

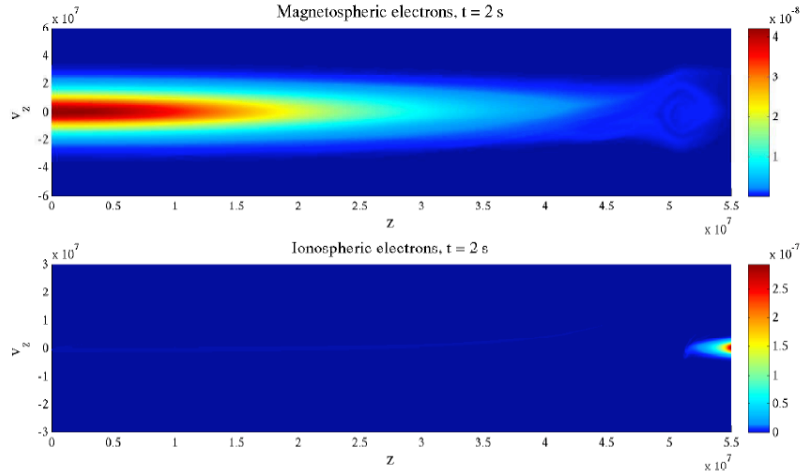


Acceleration of auroral electrons

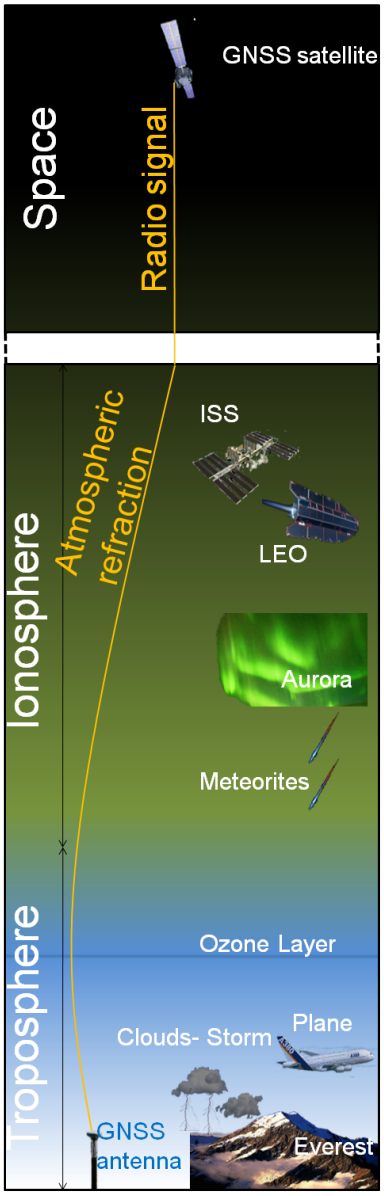


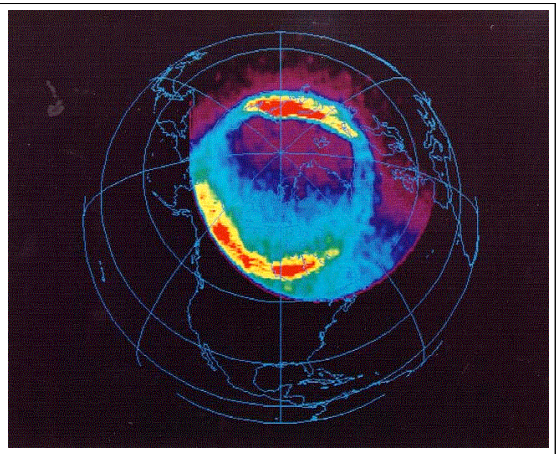
- A new model of auroral electron acceleration (at the potential difference between the magnetosphere and the ionosphere) was developed *(Gunell & De Keyser, 2010, in preparation)*.
- The test of this mechanism in a laboratory experiment was successfully modeled.





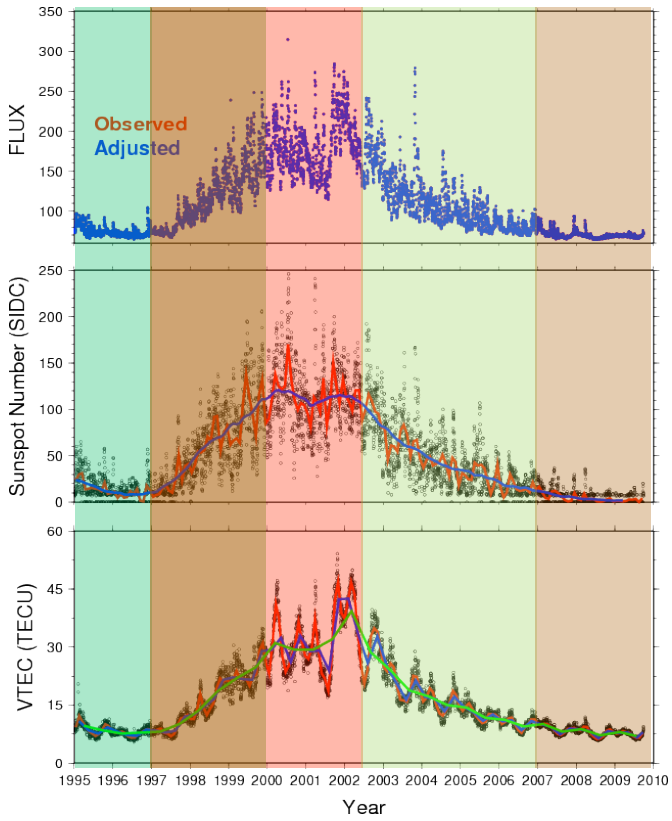
IONOSPHERE

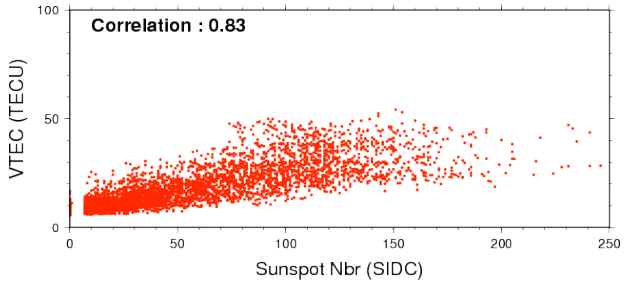




- Link of ionospheric disturbances (total electron content - TEC) with solar and geomagnetic activity.
- Influence of the ionosphere on the GNSS positioning and time transfer.

Link between solar and ionospheric parameters

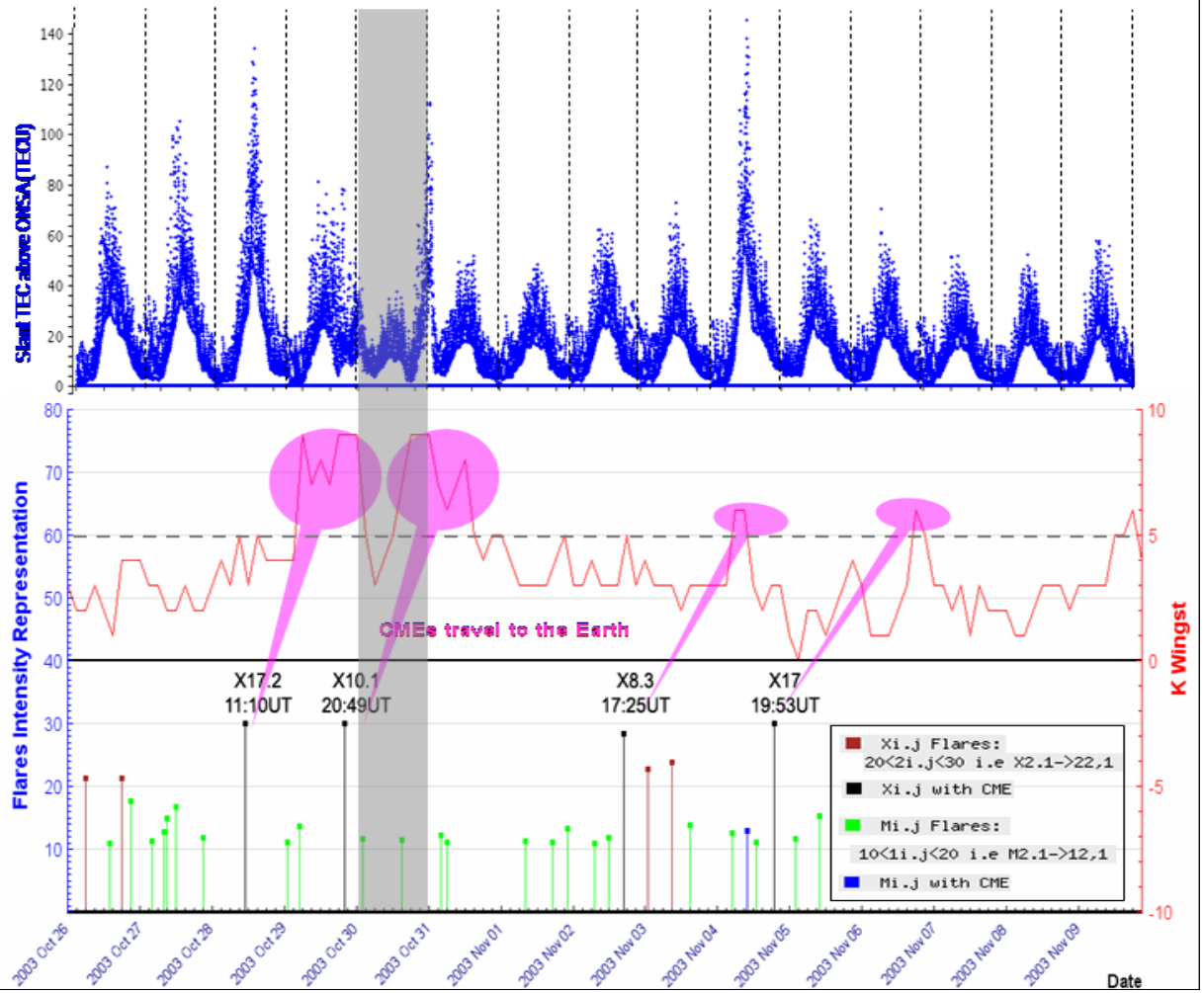




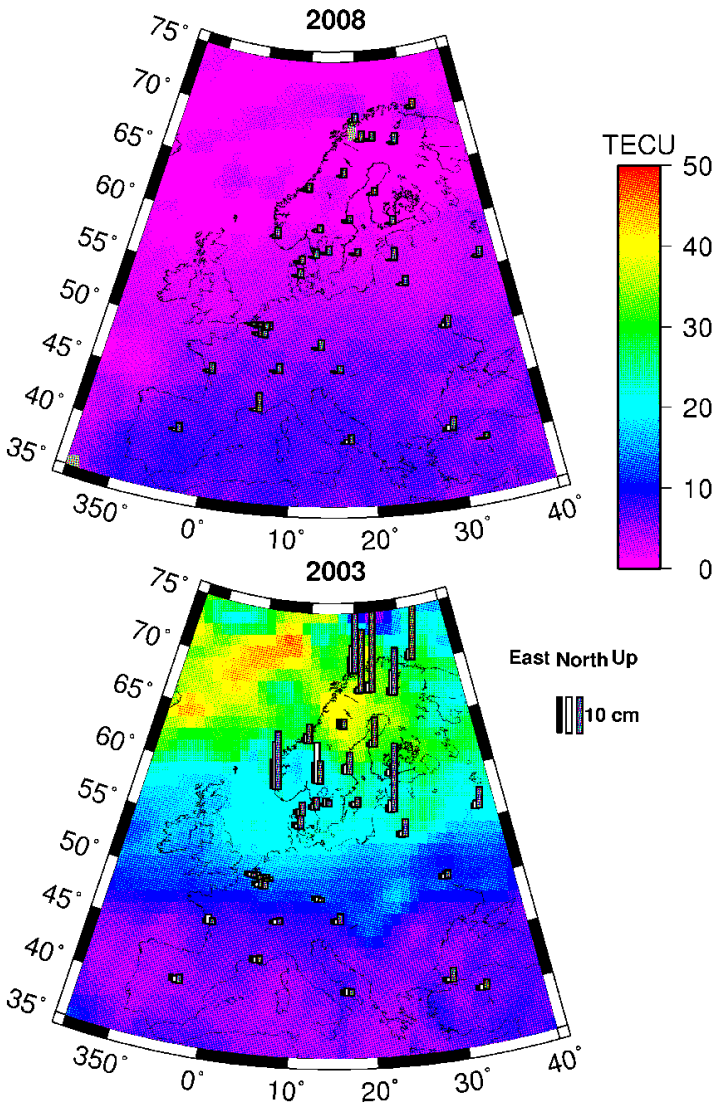
- Ionospheric disturbances are due to precipitation of particles accelerated during geomagnetic storms and to the convection of ionospheric plasma.
- There is a correlation between the daily international sunspot number and daily mean global vertical total electron content (VTEC).

TEC change during major geomagnetic storms

- TEC increases during major geomagnetic storms *(Pireaux et al., 2010, in press)*.

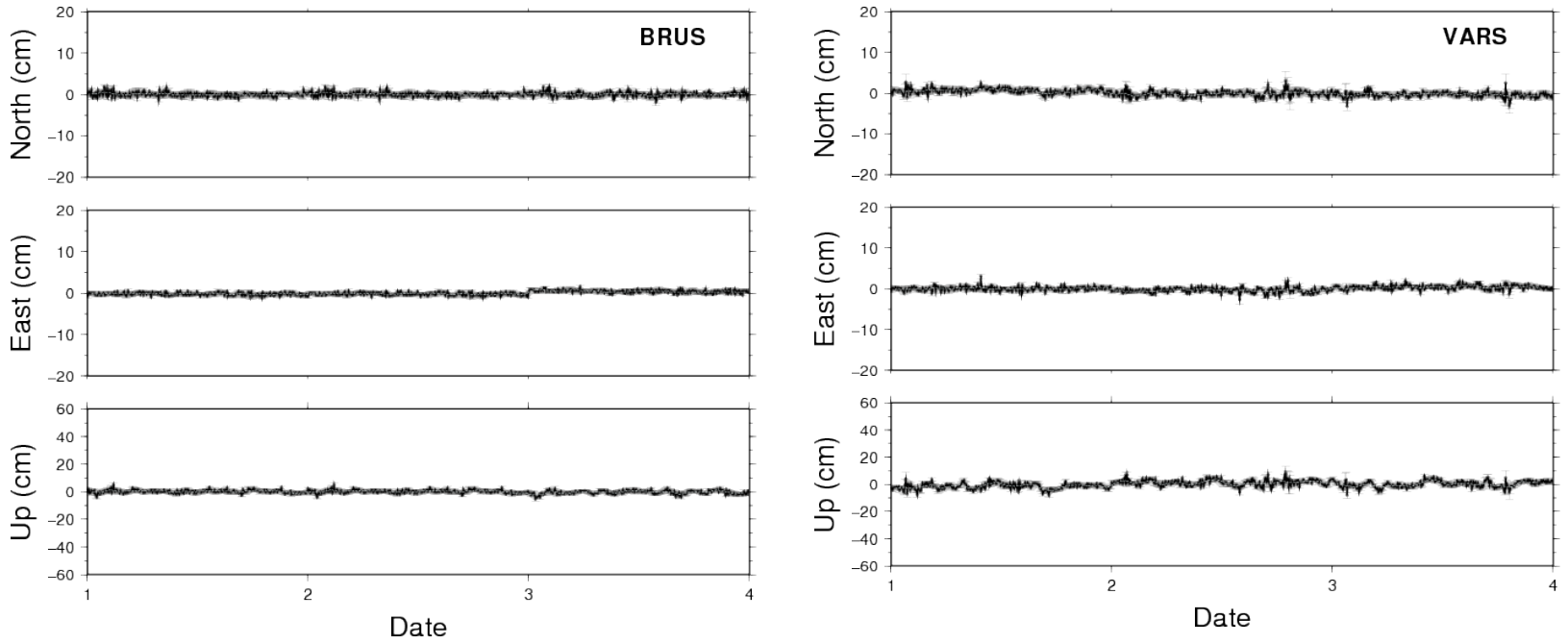


Ionosphere and Positioning



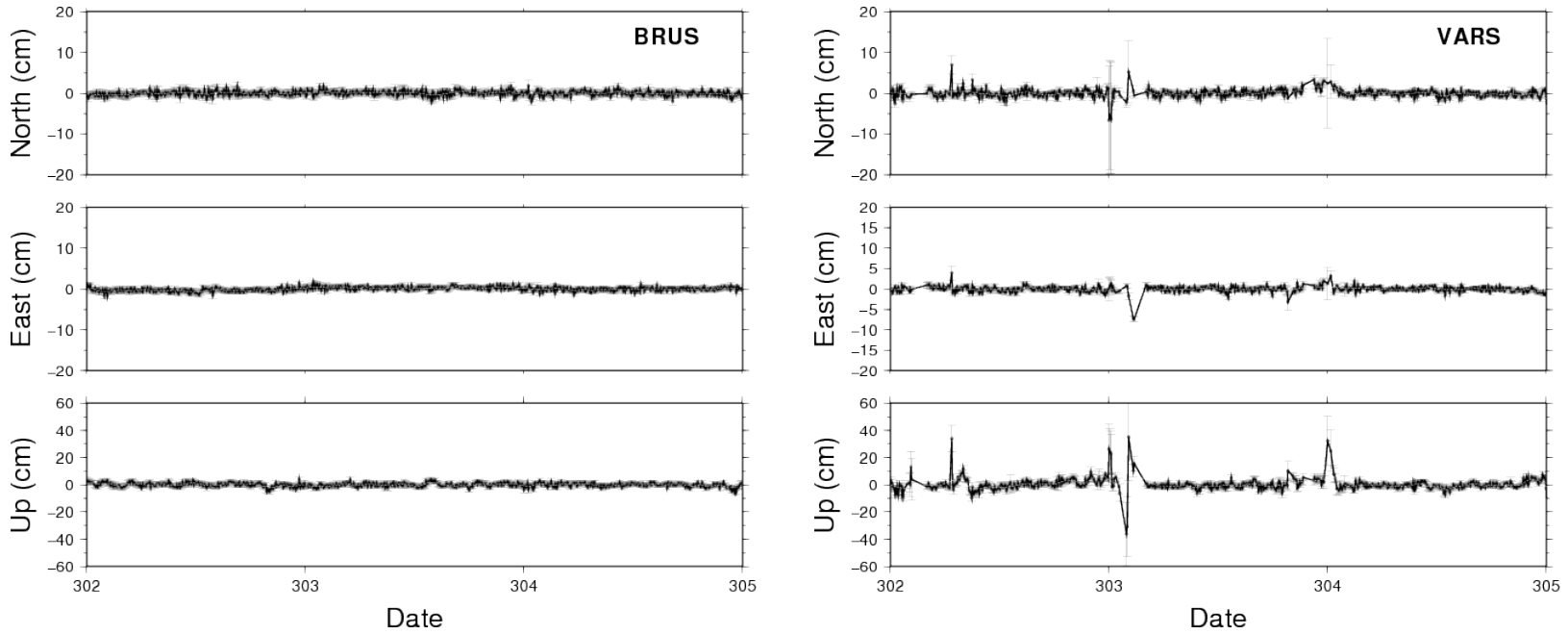
- TEC is shown both for quiet geomagnetic/ionospheric conditions (January 1, 2008 - upper panel) and for a severe geomagnetic storm (October 30, 2003 - bottom panel).
- The repeatability of the estimated positions is strongly degraded.
- Interaction between the ionosphere and troposphere is the subject of upcoming research.

January 2008 - low Ionospheric activity

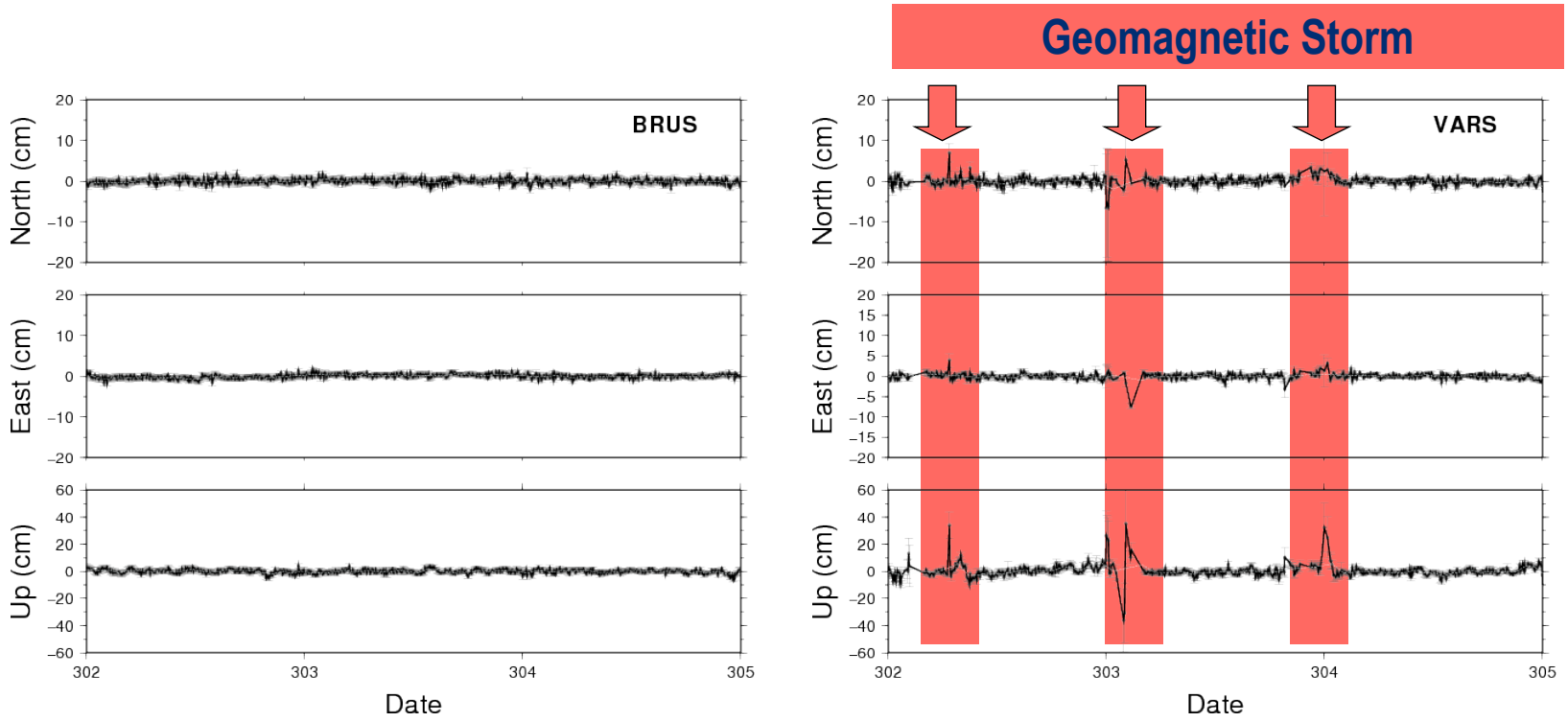


Impact of ionospheric disturbances on kinematic GNSS positioning

October 30, 2003 - a severe geomagnetic storm

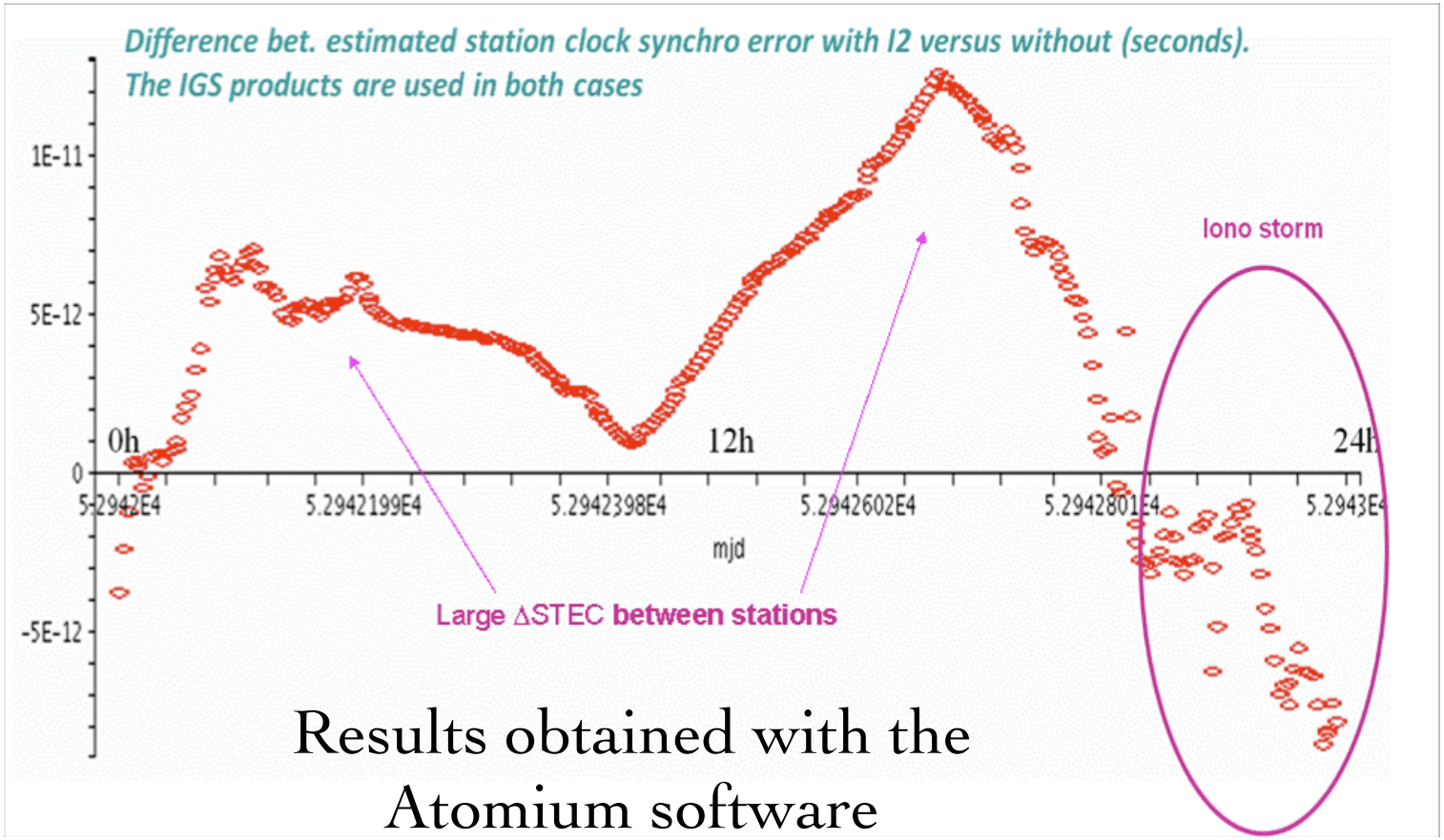


Impact of ionospheric disturbances on kinematic GNSS positioning



Impact of ionospheric disturbances on kinematic GNSS positioning

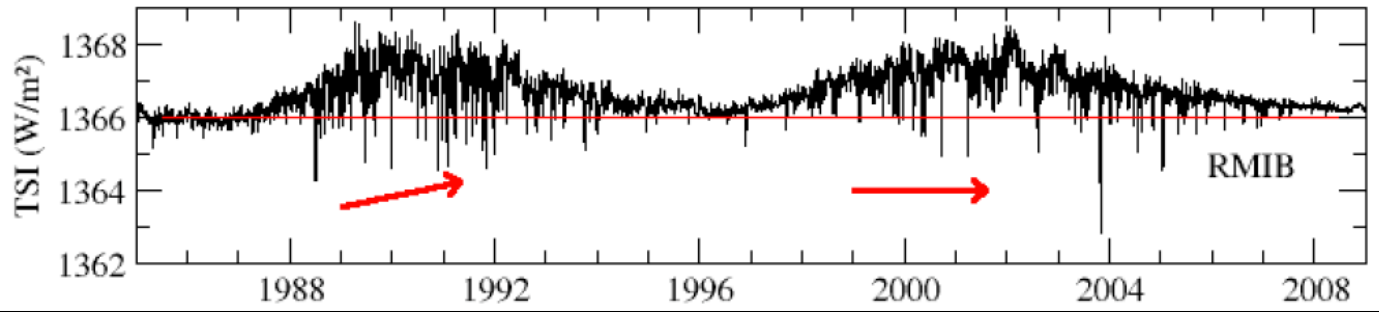
Impact of second-order ionospheric effects on long-baseline time transfer



Results obtained with the Atomium software

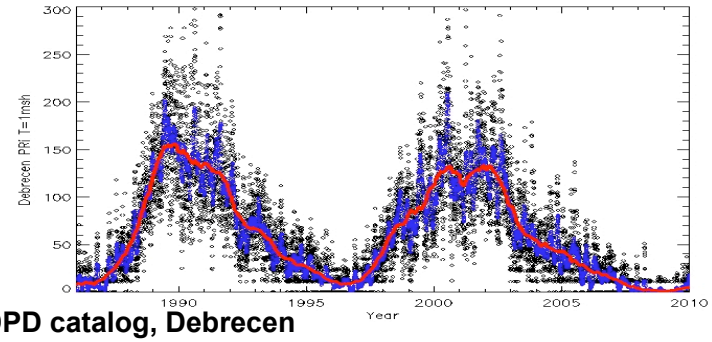
Long-term processes
(of the order of a solar cycle and beyond)

- Long-term behavior of the sunspot index.
- Measurements and modeling of the long-term changes of total solar irradiance (may be important for the Earth's climate).
- Studies of long-term variations of the concentration of the water vapor (one of the greenhouse gases) in the upper troposphere.
- Optical depth of aerosols and radiation transfer in the Earth's atmosphere.

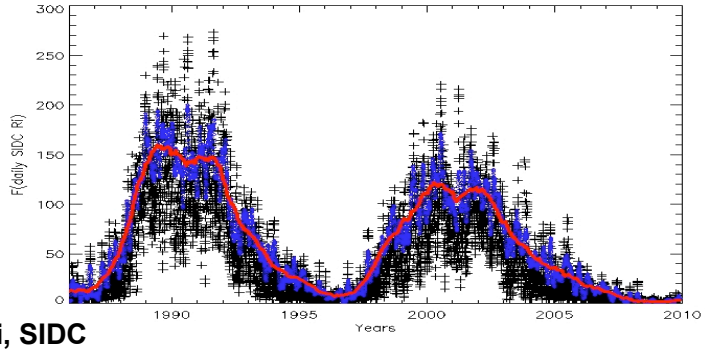


Visual sunspot observations by USET

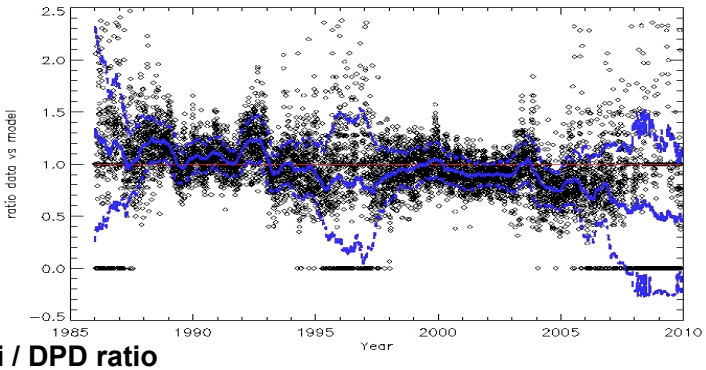
- Survey of past sunspot catalogs: contents, time coverage, compatibility.
- Validation of catalog contents (DPD catalog, Debrecen):
  - Group splitting
  - Effects of resolution limit: sunspot/pore distinction
- Investigation of catalog-based global activity indices:
  - Possibility to "play" with multiple parameters: data source, feature filters, size thresholds, etc.
  - Current target indices: international sunspot number, 10.7 cm solar radio flux.



DPD catalog, Debrecen



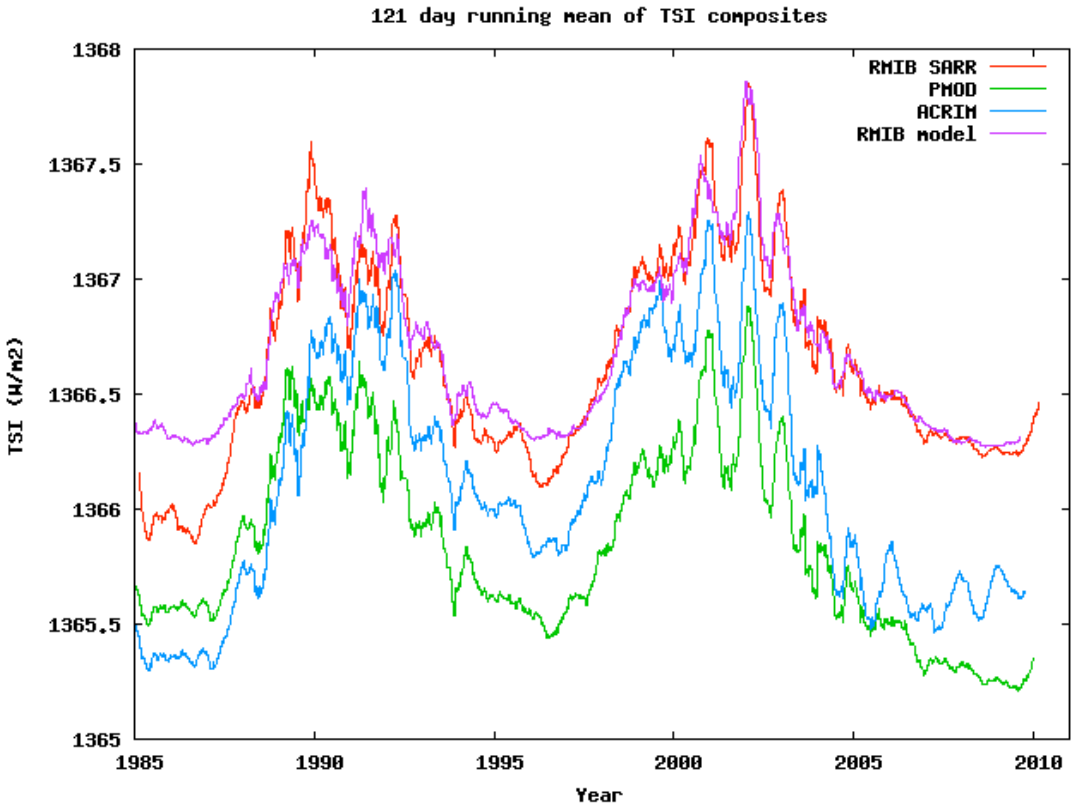
Ri, SIDC



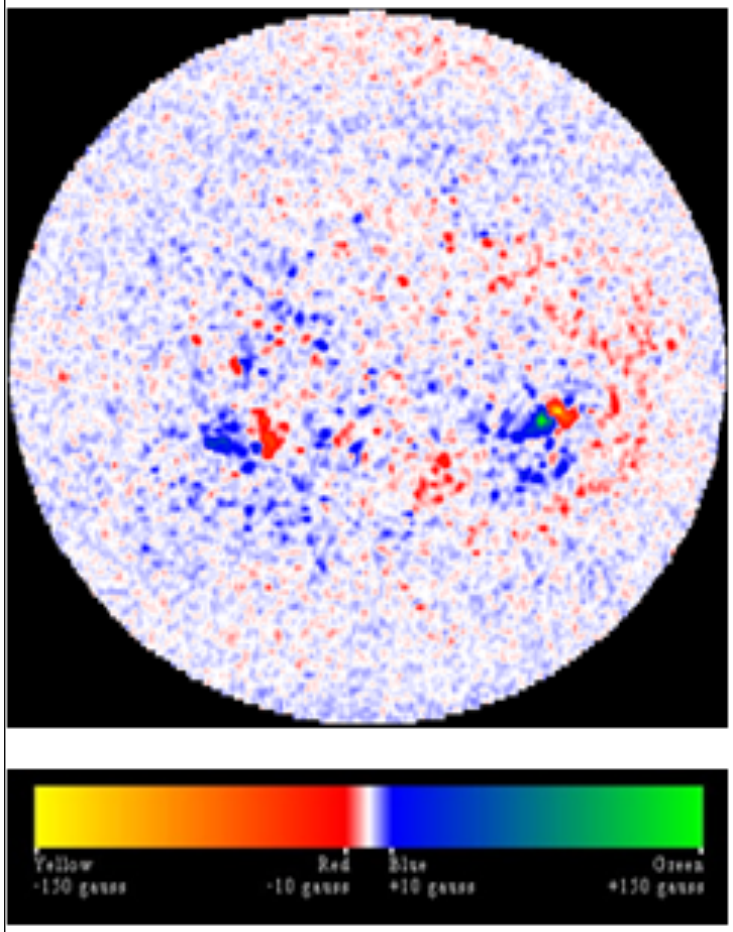
Ri / DPD ratio

Total solar irradiance (TSI) variations

- The long-term variation of the TSI is not clear. Did the recent prolonged solar minimum have a lower irradiance level than a standard minimum?
- The causes of solar irradiance variation are still debated.
- Measured irradiance variations were reconstructed from photospheric magnetic indices from the Mount Wilson Observatory *(Mekaoui & Dewitte, 2004).*

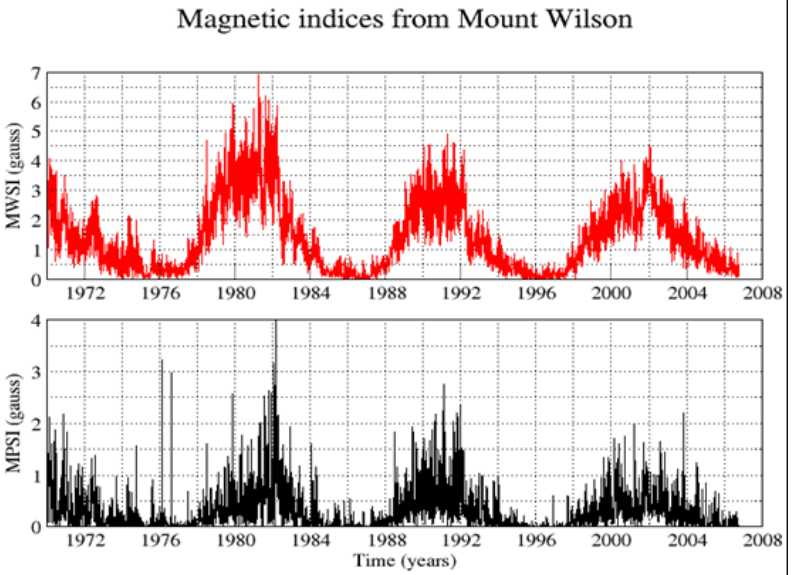


MAGNETIC INDICES FROM THE MOUNT WILSON OBSERVATORY



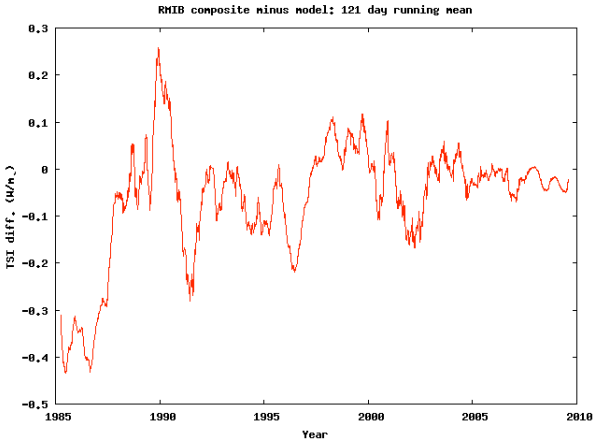
Mount Wilson sunspot index

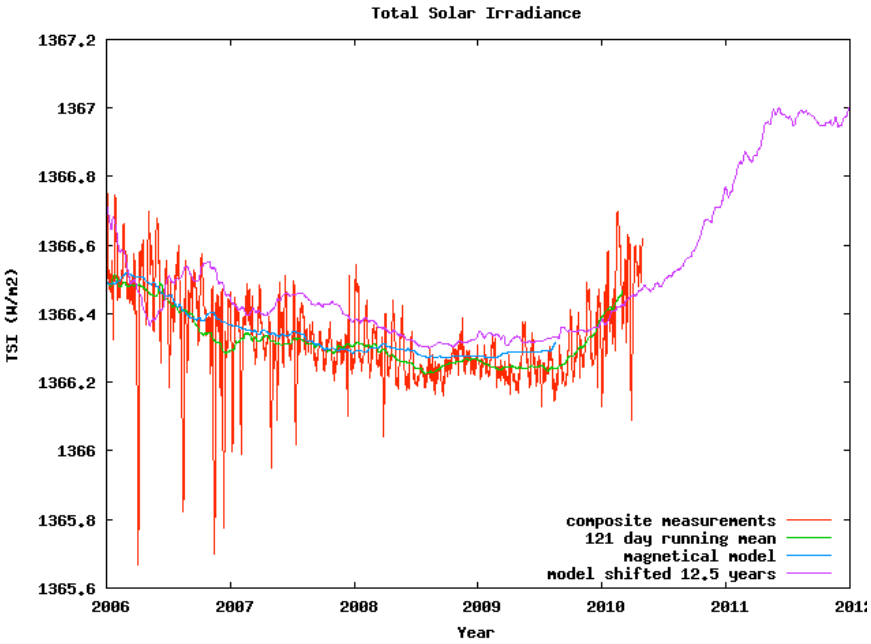
Magnetic plage strength index



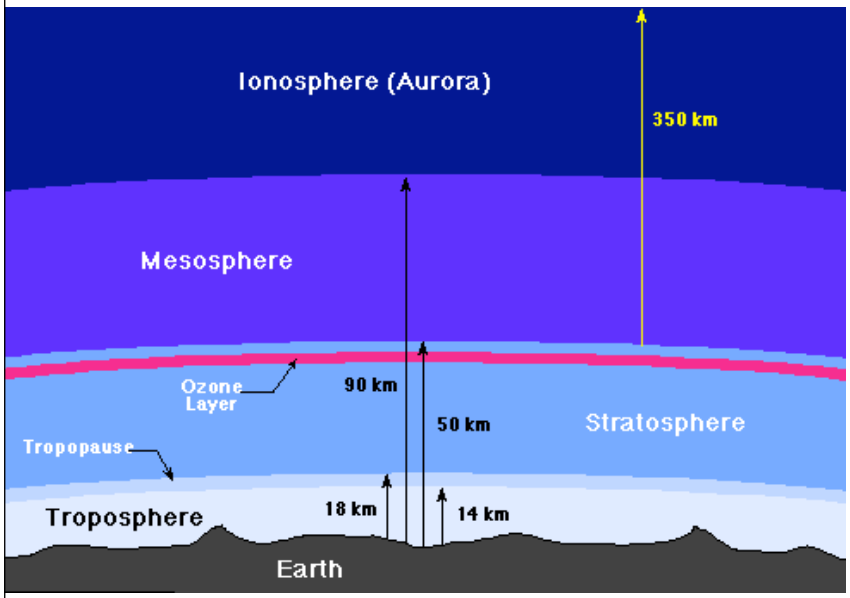
Total solar irradiance (TSI) variations

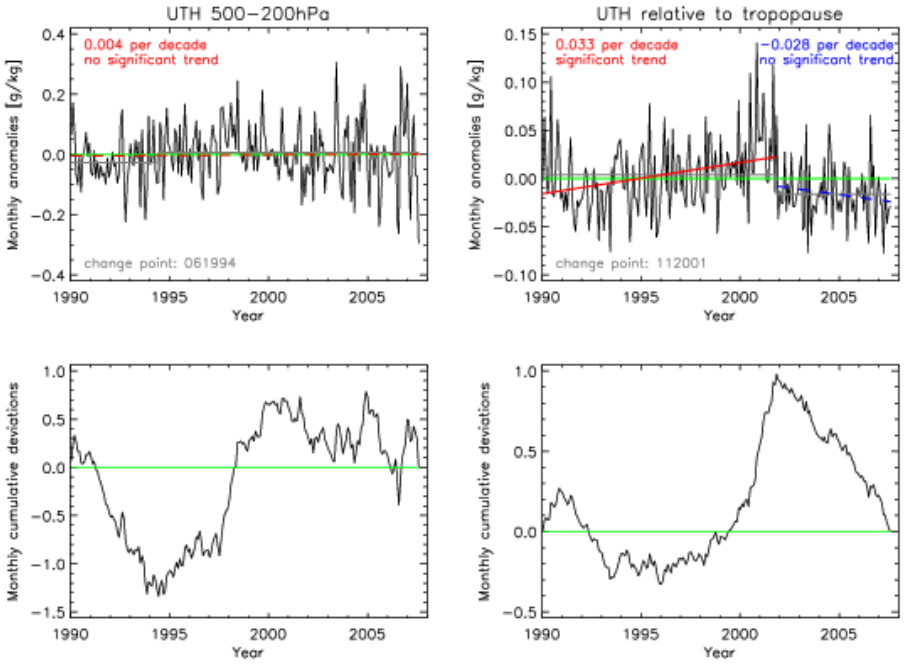
- Within the measurement uncertainty, the irradiance measurements can be fully reconstructed from photospheric magnetic fields.
- The last minimum irradiance was lower than usual because the magnetic field had more time to diffuse.





Long-term variations of the upper tropospheric humidity (UTH)



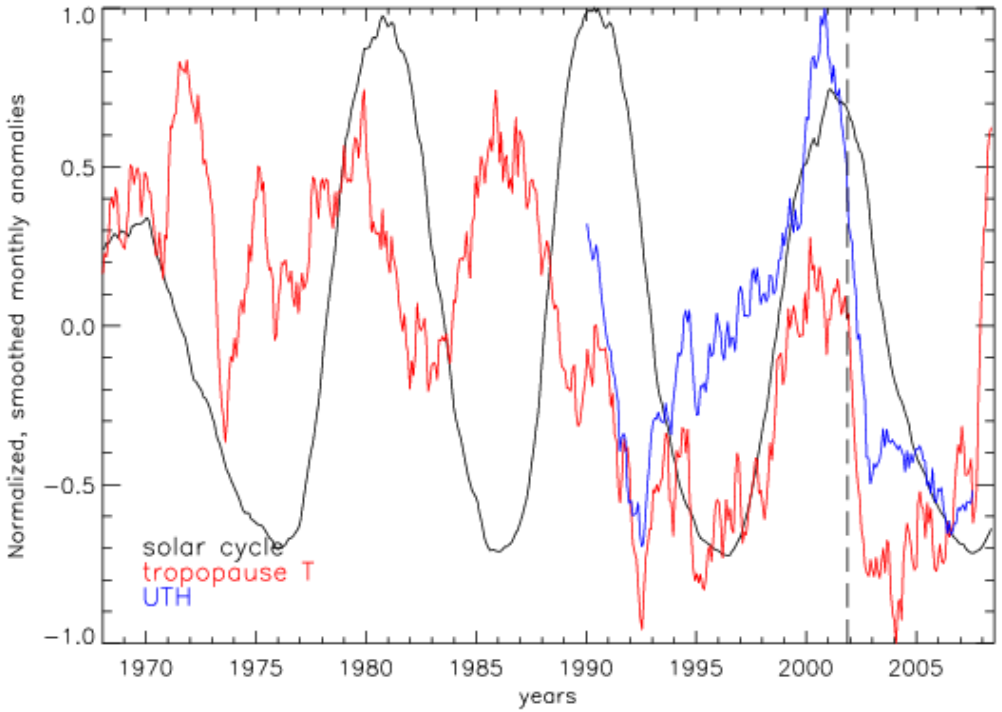


- Time series of water vapor concentration in the Upper Troposphere and Lower Stratosphere (UTLS) from balloon soundings has been analyzed for long-term changes.

- It was found that the trend changed around 2001: increasing humidity before, decreasing humidity after *(Van Malderen, De Backer & De Bock, 2010, in press).*

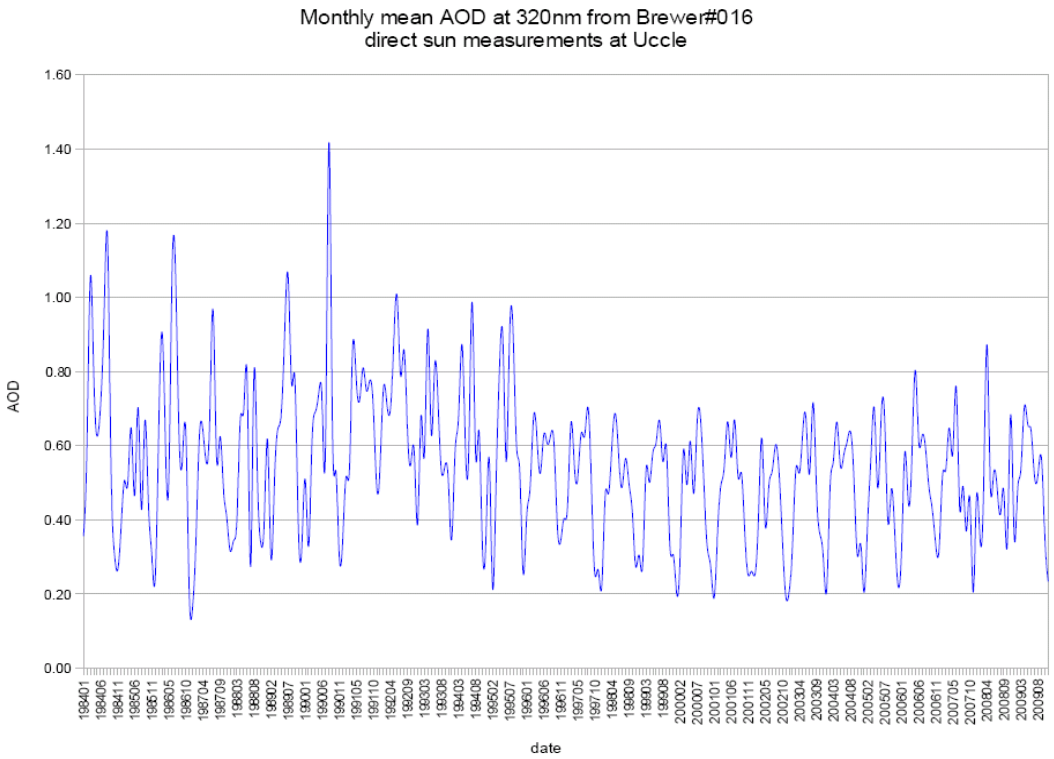
Relation between the UTH, tropopause temperature and the solar cycle

- Solar cycle 23 peaked in 2001, i.e. around the change of the UTH long-term trend.
- However, the upper tropospheric humidity, the tropopause temperature and the solar cycle are in phase only during the solar cycle 23.



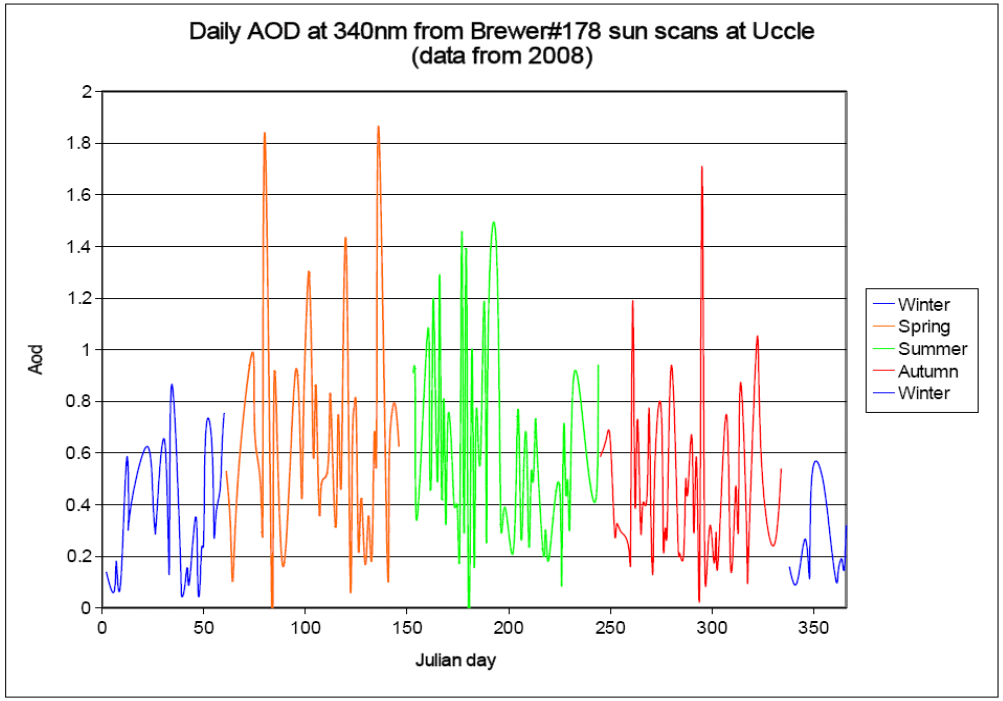
Measurements of the aerosol optical depth in the UV

- Atmospheric aerosols are another possible factor in the Earth's climate change.
- Aerosol optical depths (AOD) in the UV (320 nm) are retrieved from observations with the ozone spectrophotometer.



Measurements of the aerosol optical depth in the UV

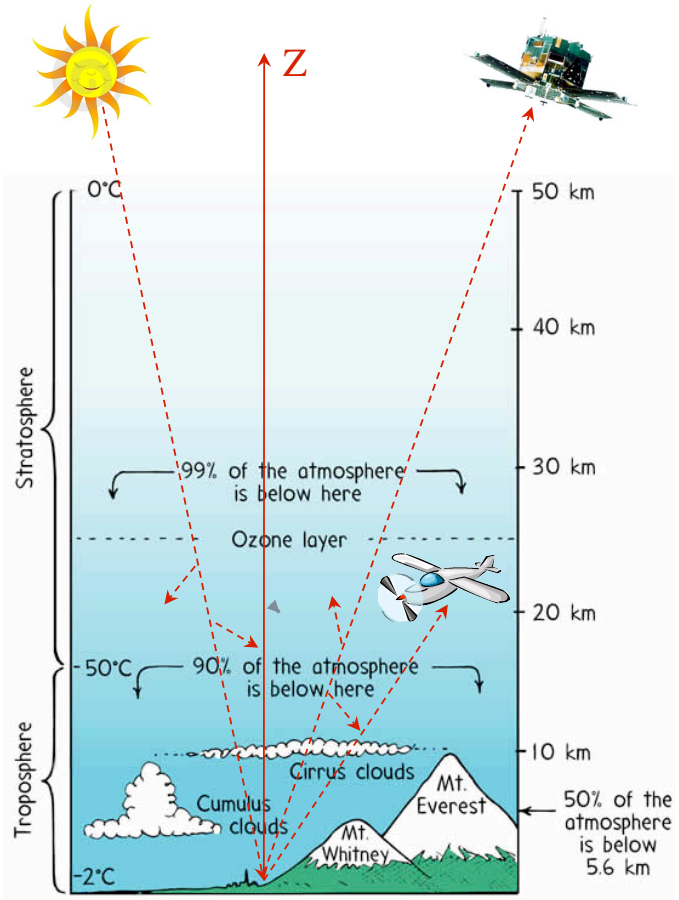
- A new type of observations with the ozone spectrophotometer was developed to determine the aerosol optical depth at 340 nm (wavelength also used in Aeronet network).
- Comparison with the new AOD retrieval method (Sun-scan measurements at 340 nm with CIMEL) is in progress.
- An improved automatic cloud-screening algorithm to be used in the AOD retrieval method is being developed.



- Advanced analyses of the time series of ozone will be performed, taking into account possible relations with the solar cycle, atmospheric circulation indices, and cosmic rays (Forbush decrease events).

Advanced Modeling of the Radiative Transfer in the Earth's Atmosphere

- The radiative transfer in the Earth's atmosphere is still not completely understood.
- A short-term goal is to create an advanced radiative transfer code capable of solving:
  - <u>the direct task:</u> simulation of remote sensing and ground-based measurements of the atmosphere on the base of known atmospheric parameters.
  - <u>the inverse task:</u> retrieval of gas and aerosol concentration profiles and other physical properties of the atmosphere.

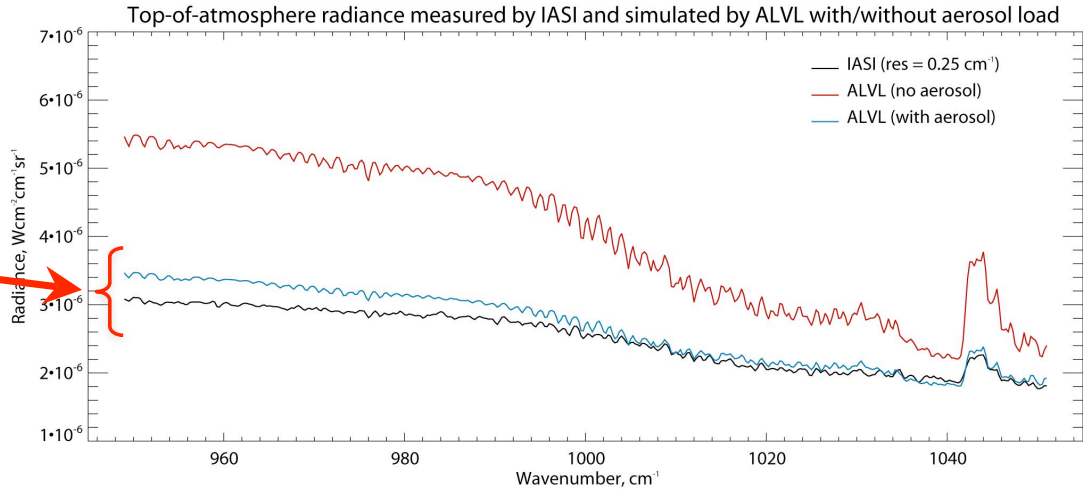


Influence of aerosols on the radiative transfer in the Earth's atmosphere

- The ALVL software package combining several different codes was created (*Kochenova et al., 2010*).
- The ALVL code is currently being successfully tested and validated.
- Using the ALVL code, one can retrieve aerosol parameters from the satellite data (early stage).

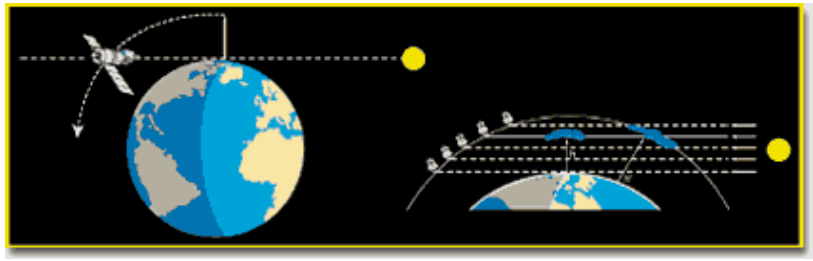
Infrared Atmospheric Sounding Interferometer (onboard METOP-A) data taken on April 15, 2010, near the Eyjafjallajökull volcano, Iceland.

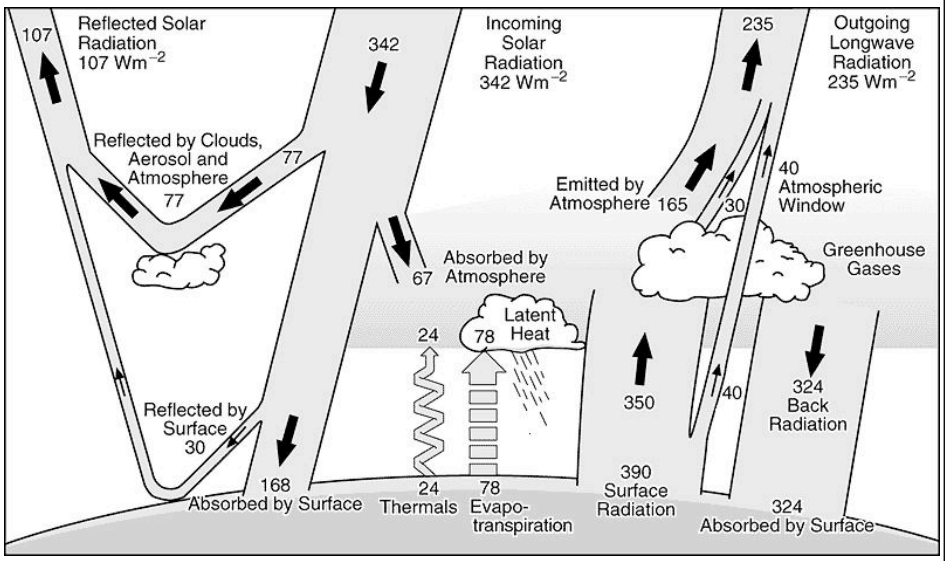
This difference is attributed to aerosol refractive indices which are quite difficult to predict correctly.



Advanced Modeling of the Radiative Transfer in the Earth's Atmosphere

- Advanced radiative transfer for limb measurements is under development.
- Advanced radiative transfer is time-consuming, especially in case of multiple scattering, thick aerosol loads and high-resolution line-by-line calculations.
- Retrieval of aerosol parameters with the help of the optimal estimation method.
- Use of ALVL to track the movement of volcanic, dust and biomass-burning aerosols.
- Possibility to use the ALVL code to simulate the Earth's radiation budget.





Summary and conclusions

- STCE is active in the research and modeling of nearly all of the components of the integrated Sun - Earth system.
- In 2009-2010, important new results were obtained in the physics of the solar atmosphere, solar wind, magnetosphere, thermosphere, ionosphere and troposphere, including space weather studies.
- A possible challenge for 2010 and beyond: to deepen further our coordinated research program in the field of solar-terrestrial physics.
- We are excited to be a part of the STCE and looking forward to continue our productive research!

Thank you for your attention!

Special thanks go to:

N. Bergeot, C. Bruyninx, R. Burston, F. Clette,
H. De Backer, J. De Keyser, P. Defraigne,
S. Dewitte, L. Dolla, H. Gunell, S. Kochenova,
R. Van Malderen, V. Pierrard, Y. Voitenko

and to all the STCE members who made this research possible.