Space Coronagraphs

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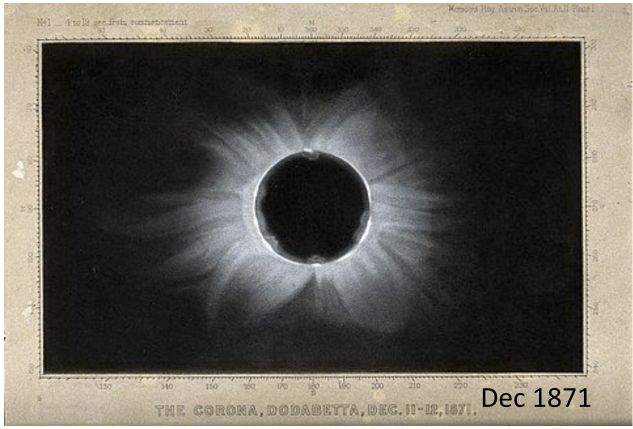
Before coronagraphs

- With the advent of spectroscopy in the middle of XIX century it becomes clear that the faint and extended brightness surrounding the Moon disk during a total solar eclipse cannot be other than a gaseous envelope surrounding the Sun (Janssen 1879). Discovery of Helium line He I 587 nm in solar prominences (Lockyer, 1868)

- The solar corona can be observed during total solar eclipse for a total time around 4 hrs in a century, most of which from remote or unreachable areas of the Earth.

18th August 1868 (Bullock)



Dec 1871

Birth of solar coronagraphy

- In 1831 **Bernard Lyot** invent and test the first coronagraph.
  It is an **internally occulted coronagraph** [Lyot, 1932]

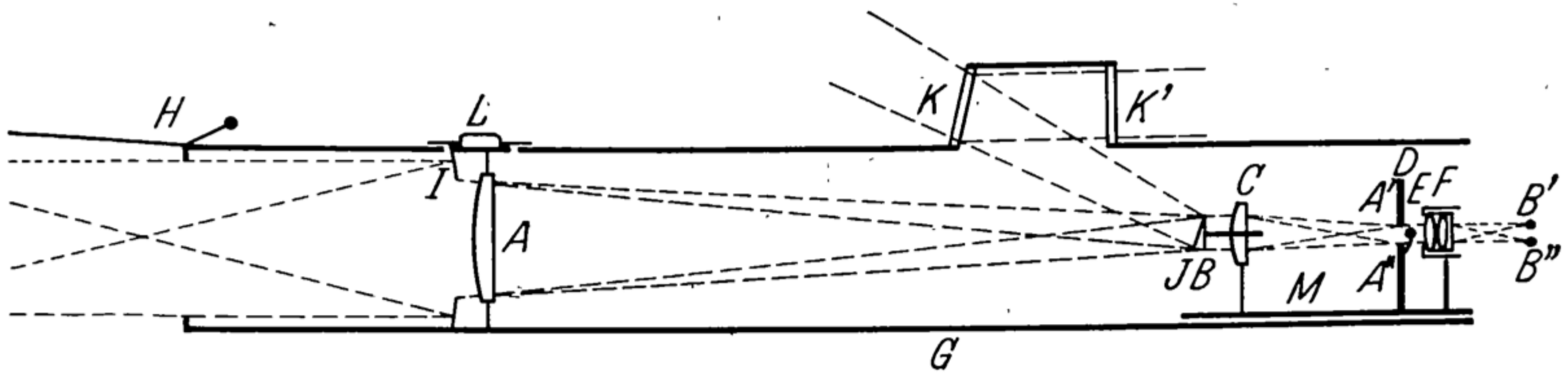


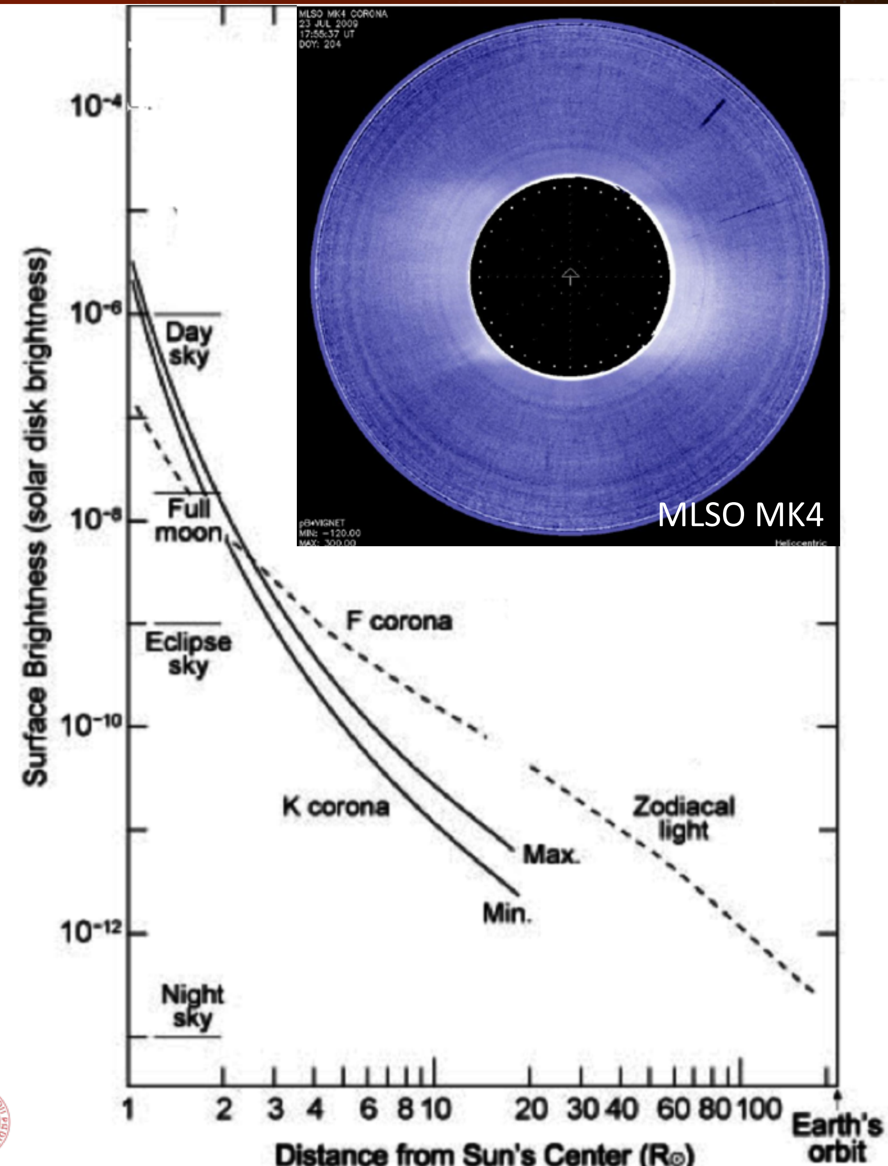
Fig. 2. Schéma du coronographe.

- **Evans (HAO)** modifies Lyot coronagraph by adding an occulter disk that shades the primary objective from the Sun with the aim of measuring the sky brightness in proximity of the Sun. This is the first **externally occulter coronagraph**. [Evans, 1943]

Need for space coronagraphs

The essential problem to observe the corona outside of solar eclipse is the low contrast of the corona above the **background sky** and instrumental **scattered light** (stray light).

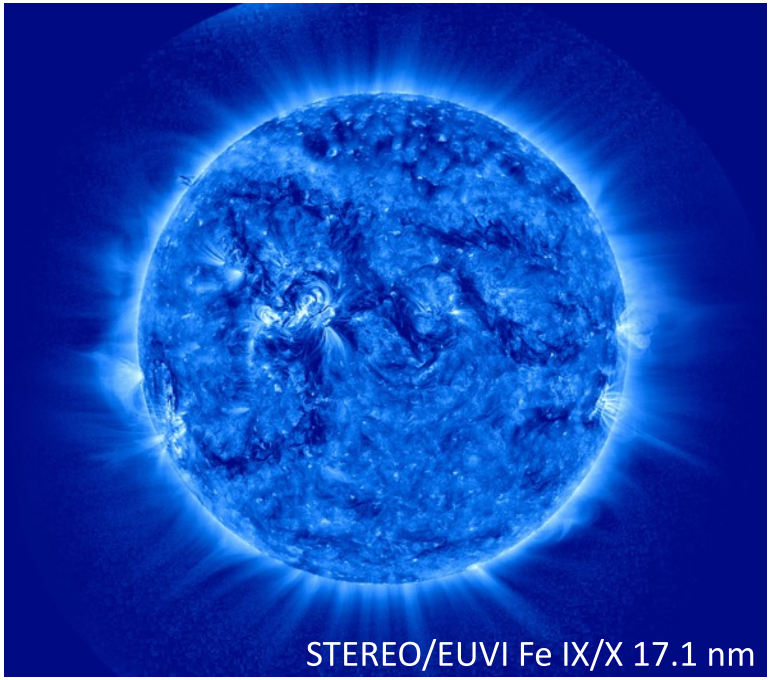
- **Stray light** is removed with technical improvements in the coronagraph optical design.
- **Day sky is too bright**. Corona is visible for a few tenth of solar radii. The solar wind acceleration region for example extends above 2 R_s
- The hot corona emits **UV and soft-X** lines, that can be observed only from space



Why observing the solar corona?

- The solar corona from the observation technique point of view can be split in an **inner corona** (< 1.5R_s), denser and brighter, that can be observed with EUV telescopes, and an **outer corona**, visible only with a **coronagraph**.

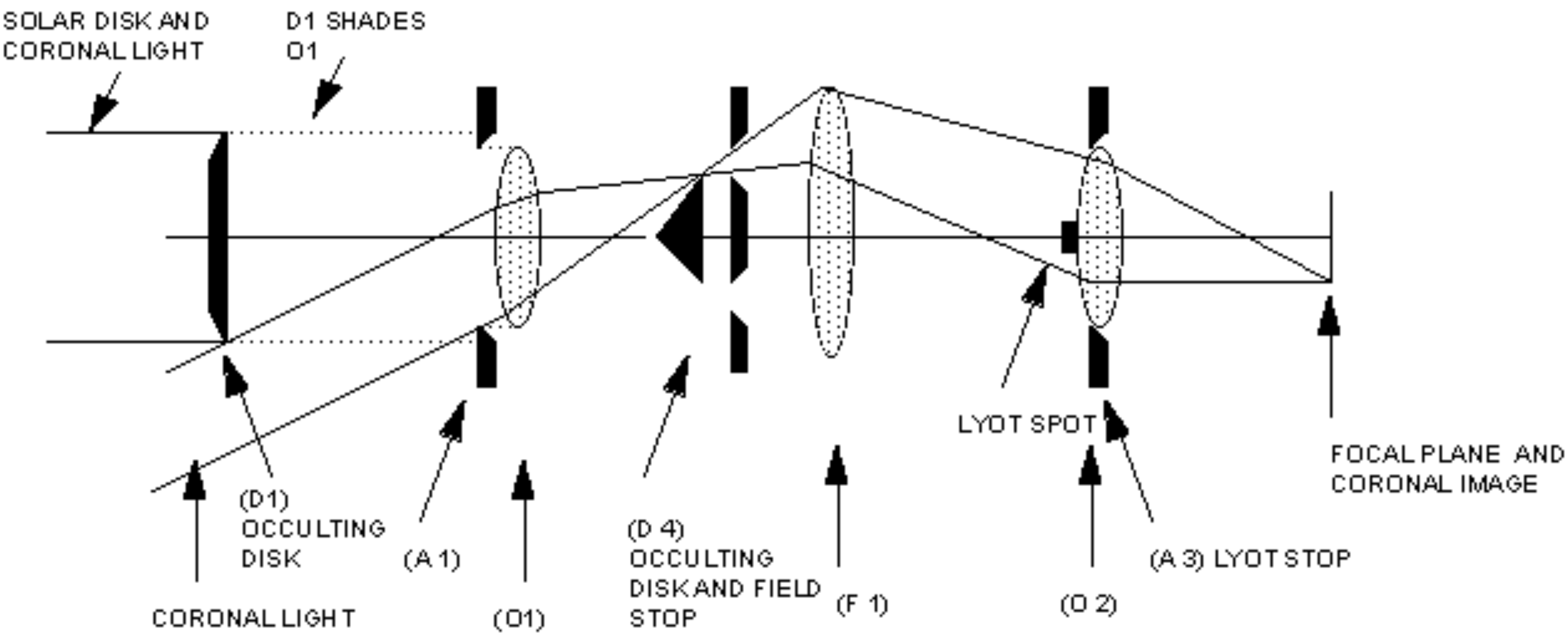
- The solar corona is plasma is heated up to 1 million degrees
- Driven and heated by the underlying layer of the solar atmosphere
- Dynamically dominated by the magnetic field
- Heavily affected by the solar cycle
- Accelerates the solar wind
- Drives the heliophysics dynamics that affects the entire Solar System -> Space weather



Inner corona as seen by an EUV telescope

Externally occulted coronagraphs

The quasi-totality of the space coronagraphs are externally occulted to be able to observe the outer solar corona (with the exception of LASCO C1 and SECCHI COR1).



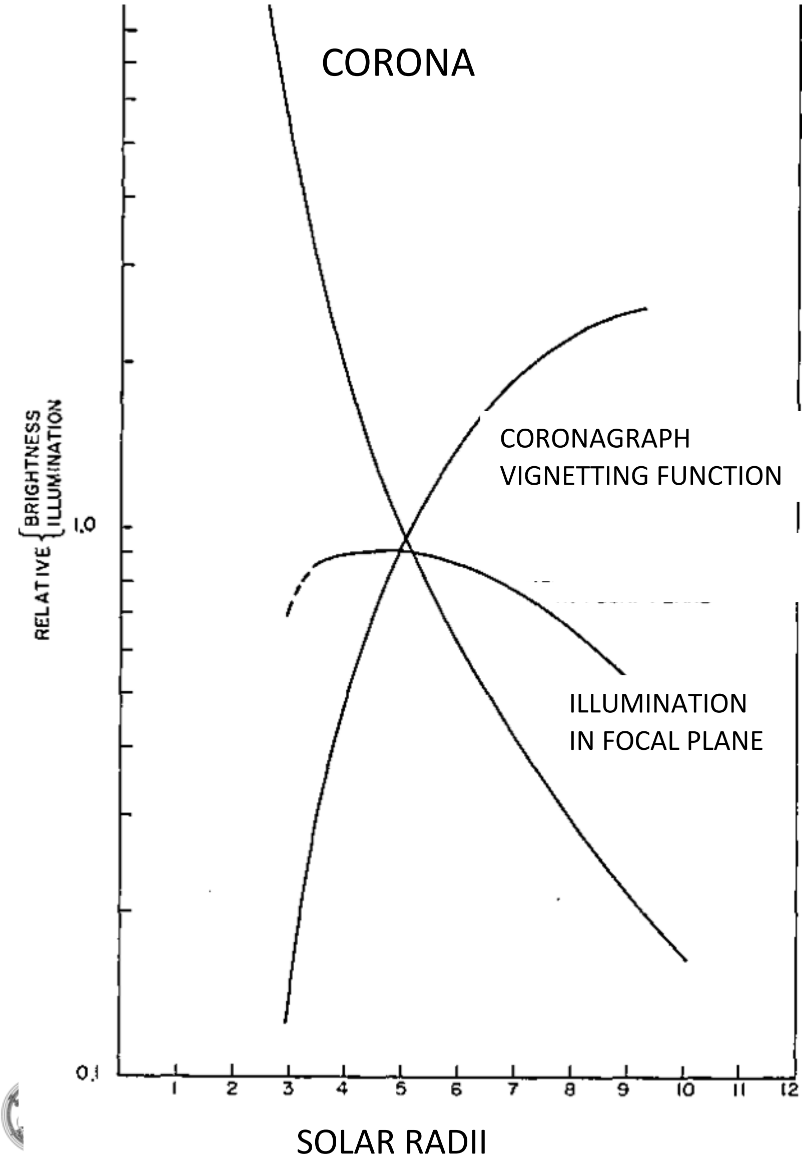
Externally occulted coronagraphs

PROs :

- Very steep vignetting function mitigates the large dynamic range of the coronal brightness
- Only way to achieve low stray light in the outer corona

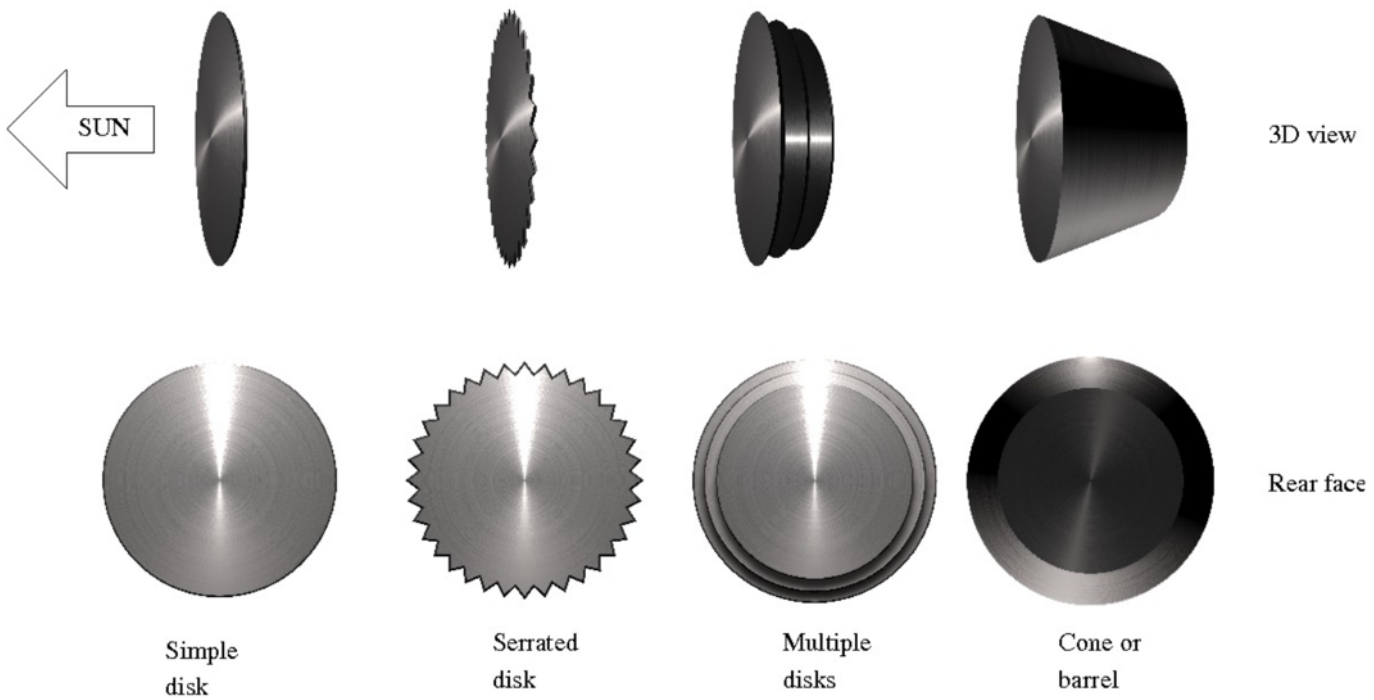
CONs :

- Lower end of FOV not lower than 1.5 R_s
- Low throughput at the lower end of the field of view



Externally occulted coronagraphs

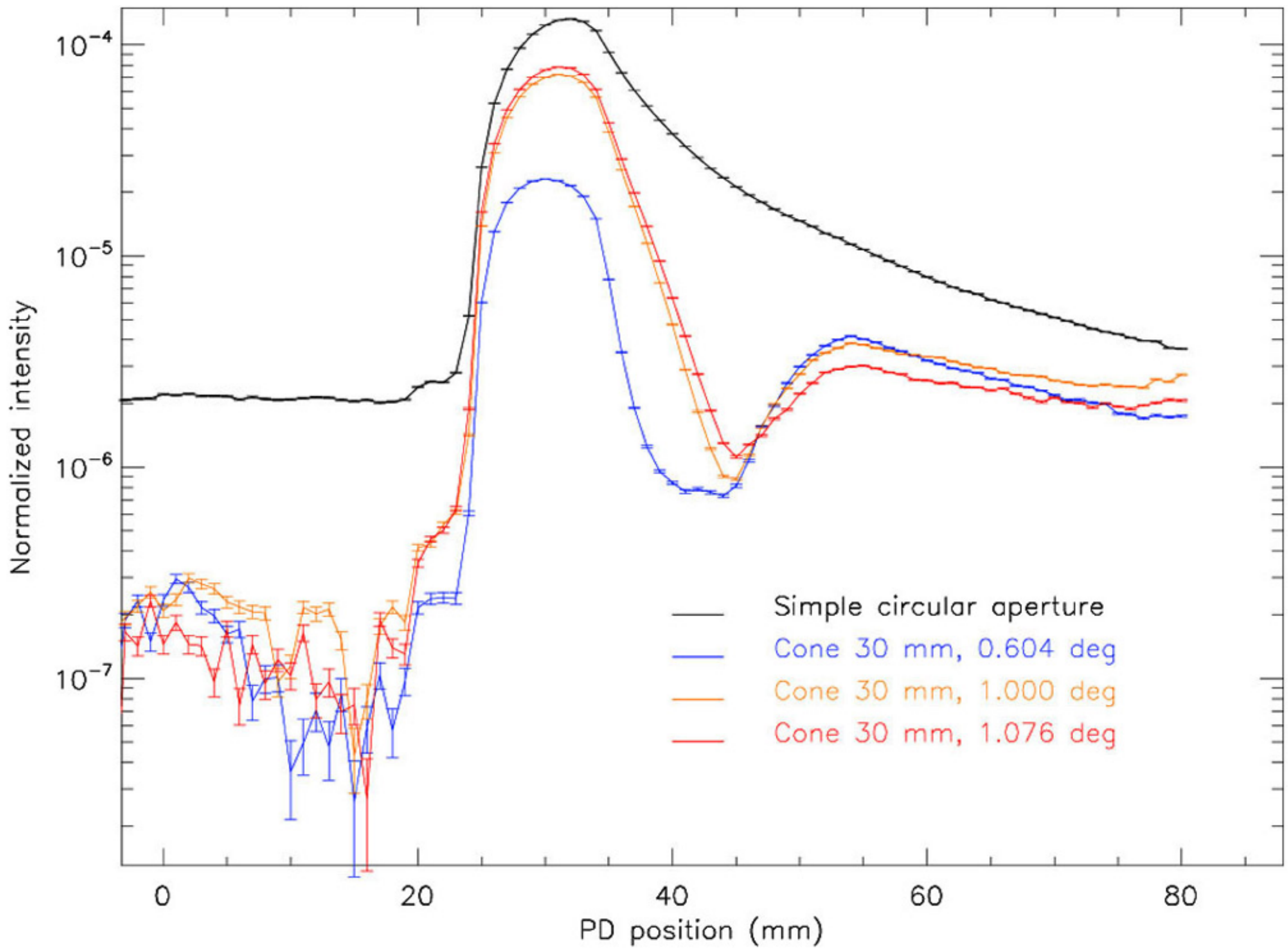
APODIZATION



Landini et al. 2010

Externally occulted coronagraphs

APODIZATION



Landini et al. 2012

First attempts in

1960 Newkirk-Eddy (HAO), balloon-borne, *single disk* (unsuccessful)

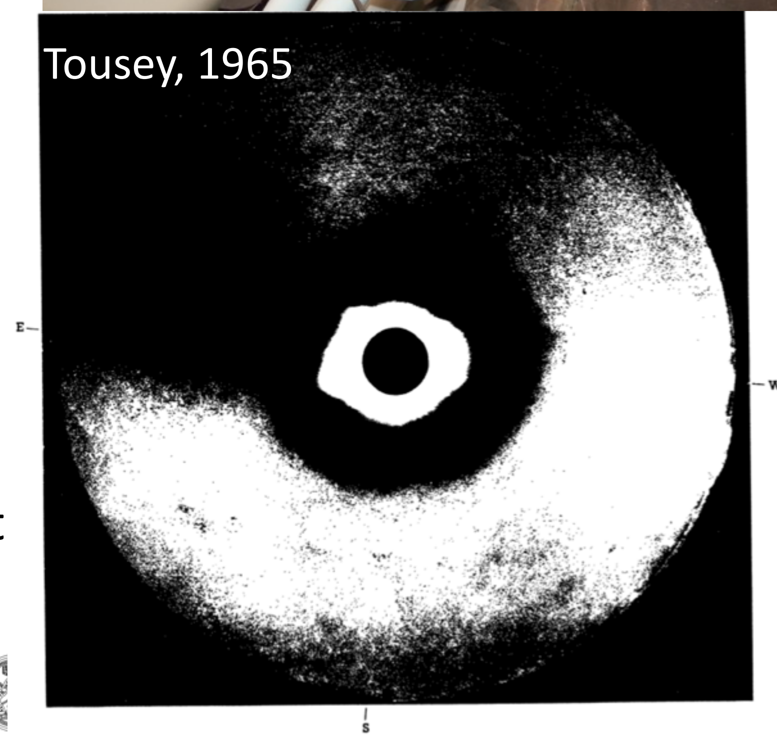
1963 Tousey (NRL), rocket first non–eclipse image *serrated edge*

1964 Newkirk-Bohlin (HAO), balloon-borne coronascope II, *3-disks*

1965 OSO-2 (NRL), satellite first flight, *3-disks* (too much stray light)

1967 MacQueen (JHU), balloon-borne, *3-straight edges*, IR dust corona

1971-74 OSO-7 Tousey (NRL), satellite, *3-disks,* First clear detection of a coronal mass ejection (CME).

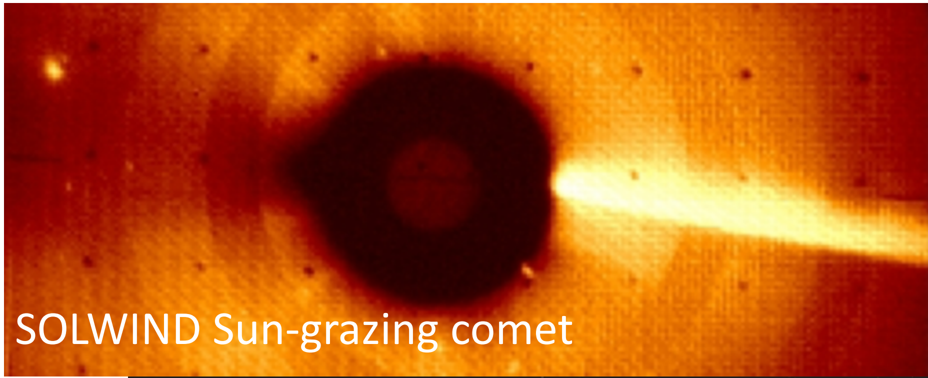


Skylab P78-1 SMM

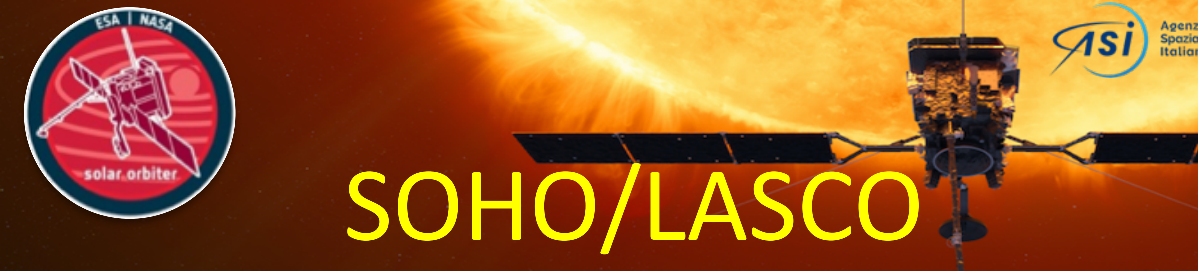
Skylab white light coronagraph (HAO), *3-disks,* provided the first accurate observations of Coronal Mass Ejections (CMEs), within 1.5 and 6.0 $R_\odot$ from Sun center (**1973-1974**).

SOLWIND P78-1 white light coronagraph (NRL) (**1979-1984**), *3-disks,* first detection of Halo-CMEs and of Sun-grazing comets.

Search on the properties of coronal mass ejections continued with the P78-1 mission, and the Solar Maximum Mission white light coronagraph (1.6–6.0 $R_\odot$) developed by HAO, launched in 1980. (**1980, 1984-1989**)


SOLWIND Sun-grazing comet

SMM Coronagraph



SOHO/LASCO

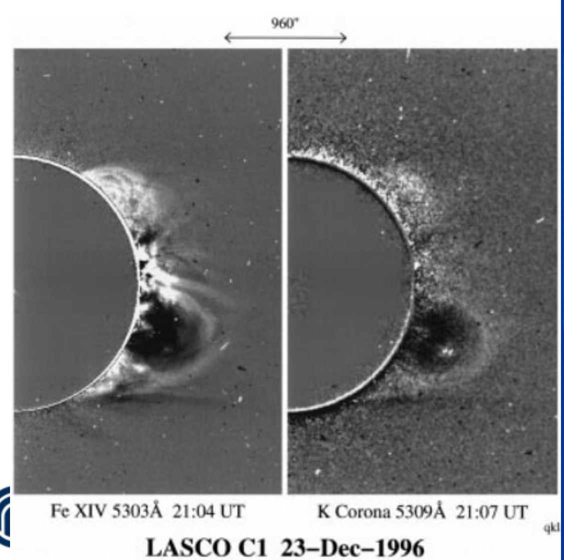
The set of LASCO coronagraphs (NRL) aboard SOHO provided **continuous coronal imaging** in a range from 2 to 30 $R_\odot$ and uninterrupted monitoring since 1996, by observing the corona from the Lagrangian point L1.

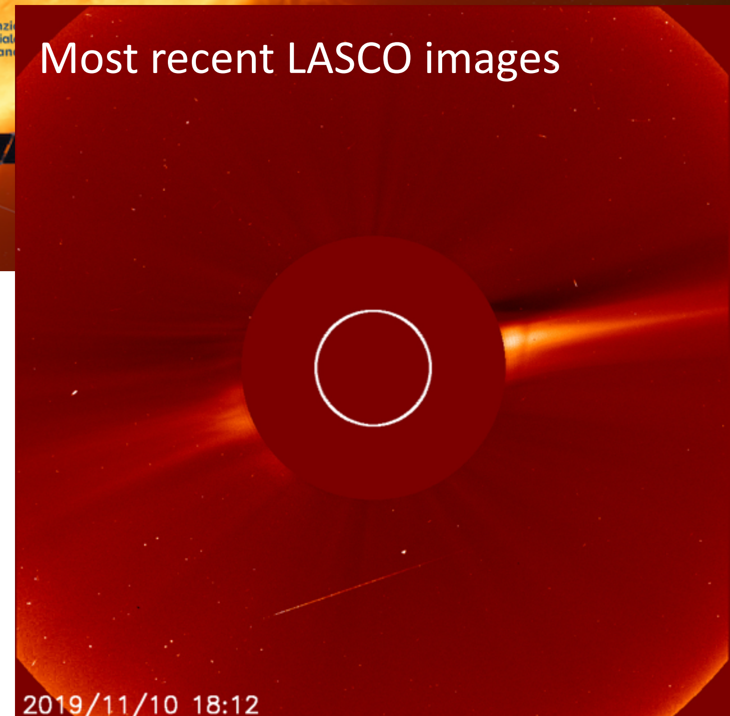
Three coronagraphs:

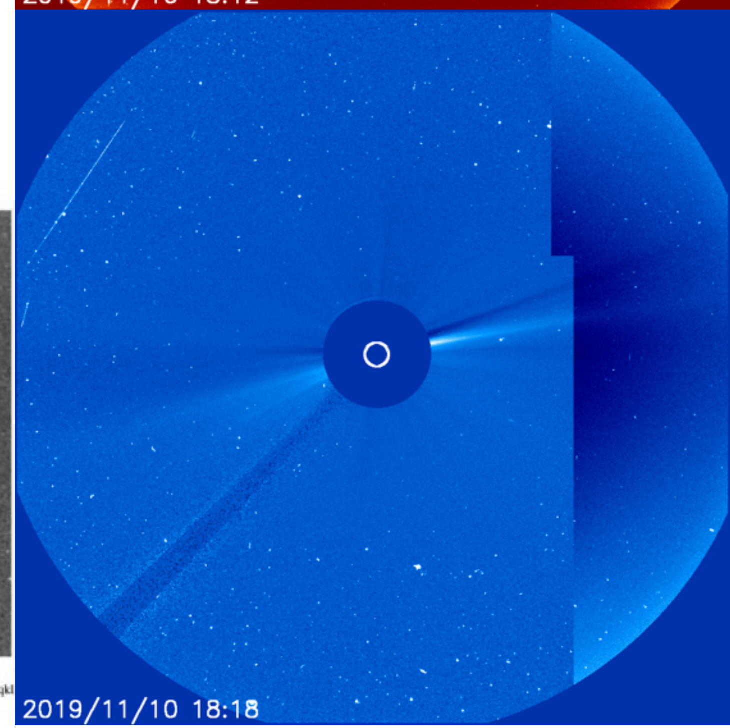
- **C1, internally occulted, FOV 1.1 - 3 R_s**
- **C2, C3, *3-disks*, FOV 1.5 – 6 R_s 3 – 30 R_s**

Major contributions were given in the **understanding of CME propagation** and evolution beyond 2 $R_\odot$. The high sensitivity and the continuity of the observations made it possible to catch systematically the. **faint halo CMEs** that are the ones that are directed toward Earth and have the highest probability of being **geo-effective**, when impacting on our magnetosphere.

Furthermore the LASCO coronagraphs contributed to the **slow wind** physics, studied through the **motion of tracers**.







Spartan 201: first UV coronagraph

Spartan 201 (**Shuttle Pointed Autonomous Research Tool for Astronomy**) mission is to probe the physics of solar-wind by observing the oxygen, hydrogen, and electron temperatures and densities, and the solar-wind velocities in a variety of coronal structures at locations from 1.5 to 3.5 solar radii from the Sun.

- **Ultraviolet Coronal Spectrometer (UVCS) [SAO]**
- **White-light coronagraph (WLC) [GSFC/HAO]**

(Withbroe et al., 1982)

The spectrometer measures the intensities of **HI Lyα** and the intensities of the **OVI lines** (103.2 - 103.7 nm).

The white-light coronagraph measures the intensity and polarization of the **electron** scattered white-light corona.

Spartan 201 is launched aboard the Space Shuttle and After deployment it performs a programmed mission for 47hrs.

It flew 5 times between 1993 and 1998.

Spartan/UVCS constitutes a prototype precursor of SOHO/UVCS

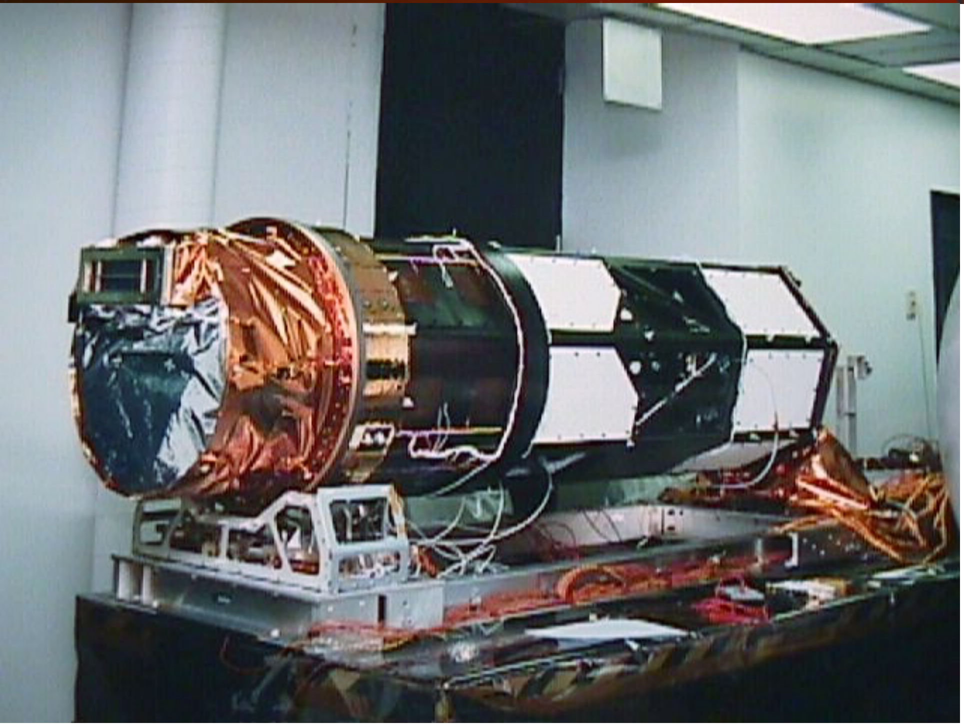
UV and VL extended corona diagnostics

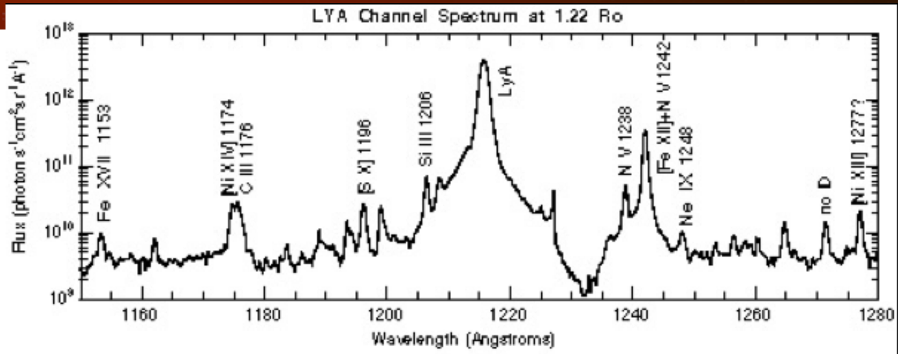
	VL imaging	UV imaging	UV spectroscopy	
			Line intensity	Line profile
Velocity	POS velocity (rising features)	POS velocity (rising features) Doppler dimming	Radial velocity (Doppler dimming)	LOS velocity (line shift) Turbulence
Density	Electrons (pB)	Hydrogen Maps	Hydrogen	Hydrogen
Abundance		Elemental Maps (He, Fe, O, etc.)	Elemental (He, Fe, O, etc.)	Elemental (He, Fe, O, etc.)
Temperature			Electron Temp. (line ratio)	Kinetic (H, ions) Electron temp.
Magnetic Field	Morphology		Spectro-polarimetry needed for MagField intensity measurement through Hanle Effect	

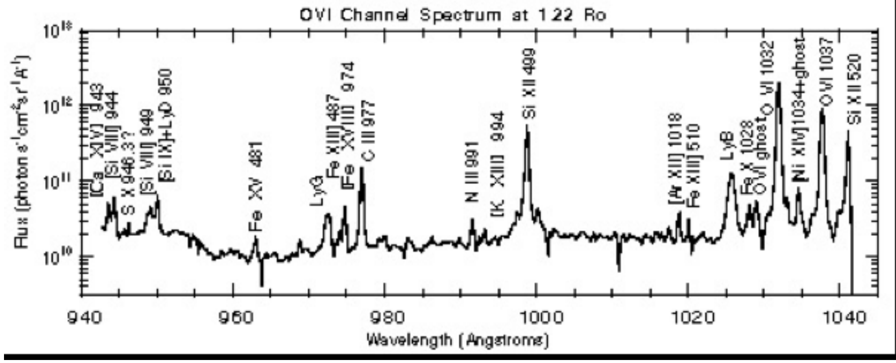
Most of the diagnostics requires the knowledge of the electron density

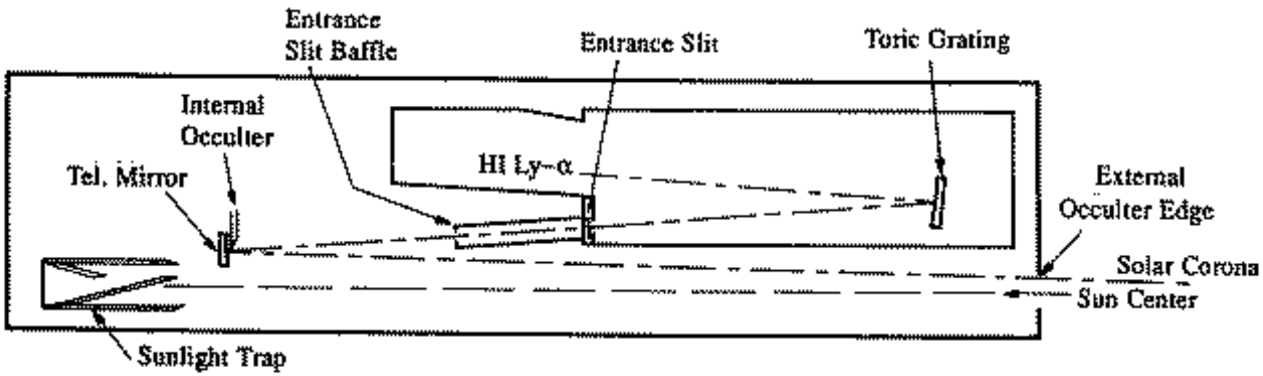
Withbroe et al. (1982), Kohl et al. (2006)

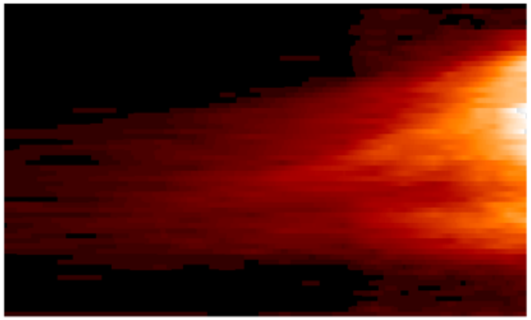
SOHO/UVCS







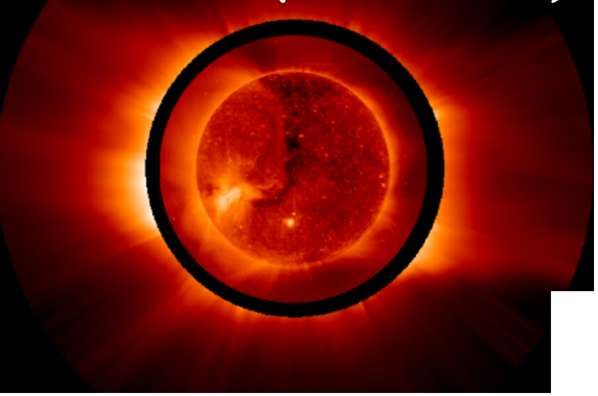




Streamer in OVI (1032 A)

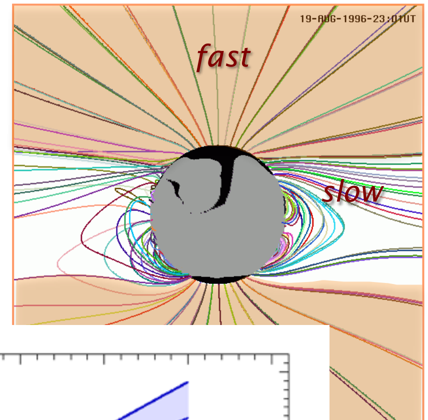
Coronal expansion of the solar wind

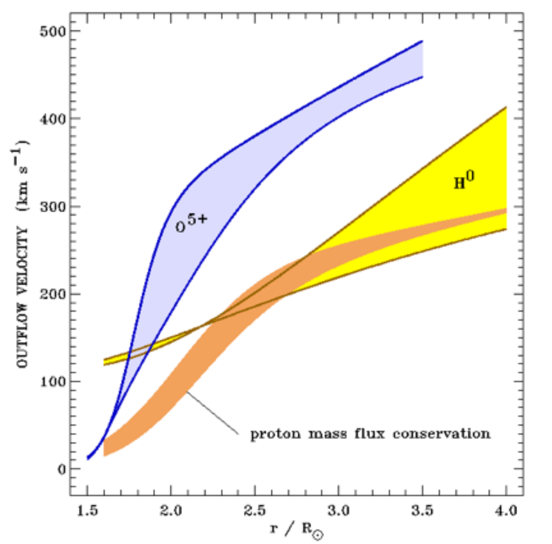
Coronal wind (UVCS-SOHO)



Kohl et al 1995, 1997

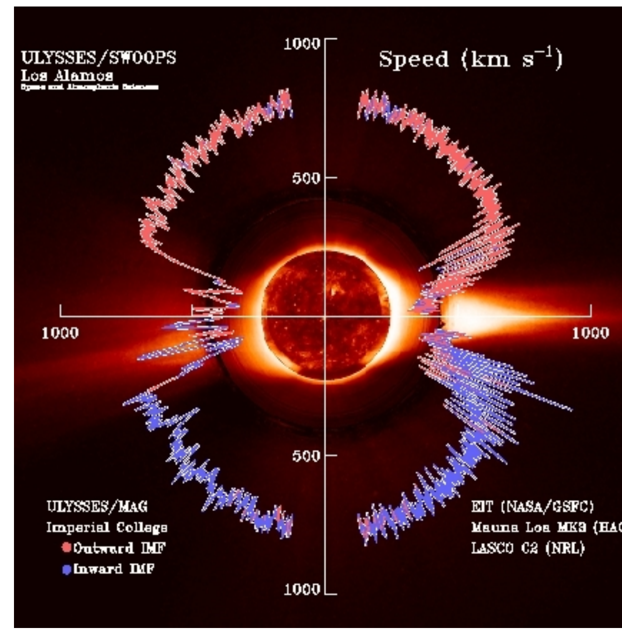
The velocity is measured with the Doppler dimming Technique [Noci, 1987)





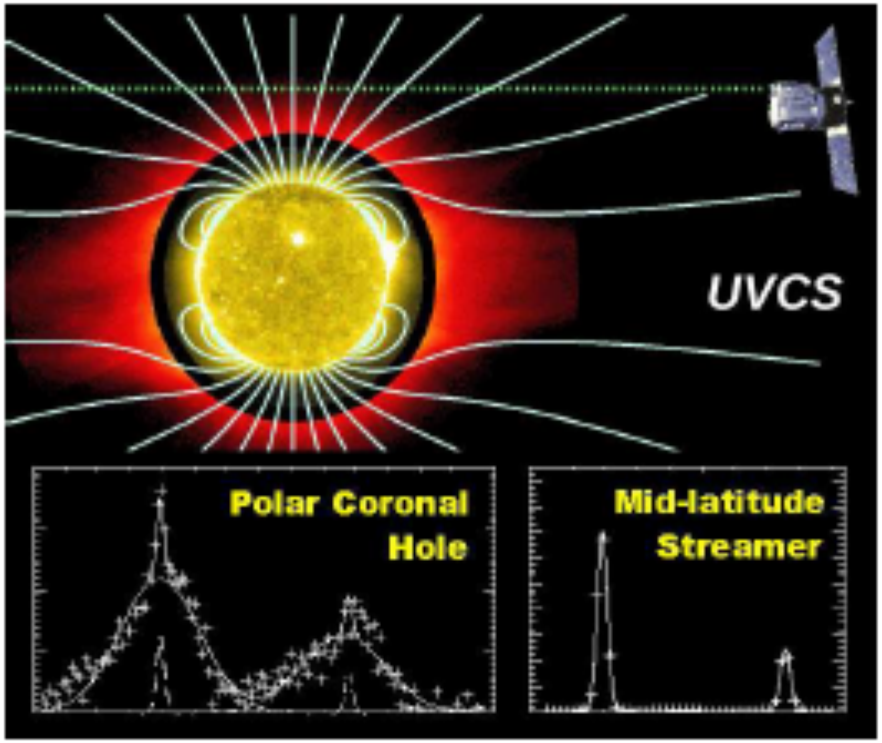
Heliospheric wind (Ulysses)

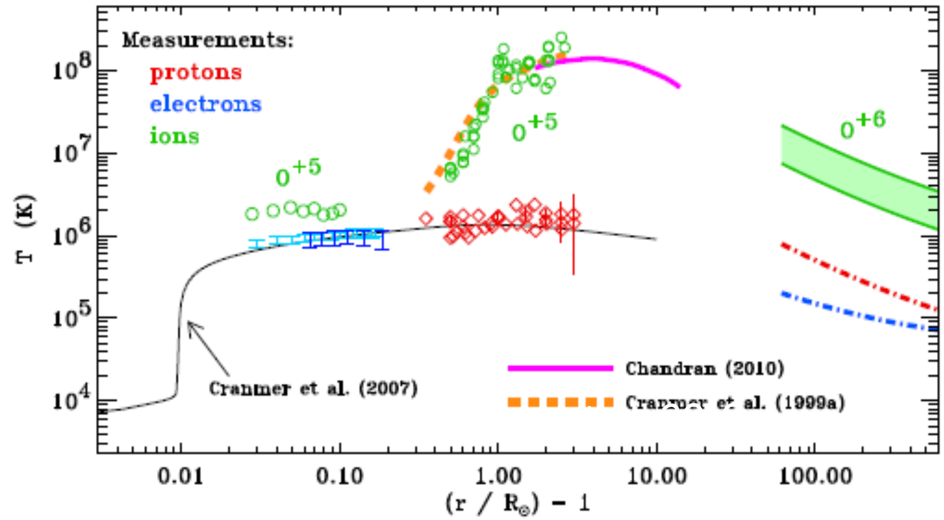
Mc Comas et al. 1998



*The open field lines emerging from solar minimum polar coronal holes channel toward the heliosphere both the **fast** and **slow** wind*

Kinetic temperatures

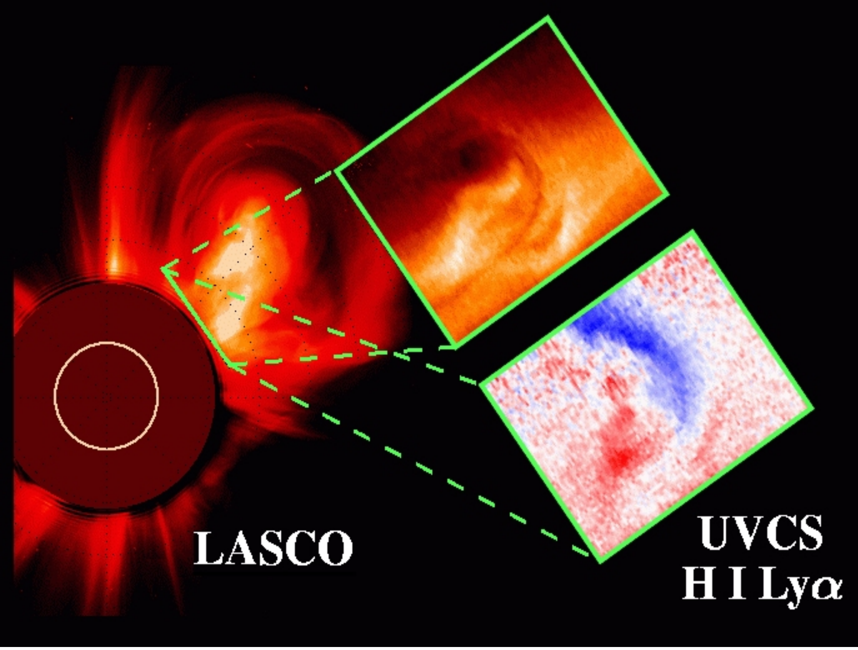


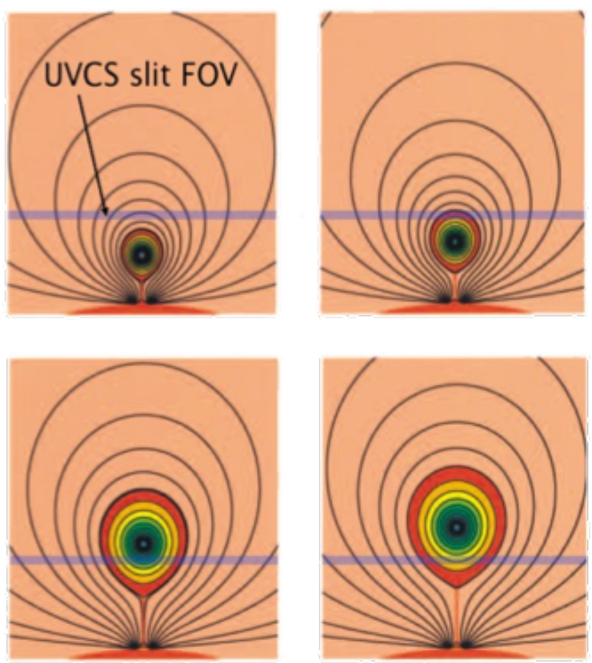


$$\begin{cases} T_{\rm ion} \gg T_p > T_e \\ (T_{\rm ion}/T_p) > (m_{\rm ion}/m_p) \\ T_\perp \gg T_\parallel \\ u_{\rm ion} > u_p \end{cases}$$

Very high temperatures and anisotropies of coronal heavy ions → (high frequency) wave-particle interactions contribute strongly to the expansion of the fast wind (Cranmer et al. 1999)

CMEs with UVCS





CME structure

- **Front**: Lya Doppler shifted
lack of SiXII → loop from streamer core
- **Cavity**: line ratio→ T_e>$10^{6.2}$K
- **Core**: abundance → no coronal origin; T_p from Lyman lines and T_e from line ratio → broad temperature range from $10^{4.4}$ to $10^{5.4}$ K
- **Helicoidal structure**: line Doppler shift e *dimming* → toric structures

HERSCHEL

HERSCHEL sub-orbital mission 2009 (NRL, IAS, INAF)

The **HERSCHEL instrument package** consists of:

1.The HERSCHEL Extreme Ultraviolet Imaging Telescope (HEIT)

a) He II (30.4 nm) images from disk to 1.5 $R_\odot$

b) Fe XI, FeXII, & FeXV coronal images from disk to 1.5 $R_\odot$ for Si XI extraction

2.The Sounding Coronagraph Experiment (SCORE)

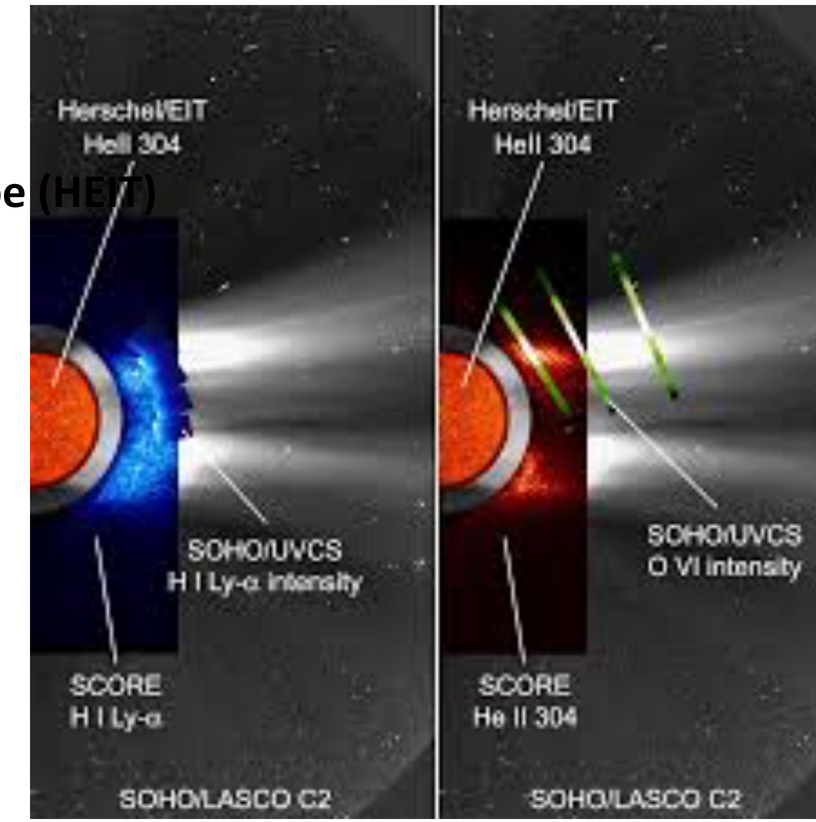
a) pB images from 1.4 to 4.0 $R_\odot$

b) HI Ly-α (121.6 nm) images from 1.4 to 4.0 $R_\odot$

c) HeII Ly-α (30.4 nm) images from 1.4 to 4.0 $R_\odot$

3.The Helium Coronagraph (HeCor)

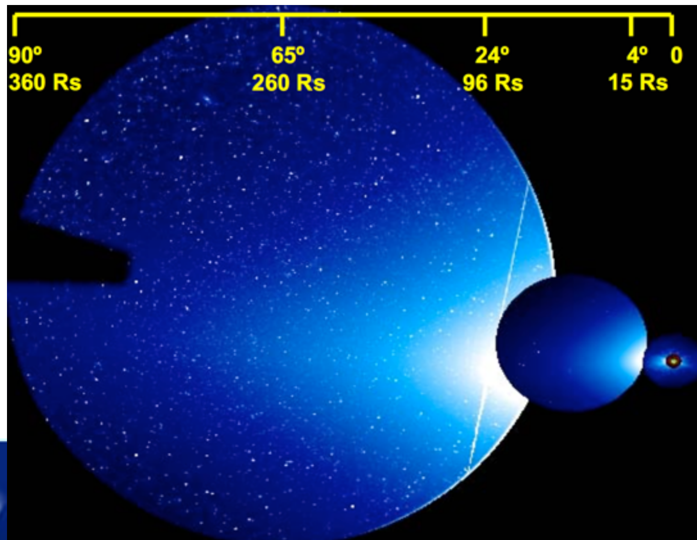
a) HeII Ly-α (30.4 nm) images from 1.2 to 4.4 $R_\odot$

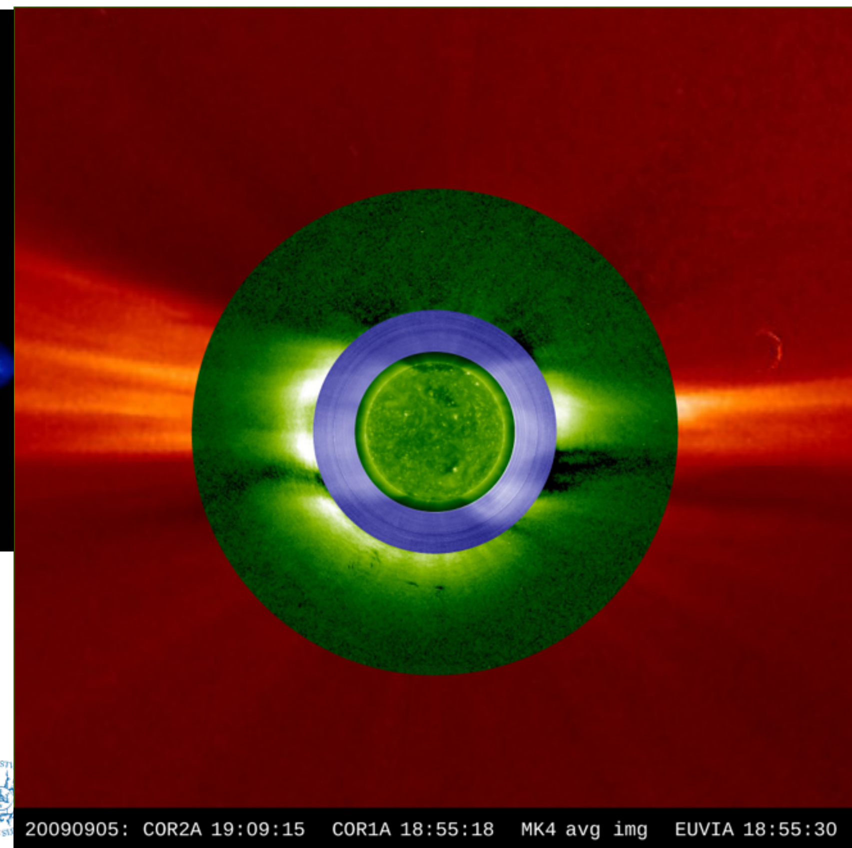


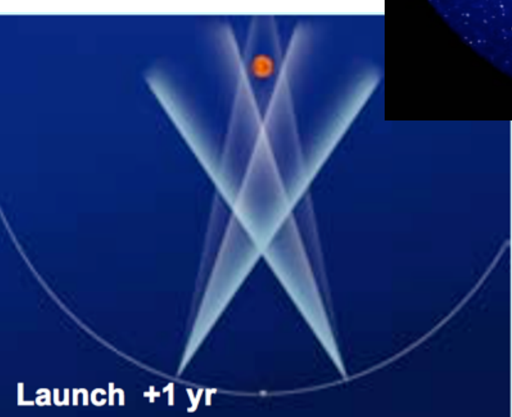
STEREO

SECCHI coronagraphs of the STEREO mission, launched in 2006.

STEREO consists of two spacecraft viewing the corona from different angles in order to observe the 3D structure of coronal mass ejections. They provide imaging and stereoscopy in polarized visible light from 1.5 $R_\odot$ in the corona to the inner heliosphere.



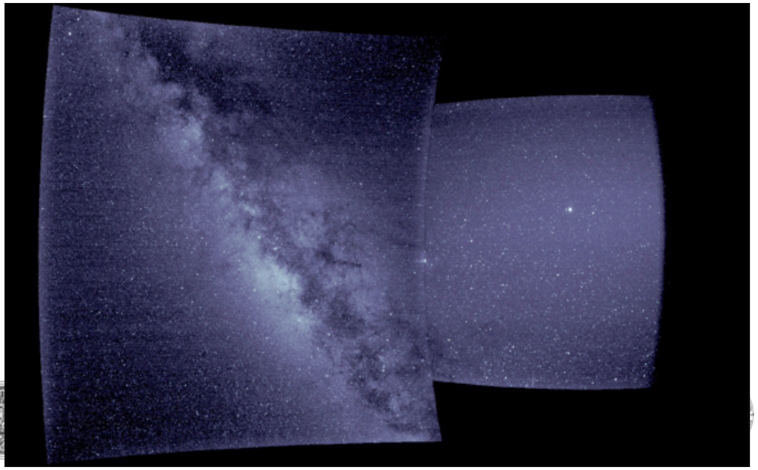




Heliospheric imagers

Heliospheric imagers explore the outer corona and the heliosphere in VL. Post-processing of images are required to extract the faint variation in the Thomson scattered radiation for the background star field, zodiacal light and stray light

- **Solar Mass Ejection Imager (SDEI) -** UCSD/CASS (2004-2011)
- **STEREO/SECCHI** NRL (2006 -) Two identical S/Cs A and B to provide stereoscopic views of the solar corona.
- **PSP Wide-field Imager for Solar PRobe (WISPR)** NRL (2018 -)
  Provides images of the solar wind, shocks and other structures as they approach and pass the spacecraft.
  (FOV 58.5˚ - 160˚ elongation)

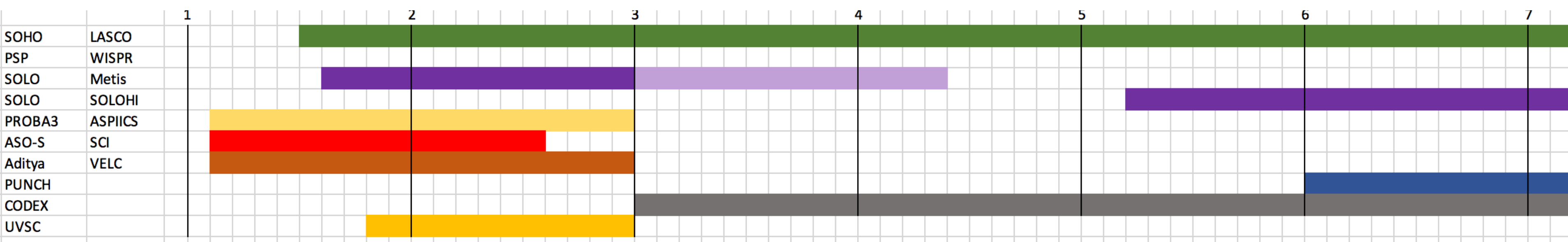


What is needed

- Magnetic field: Spectro-polarimetry
- Low FOV (1.1 – 1.6 R_s)
- Polar observations
- Space weather

Future planned coronagraphs

- **Solar Orbiter**: Metis [INAF] and SOLOHI [NRL]
- **Proba3**: ASPIICS
- **ASO-S**: Lyman-alpha Solar Telescope (LST) [CAS]
- **Aditya**: Visible Emission Line Coronagraph (VELC) [IIA]
- **PUNCH**: Polarimeter to Unify the Corona and the Heliosphere [SWRI]
- **CODEX** Coronal Diagnostics Experiment [NASA-GSFC] ISS coronagraph
- **UVSC** Ultraviolet Spectro-Coronagraph [NRL]



Spaceborne coronagraphs, 1970−1995. All externally occulted.