Remote sensing of the Sun K-corona with the VIS polarimetric channel of the METIS coronagraph on-board Solar Orbiter

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e-COST Conference - Helsinki, 2013 August 19th

Summary

- ✓ The ESA Solar Orbiter Mission
- ✓ METIS scientific objectives
- ✓ METIS design
  - ✓ VIS and UV channels
  - ✓ The VIS light polarimetric path
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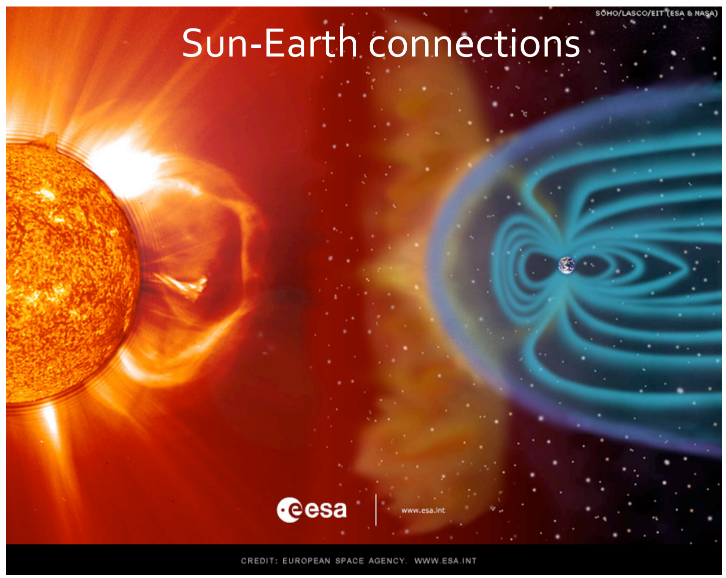
- ✓ METIS polarimetry
  - ✓ Deriving the VL polarized images Stokes parameters
  - ✓ Useful equations and matrices calculus
  - ✓ K-corona electron densities maps
- ✓ Conclusions
- ✓ References

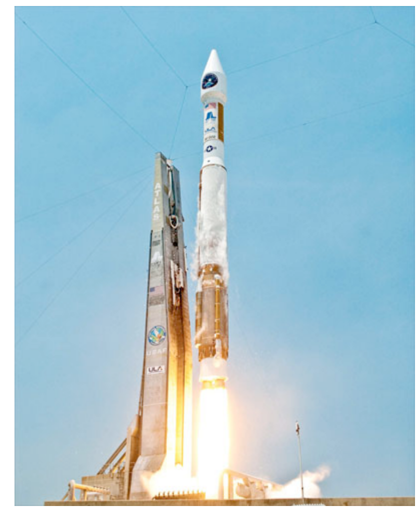
The Solar Orbiter Mission

Solar Orbiter is the first ESA M-missions class (~450 M€) selected to be flown as a part of the ESA Cosmic Vision 2015-25 program. It is conceived to refine our knowledge of how the inner solar system works and is driven by the solar activity.

European Space Agency
Agence spatiale européenne



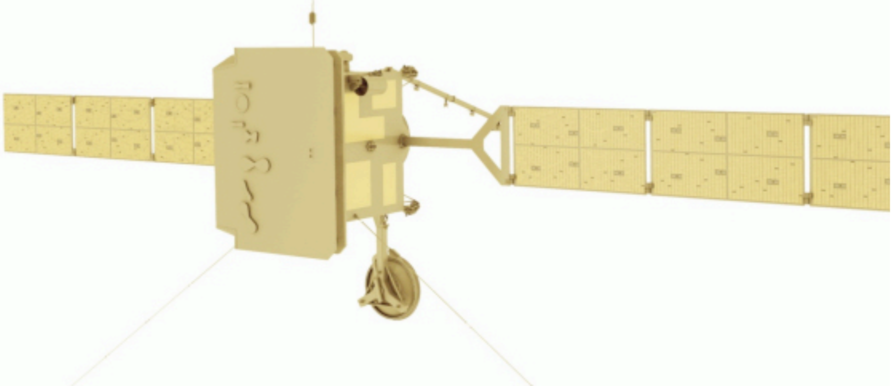
Atlas v-401

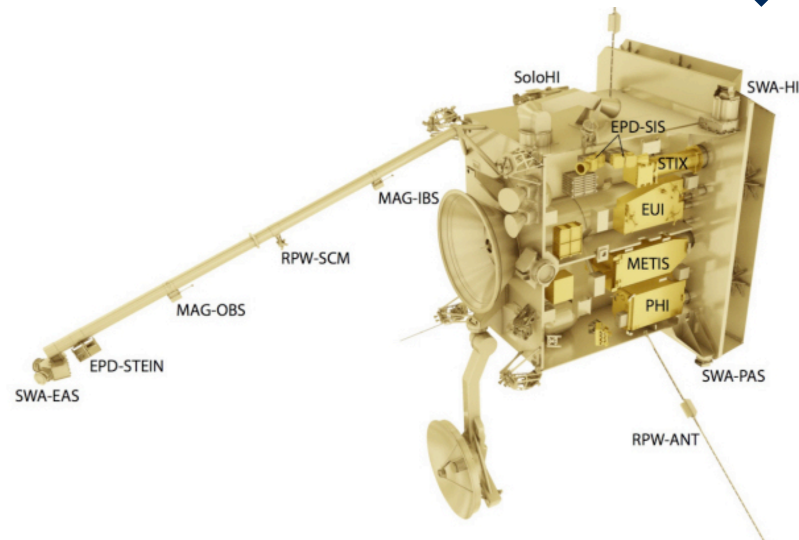


The main questions that define the scientific objectives of the Solar Orbiter mission are related to the origin and acceleration of **the slow and fast solar wind components**, to the **heliospheric variability**, and to the role of the **solar dynamo** in the physics of the heliosphere.

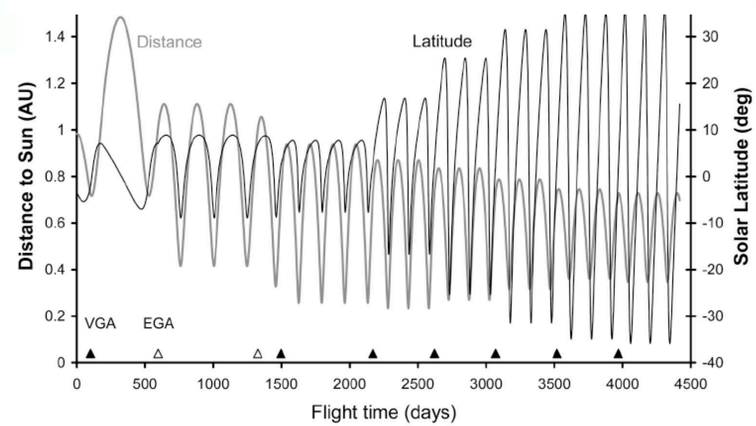
The Solar Orbiter Mission

Scheduled for launch in January 2017, the mission will provide **close-up, high-latitude observations of the Sun.**



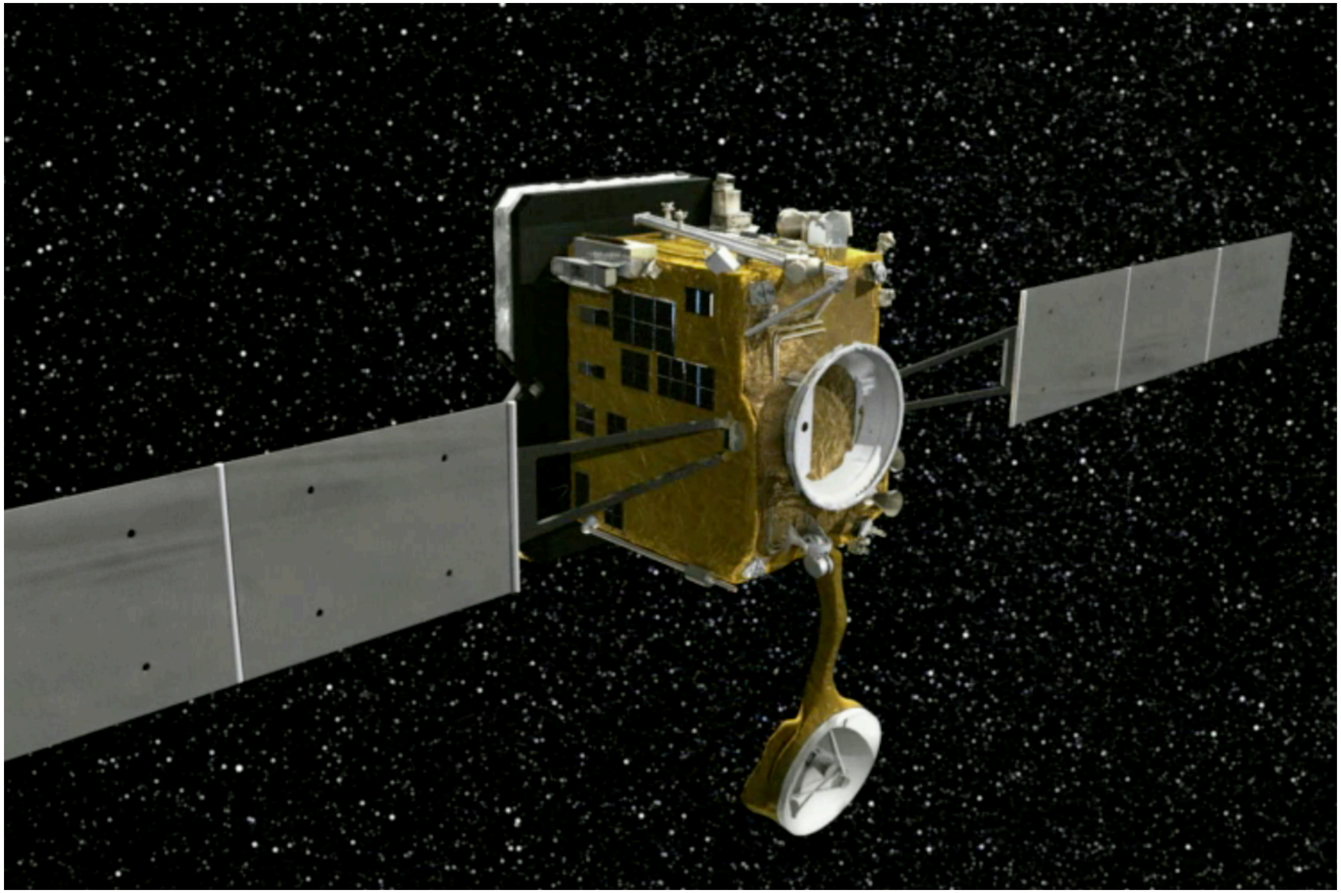


SO will have a highly elliptic orbit (between **0.9 AU** at aphelion and **0.28 AU** at perihelion). It will reach its operational orbit 3.5 years after launch by using gravity assist manouvres (GAMs) at Earth and Venus.



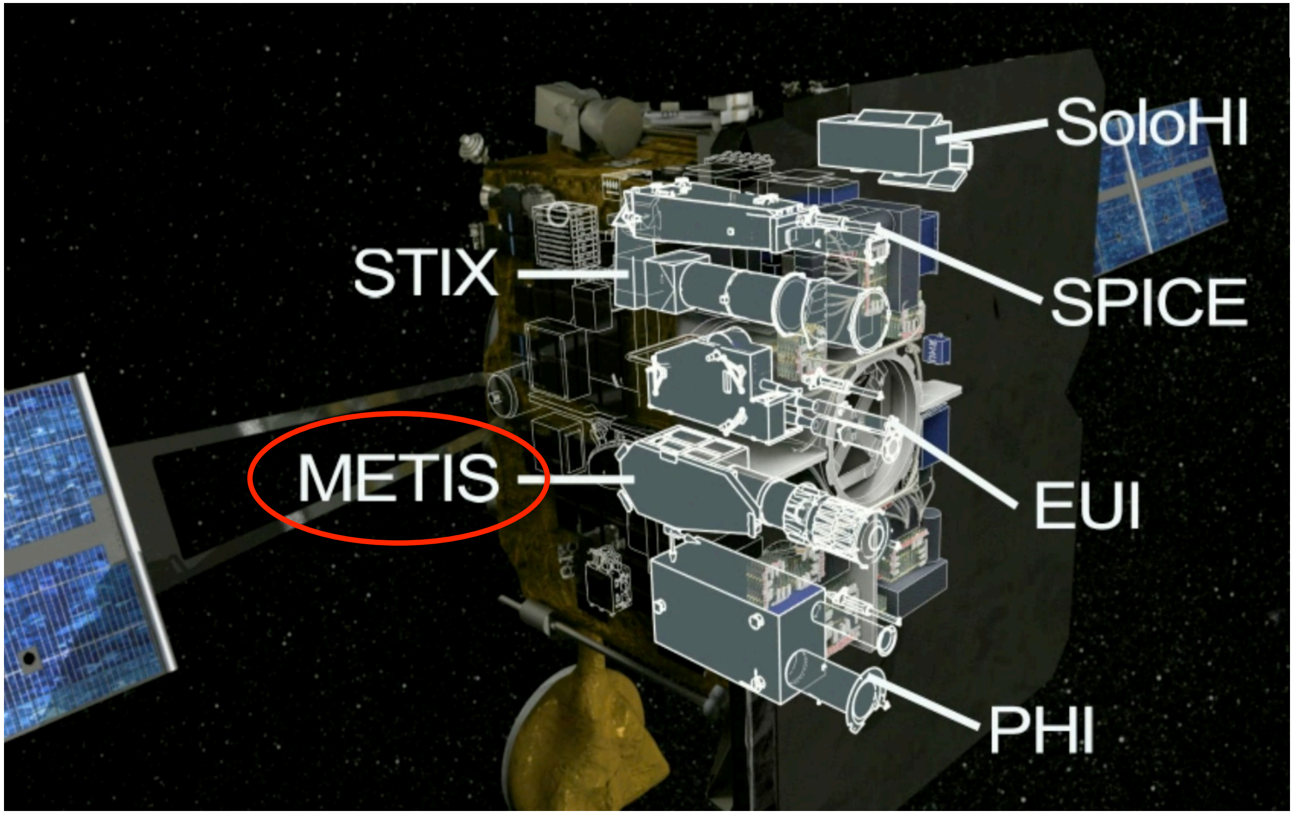
Subsequent GAMs at Venus will increase its inclination to the solar equator over time, reaching up to 25° at the end of the nominal mission (approximately 7 years after launch) and up to 34° in the extended mission phase.

The Solar Orbiter Mission



The SO's payload, designed to address the science goals of the mission, accommodates a set of **in-situ (4)** and a set of **remote sensing (6)** instruments, with a total payload mass of 180 kg.

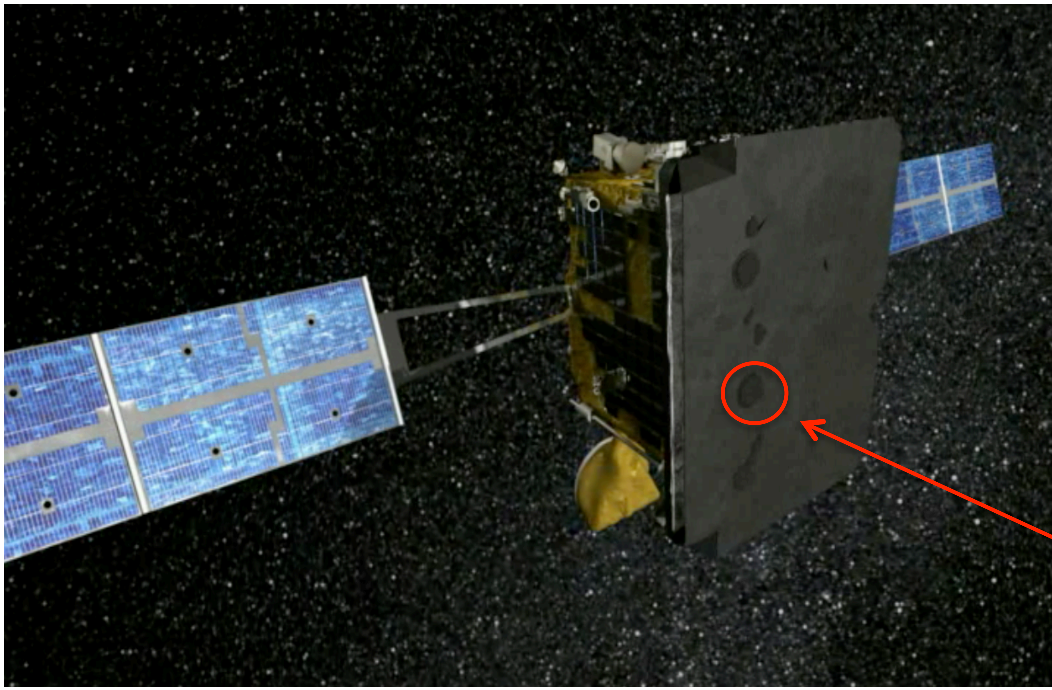
The Solar Orbiter Mission



METIS, the **Multi Element Telescope for Imaging and Spectroscopy** is the mission's Coronagraph, a powerful and innovative instrument aimed at the fully characterization of the solar Corona in **polarized visible light (580-640 nm)** and in **UV light (@ 121.6 nm with 10 nm bandpass)**.

METIS scientific objectives

METIS is based on a **novel externally occulted design**, in which light enters through a circular aperture (**the inverted external occulter**) located at the outside panel of the spacecraft (S/C) heat shield.



P.I. Prof. ***Ester Antonucci***

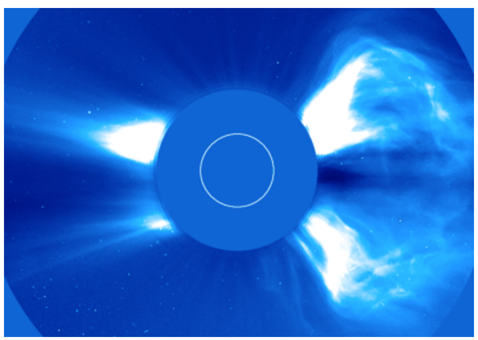
METIS heat shield aperture

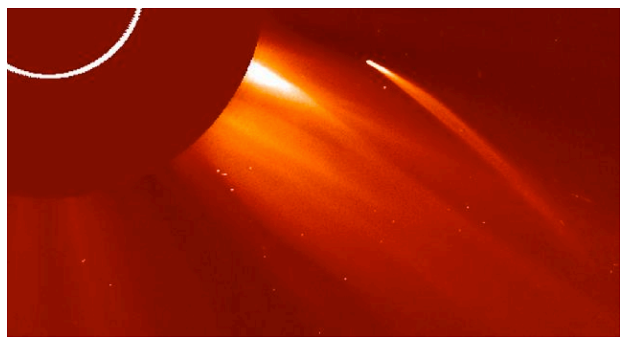
The instrument is conceived to perform off-limb, near-Sun (from 1.5 to 3 solar radii @ 0.28 AU), coronal observations in order to address some still open issues in solar physics, concerning the **origin and heating/acceleration of the solar wind streams and SEPs** and the **transient ejection of coronal mass and its evolution in the inner heliosphere** (CMEs, i.e. coronal mass ejections).

METIS scientific objectives

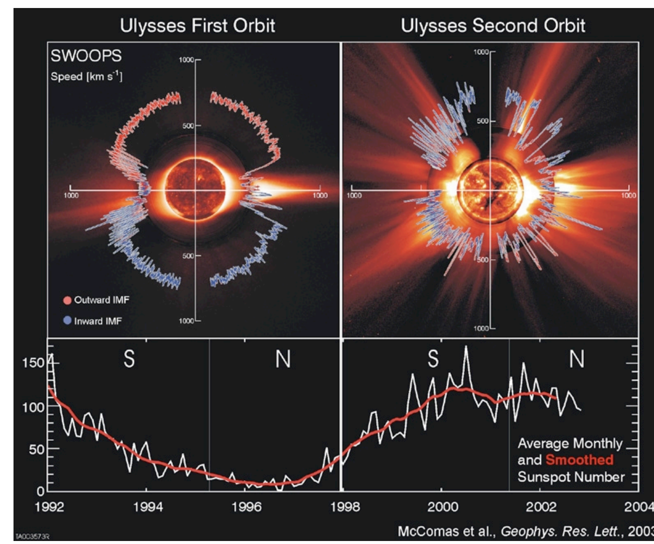
METIS will obtain for the first time simultaneous imaging of the full corona in **linearly polarized visible-light (580-640 nm)** and **narrow-band (10 nm) ultraviolet HI Ly-α (121.6 nm) light**.
These measurements will allow a complete characterization of the most important plasma components of the corona and the solar wind, i.e. **electrons** and **protons**.
The coronagraph's three main key scientific issues concerns:

- ✓ the origin and acceleration of the fast and slow **solar wind streams**;
- ✓ the origin, acceleration and transport of the **solar energetic particles (SEPs)**;
- ✓ the transient ejection of coronal mass **(coronal mass ejections, CMEs)** and its evolution in the inner heliosphere.

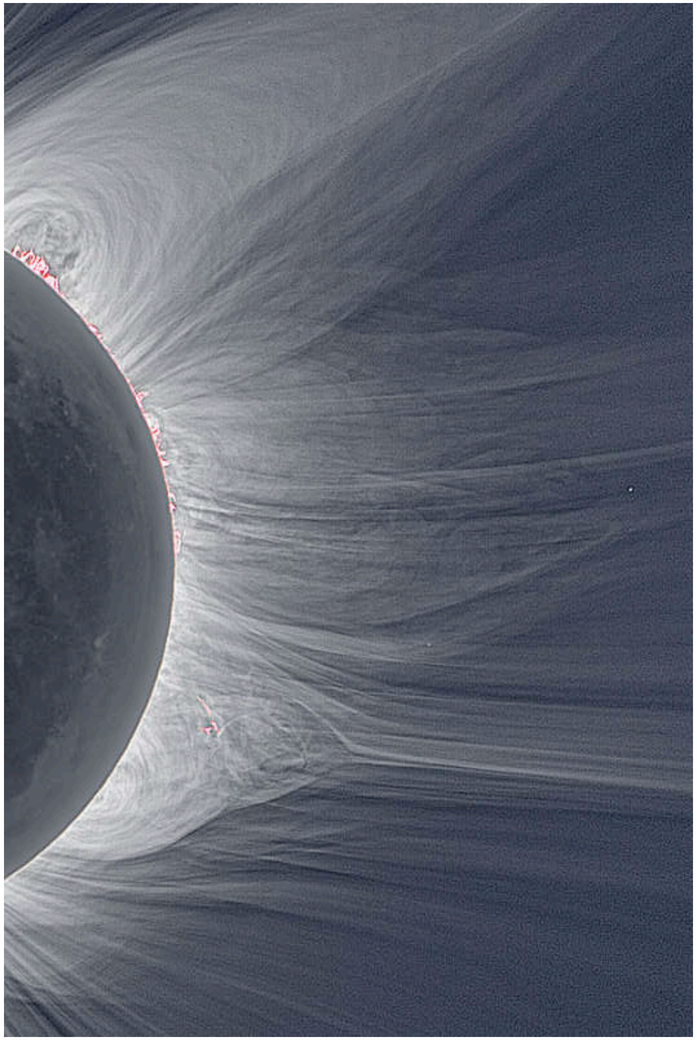




In addition, METIS will contribute to the study of the properties and evolution of **Sun-grazing comets**.



METIS scientific objectives



The Sun corona light sources

Light from the corona comes from three primary sources, which are called by different names although all of them share the same volume of space.

- ✓ The **K-corona** (K for kontinuierlich, "continuous" in German) is created by *sunlight scattering by free electrons*; Doppler broadening of the reflected photospheric absorption lines completely obscures them, giving the spectral appearance of a **continuum with no absorption lines.**

- ✓ The **F-corona** (F for Fraunhofer) is created by sunlight bouncing off by *dust particles*, and is observable because its light contains the **Fraunhofer absorption lines** that are seen in raw sunlight; the F-corona extends to very high elongation angles from the Sun, where it is called the zodiacal light.

- ✓ The **E-corona** (E for emission) is due to *spectral emission lines* produced by ions that are present in the coronal plasma; it may be observed in broad or forbidden or hot spectral **emission lines** and is the main source of information about the corona's composition.

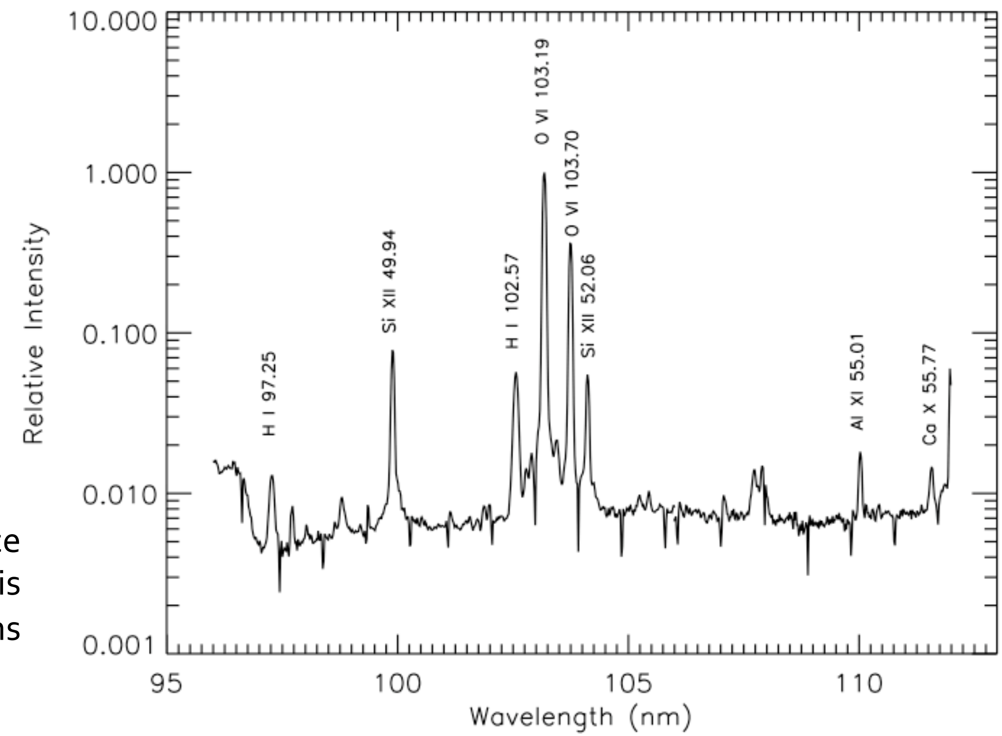
METIS scientific objectives

Solar corona is made of a hot (1-2 MK) thin fully ionized plasma.
EUV line emission from E-corona occurs via spontaneous de-excitation following either **collisional** or **resonant** excitation in a stationary plasma.

$$I_c = const \times A_{\mathrm{el}} \times R(T_e) \times q \times \int_{-\infty}^{+\infty} N_e^2 dx$$

$$I_r = const \times A_{\mathrm{el}} \times R(T_e) \times \int_{-\infty}^{+\infty} N_e \, dx$$

Where A_{el} is the considered element abundance relative to H, $R(T_e)$ is the ionization ratio @ T_e and q is the collisional coefficient (the probability of collisions occurrence). **N_e is the electron density**.



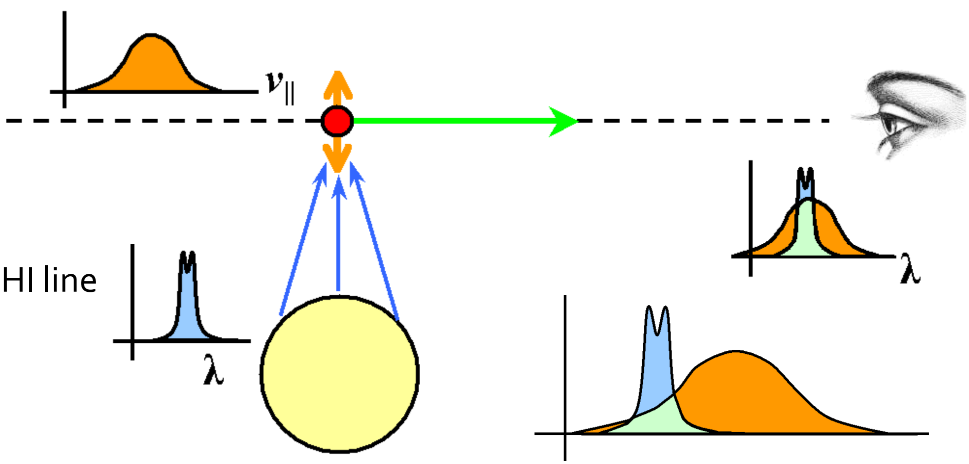
METIS scientific objectives

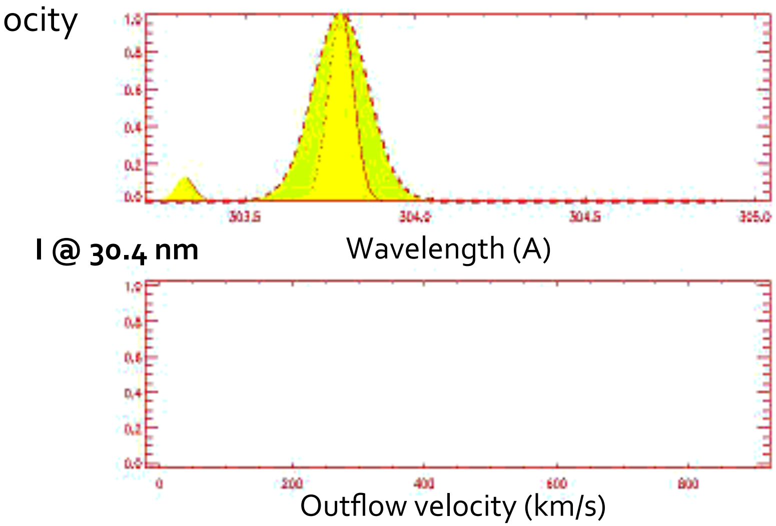
Models predicts that when e.g. a solar prominence erupts into the corona, the intensity of an **emission atomic resonance line** will decrease as a function of the **radial velocity of the plasma**. This predicted change in the radiation output is due to the **Doppler dimming effect** i.e. the decrease in intensity of an *atomic resonance line* when the plasma in which it forms moves so that the line is Doppler shifted out of resonance.
Doppler dimming is widely used to diagnose the **solar wind speed**.
HI 121.6 nm and **HeII 30.4 nm** emission lines are formed via resonance scattering.

$$I_r = const \times A_{el} \times R(T_e) \times < D(w, T_{||}) > \times \int_{-\infty}^{+\infty} N_e \, dx$$

Plasma radial velocity

HeII and Si XI lines





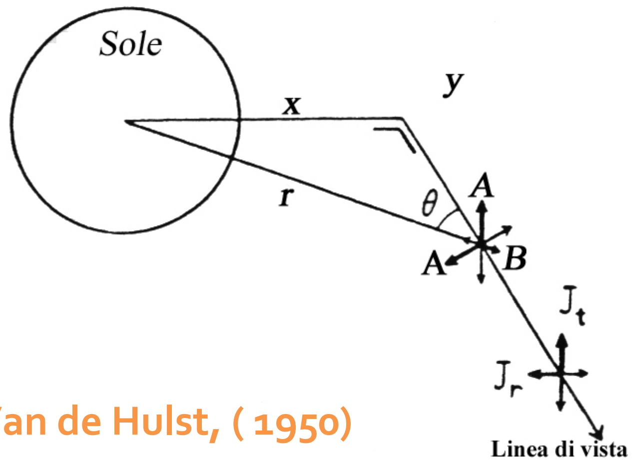
METIS scientific objectives

The K-corona emission is produced by the sunlight Thompson scattering of free electrons and is linearly polarized.

The linearly polarized brightness (or intensity) is a function of the electron density N_e:

$$\boxed{I_k = const \times \int_{-\infty}^{+\infty} N_e \, dx}$$

$$pB_K = \frac{3}{4} I\, R\, S_T \int_{-\infty}^{x} N_e(r,x)\left[A(r) - B(r)\right] \frac{x^2}{r\sqrt{r^2 - x^2}}\, dr$$



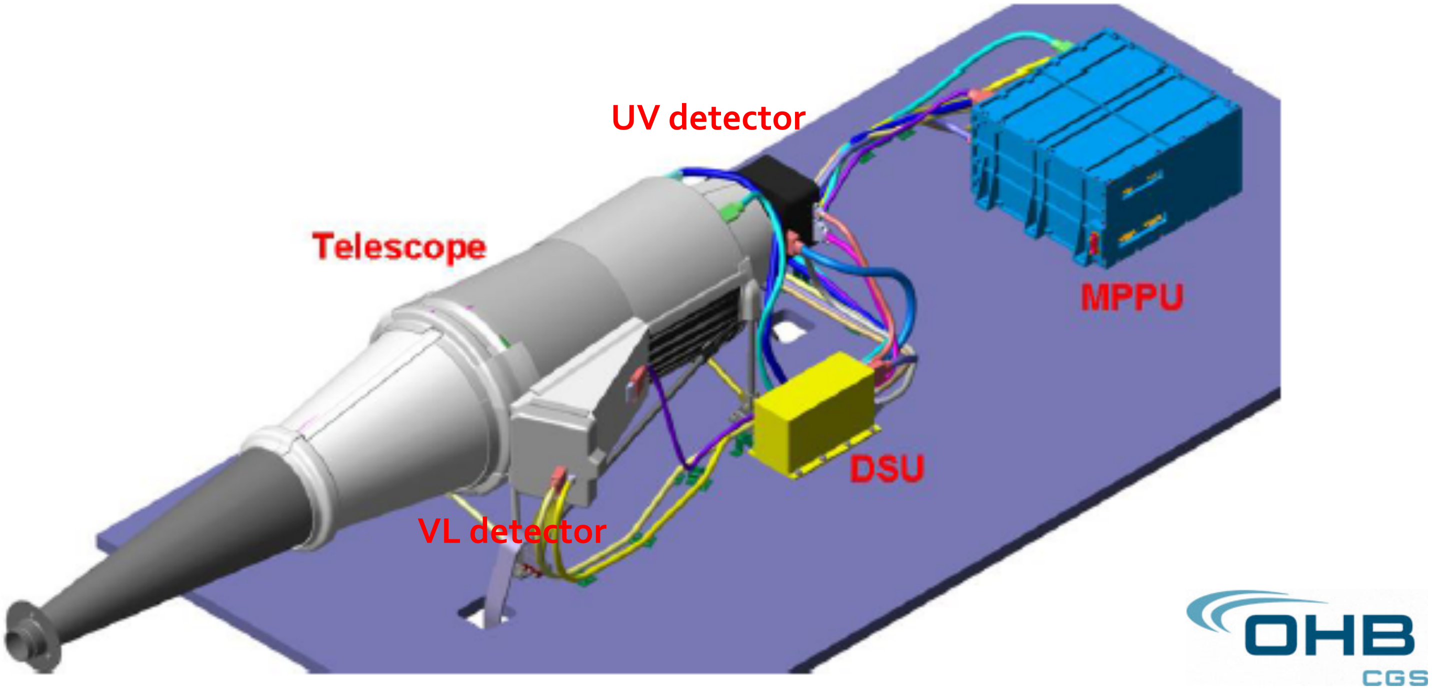
Van de Hulst, (1950)

where I is the averaged Sun disk intensity, S_T the Thompson electron cross section, A and B are geometrical functions depending by r and by the Sun limb obscuring factor R.

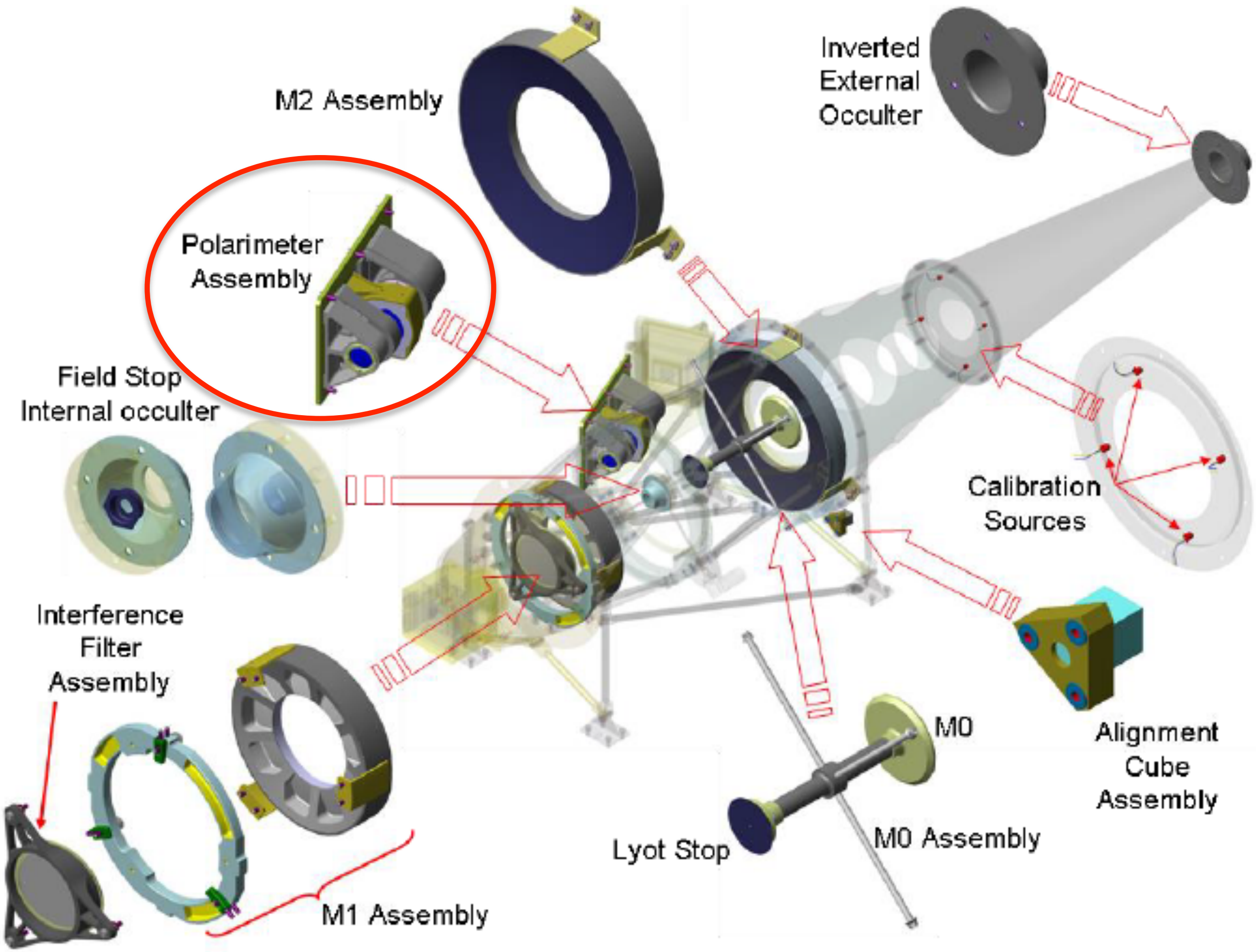
So, measuring linearly pB_K, is of fundamental importance in order to characterize the main coronal plasma components (electrons and protons) and to determine the origin and acceleration of the fast and slow solar wind streams.

METIS design

METIS is able to characterize the main coronal plasma components and to gets its scientific targets thanks to its powerful **two-channel design**:

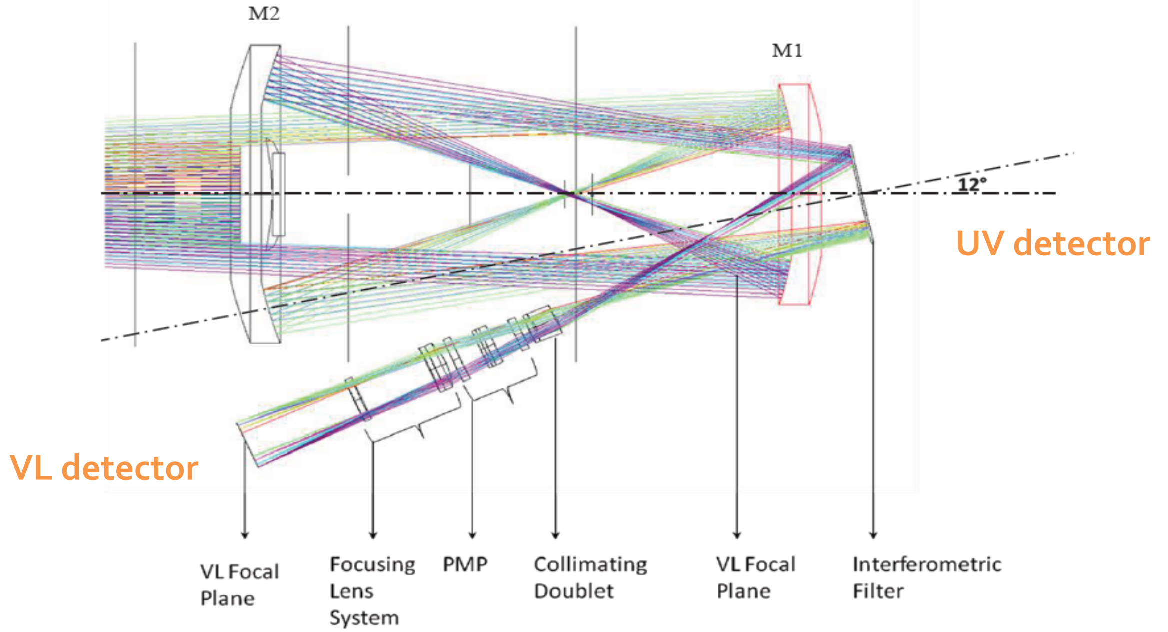


METIS design



METIS design

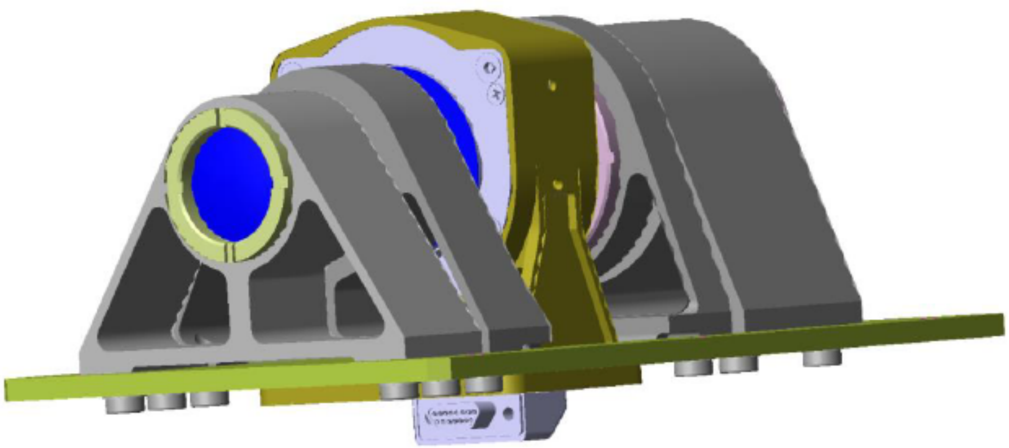
The science objective of the **METIS VL path** is the measurement of the **K-corona electron density (N_e)** as a diagnostic mean to characterise the physical properties of the hot coronal plasma.
This goal is achieved by **imaging the linearly polarised K-corona on the VL channel detector.**

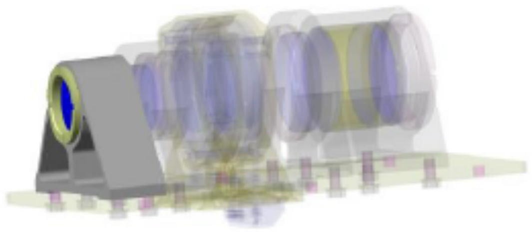


The METIS science driver of deriving N_e from polarised-brightness (pB) images **requires an accuracy of better than 1% in the measurement of linear polarisation**. This requirement poses some implications and limitations on the METIS optical design in order **to minimise the instrumental residual polarisation** associated to the broad-band visible-light polarimeter assembly and to the other optics constituting the visible-light path, like the IF.

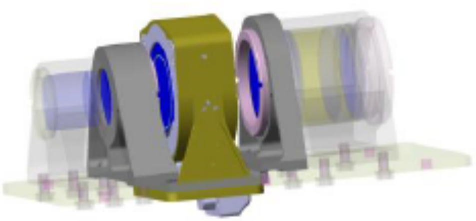
METIS design

The Linear Polarimeter Assembly

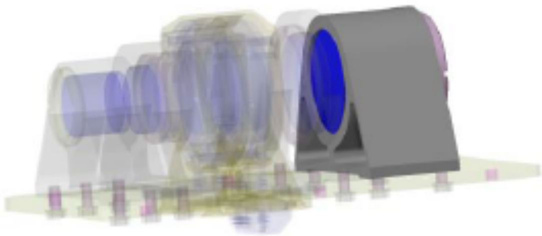




Collimating doublet assy



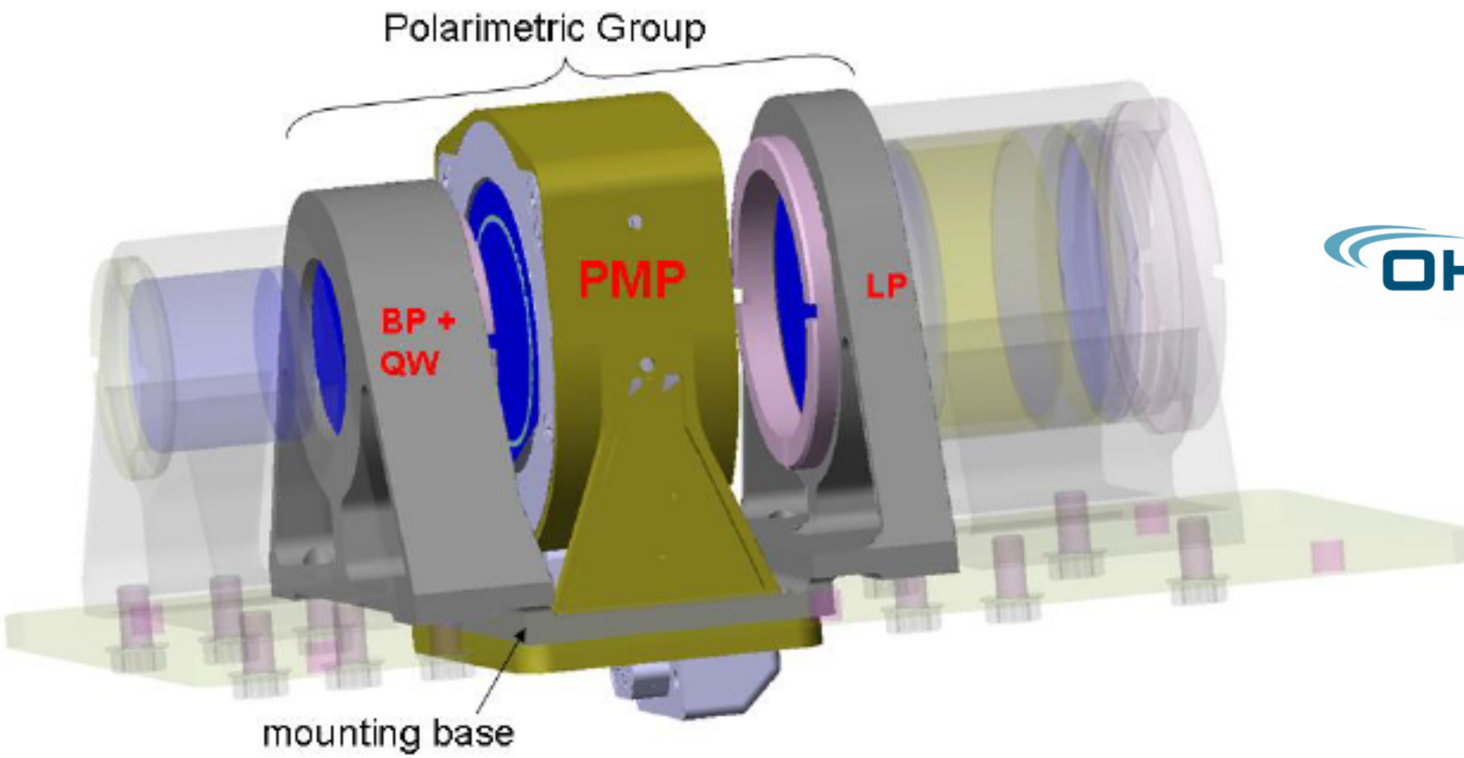
Polarimetric group assy



Focusing lens assy

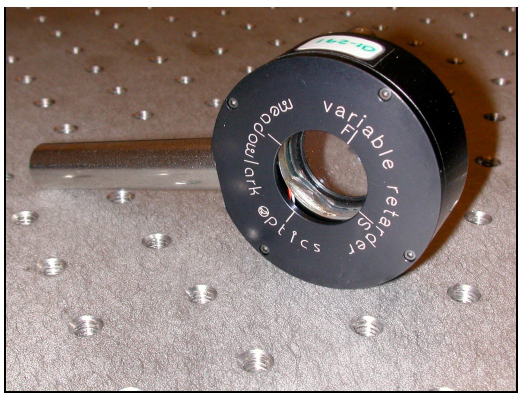
METIS design

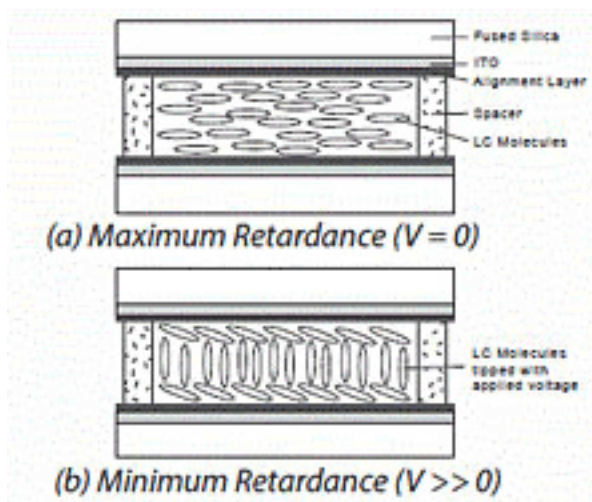
The Polarization Modulation Package (PMP) ensemble is constituted by two **Liquid Crystal Variable Retarders (LCVRs)**, with the temperature sensors and heaters for the LCVR thermal control, the electrical cables and connectors and the mechanical housing in which all the above elements are integrated.



METIS design

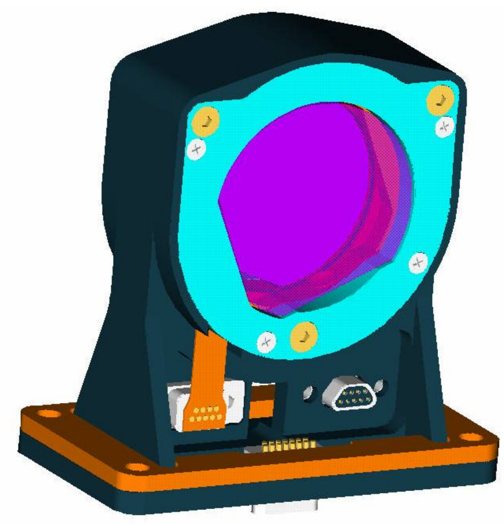
A "classical" polarimeter, in the easiest configuration, comprises a **rotating quarter wave plate** and a **fixed linear polarizer**. Using the Stokes formalism, the polarization state of a light beam can be expressed by the **Stokes vector S (I, Q, U, V)^T**. For the fully characterization of the **linear polarization** the knowledge of the I, Q and U parameters are needed. For that reason **at least 3 measurements** in a 3 different positions (or retardances) of the quarter wave plate are required.





(a) Maximum Retardance (V = 0)

(b) Minimum Retardance (V >> 0)



The LC-based retarder (LCVR) is a variable retarder without moving parts. The variation in retardance is introduced by the **variation of birefringence** that change with the alignment of the liquid crystals sensible to an applied electric field. By the application of calibrated external voltages, the retardances values are immediately set without movement of mechanical parts.

This is one of the most relevant advantages on the use of this technology, especially for space missions.

METIS polarimetry

The measured signal on a single **METIS VLD image** can be written as (e.g. in ADU, pixel by pixel):

$$m_i = g(I + Q\cos\delta_i + U\sin\delta_i) + b$$

where g is the efficiency of the system (containing the transmission of the polarimeter and the quantum efficiency of the detector), I, Q and U are the Stokes parameters, **δ_i are the LCVR retardances** and b is the detector bias and the integrated dark current along the exposition time.

The linear combination of the 4 measurements (3 at least) acquired with **the same exposure time** but with **different retardances** are used to obtain the Stokes parameters I, Q and U.
Using the matrix formalism we can write:

$$\begin{pmatrix} m_0 \\ m_1 \\ m_2 \\ m_3 \end{pmatrix} = g \begin{pmatrix} 1 & \cos\delta_0 & \sin\delta_0 & 0 \\ 1 & \cos\delta_1 & \sin\delta_1 & 0 \\ 1 & \cos\delta_2 & \sin\delta_2 & 0 \\ 1 & \cos\delta_3 & \sin\delta_3 & 0 \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix},$$

METIS polarimetry

… and applying the following values for g and the retardances:

$$\begin{cases} g = \frac{1}{2} \\ \delta_0 = \frac{3\pi}{2} \\ \delta_1 = \pi \\ \delta_2 = \frac{\pi}{2} \\ \delta_3 = 0 \end{cases} \rightarrow \begin{pmatrix} m_0 \\ m_1 \\ m_2 \\ m_3 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 0 & -1 \\ 1 & -1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \end{pmatrix} \equiv M = X \cdot S;$$

Inverting the system:

$$S = X^{+} \cdot M$$

Where **X^{+} is the demodulation matrix** for 4 (or 3) measurements.

At this point it is possible to extract the S vector, containing the I, Q and U values. This operation is a simple pixel by pixel linear combination of the 4 (3) images **m_i**:

METIS polarimetry

$$\begin{cases} I = X^+_{00} \cdot m_0 + X^+_{01} \cdot m_1 + X^+_{02} \cdot m_2 + X^+_{03} \cdot m_3 \\ Q = X^+_{10} \cdot m_0 + X^+_{11} \cdot m_1 + X^+_{12} \cdot m_2 + X^+_{13} \cdot m_3 \\ U = X^+_{20} \cdot m_0 + X^+_{21} \cdot m_1 + X^+_{22} \cdot m_2 + X^+_{23} \cdot m_3 \end{cases}$$

or

$$\begin{cases} I = X^+_{00} \cdot m_0 + X^+_{01} \cdot m_1 + X^+_{02} \cdot m_2 \\ Q = X^+_{10} \cdot m_0 + X^+_{11} \cdot m_1 + X^+_{12} \cdot m_2 \\ U = X^+_{20} \cdot m_0 + X^+_{21} \cdot m_1 + X^+_{22} \cdot m_2 \end{cases}$$

The coefficients of the demodulation matrix, X^+, are function of the temperature, $X^+(T)$, and they have to be suitably calibrated.

Is at that point possible to evaluate the **polarization *p*** and the **polarization brightness *pB***, pixel by pixel, by means of the I, Q, U values and **the direction of the polarization *Θ***:

$$p = \frac{\sqrt{Q^2+U^2}}{I}; \quad pB = \sqrt{Q^2 + U^2} \qquad \tan(2\theta_0) = U/Q$$

From these measurements and calculus we can finally infer **the map of the K-corona electron densities (N_e).**

METIS polarimetry

A&A 393, 295–304 (2002)
DOI: 10.1051/0004-6361:20021019

Astronomy & Astrophysics

Two-dimensional electron density in the solar corona from inversion of white light images – Application to SOHO/LASCO-C2 observations

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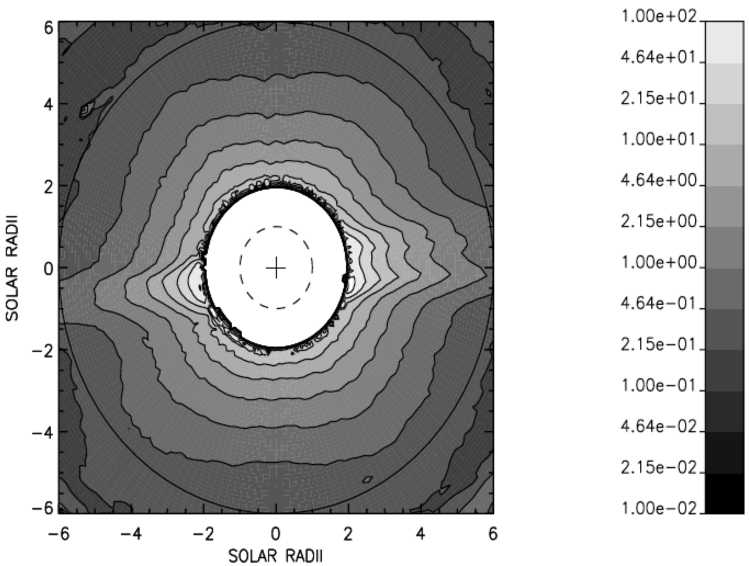

Fig. 3. The white-light image of the K-corona obtained on December 29, 1996. The right-hand scale is in units of 1.e-10 $B_{\odot}$. The solar disk is shown by the dash circle while the outer circle corresponds to 6 $R_{\odot}$.

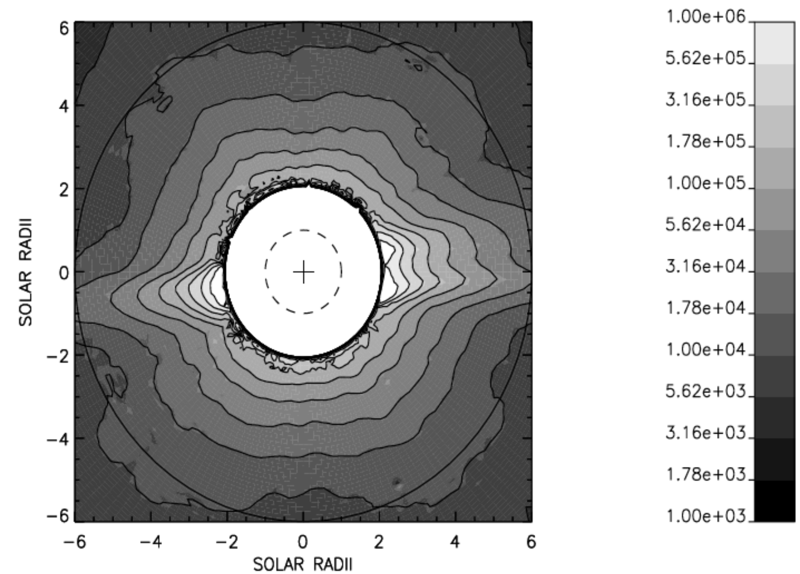

Fig. 4. The N_e map resulting from the inversion of the K-corona shown in the previous figure. The right-hand scale is in units of cm^{-3}.

METIS polarimetry

Electro-optical polarimeters for ground-based and space-based observations of the solar K-corona

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Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II,
edited by Ramón Navarro, Colin R. Cunningham, Eric Prieto, Proc. of SPIE Vol. 8450, 845040
© 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.926896

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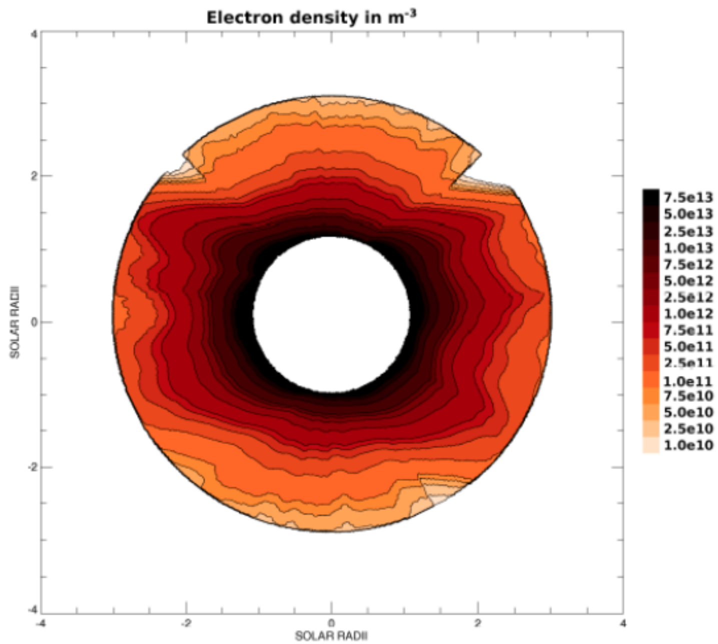
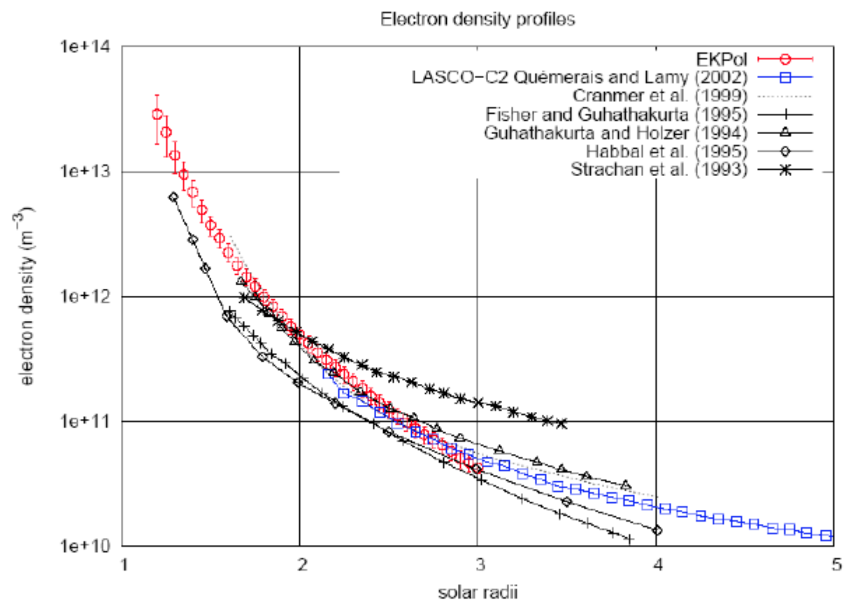


Map of electronic density obtained with the E-KPol data



Comparison of the electronic density profile at the solar north pole with other works

Conclusions

METIS instrument as a **VIS and UV coronal imager** will provide:

- ✓ global maps of the HI Ly-α (121.6 nm) emission;
- ✓ global maps of polarized VL in the range 580-640 nm;
- ✓ at spatial resolution 40 arcsec (adopting pixel binning);
- ✓ above ≥ 1.6 R_{Sun}

to derive **global maps of the outflow velocity of the H component**, obtained by applying the Doppler dimming technique to the resonantly scattered component of the HI Ly-α emission line.

The **coronal electron density**, needed to apply the Doppler dimming technique to the HI emission measurements, will be derived from the VL images polarized emission digital processing.

Fast and slow solar wind streams will be identified in the global maps according to the values of the outflow velocity of the H component.

Thank you!

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