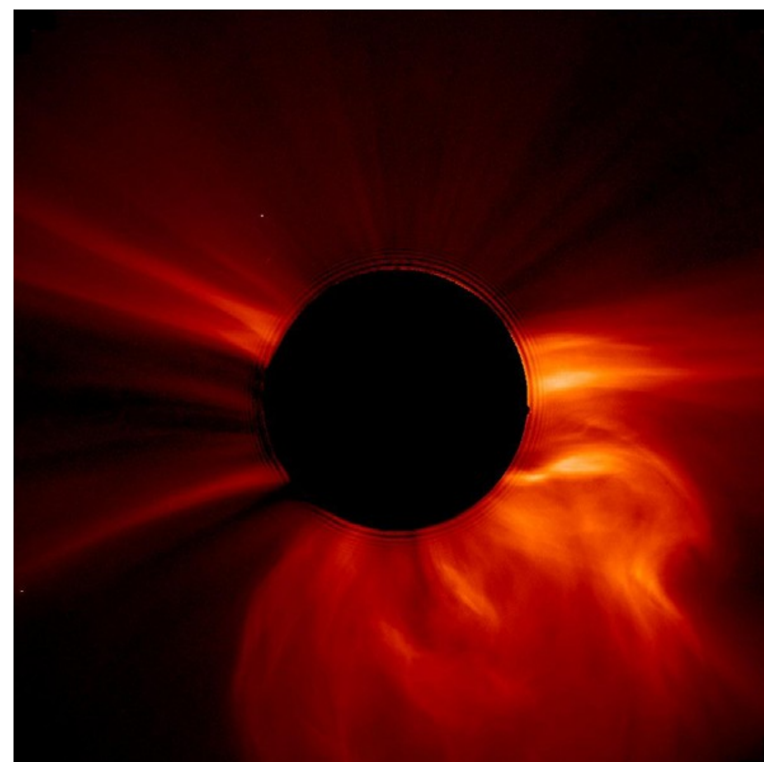
What do we see in white-light coronagraph images

Marilena Mierla

The aim

Remove all unwanted signal and stay with the CME emission plasma, i.e. the Thomson scattered radiation.

From Thomson scattering geometry the CME electron density and CME mass can be derived. Also, its position in 3D can be inferred.



Outline

The components of the solar corona

The coronagraph

Data pre-processing

CME visualization

Thomson scattering

H alpha emission in WL coronagraph images

CME propagating into the heliosphere

Summary

The solar corona

The solar corona is optically thin: what we usually observe in coronagraph images is integration along the line-of-sight (LOS)

The solar corona components:

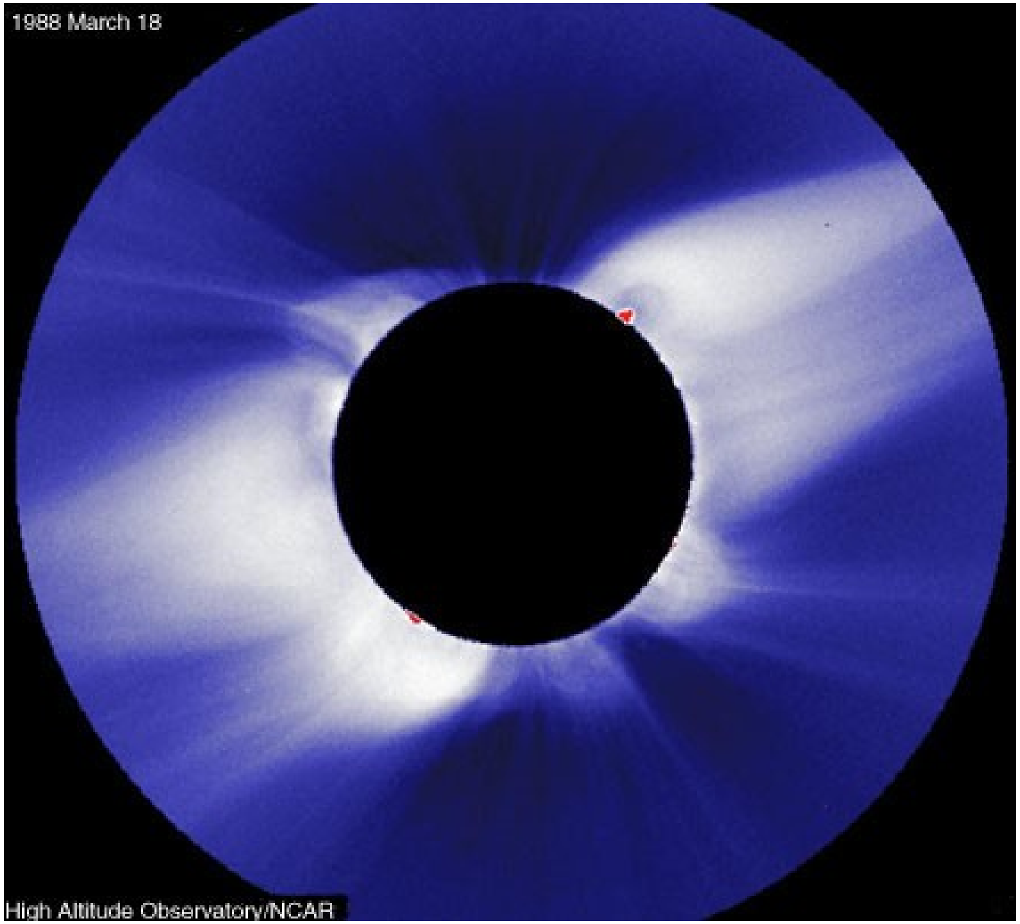
-K-corona: electron or continuum corona – Thomson scattering

-F-corona: Fraunhofer or dust corona – scattering of the light on the dust particles (contains Fraunhofer absorption lines)

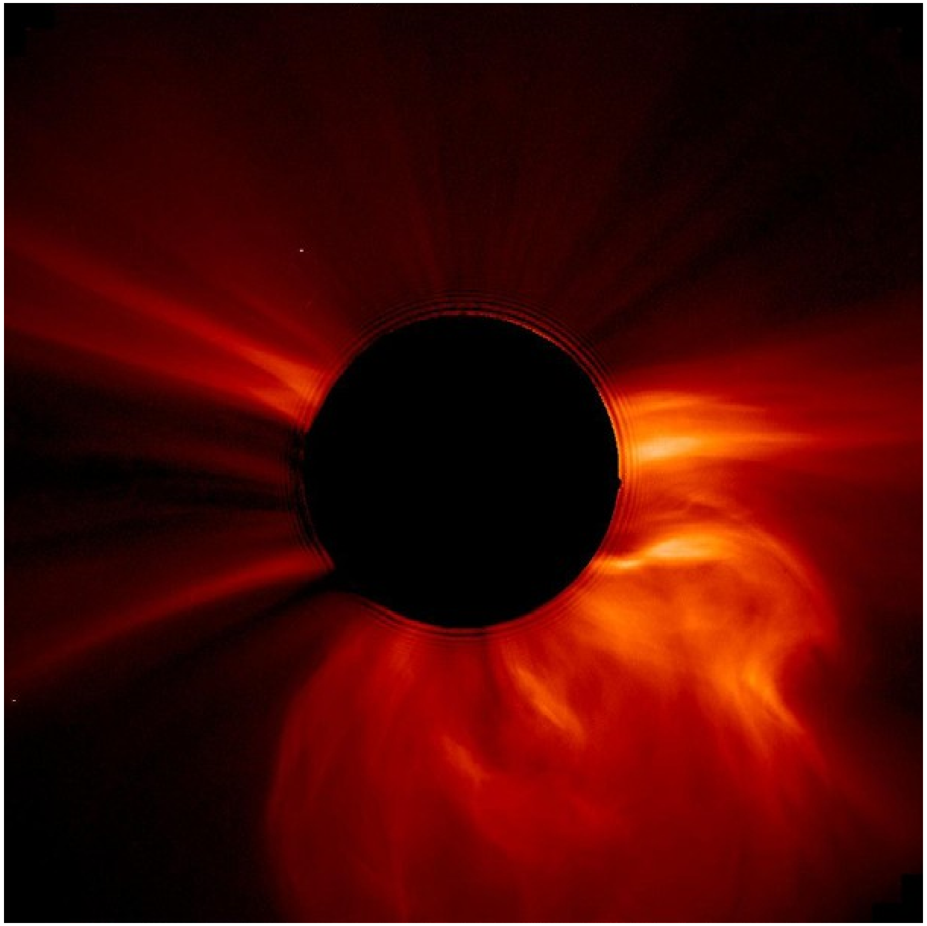
-E-corona: emission corona – emission of highly ionized atoms (and sometimes also H alpha emission)

The solar corona

K - (Electron or continuum) corona is due to scattering of sunlight (photospheric light) on free electrons of the corona (Thomson scattering).



The solar corona during the 1988 solar eclipse (courtesy HAO)

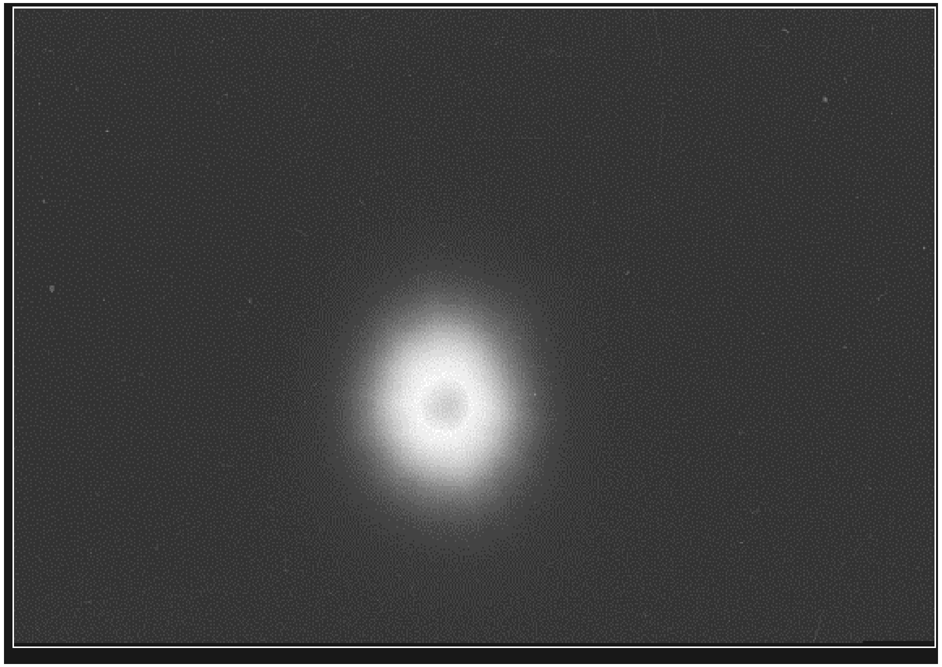


LASCO-C2 images recorded on 29 March 1998, 03:48 UT

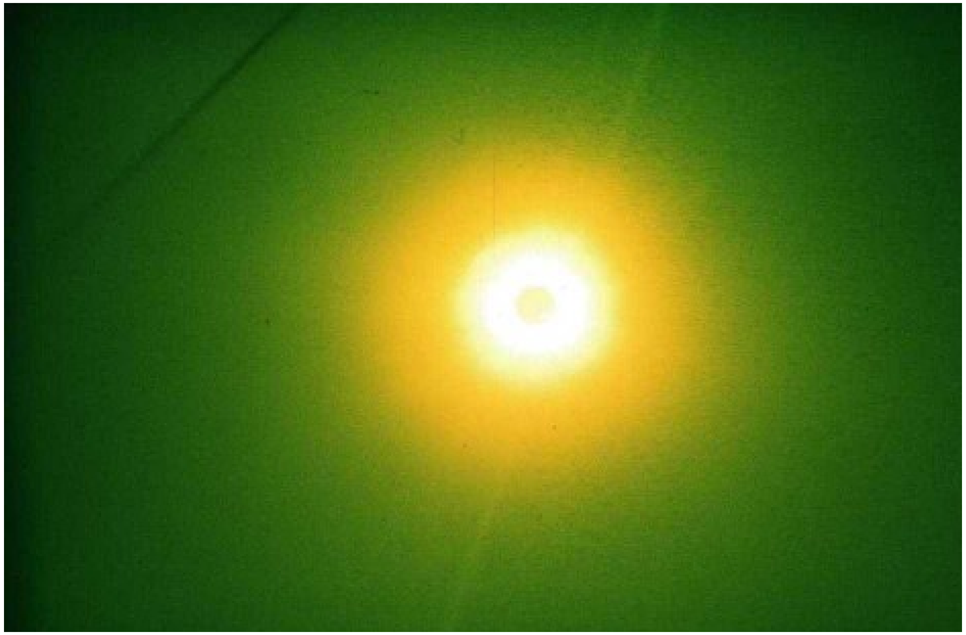
The solar corona

- F - (Fraunhofer or Dust) corona is due to scattering of sunlight on dust particles.

Thermal (T) corona is produced by thermal emission of dust particles heated by the Sun.



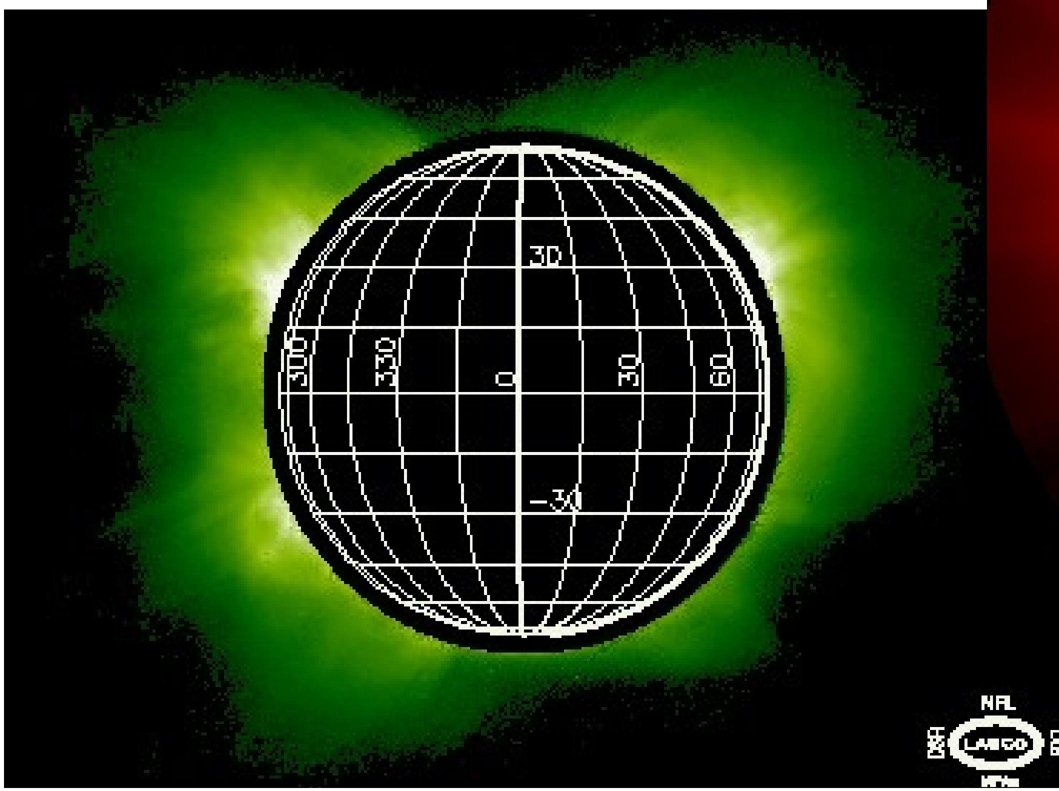
F- corona during the solar eclipse in 1999 in near Infrared light (690-950 nm)
(Shopov et al. 2008)



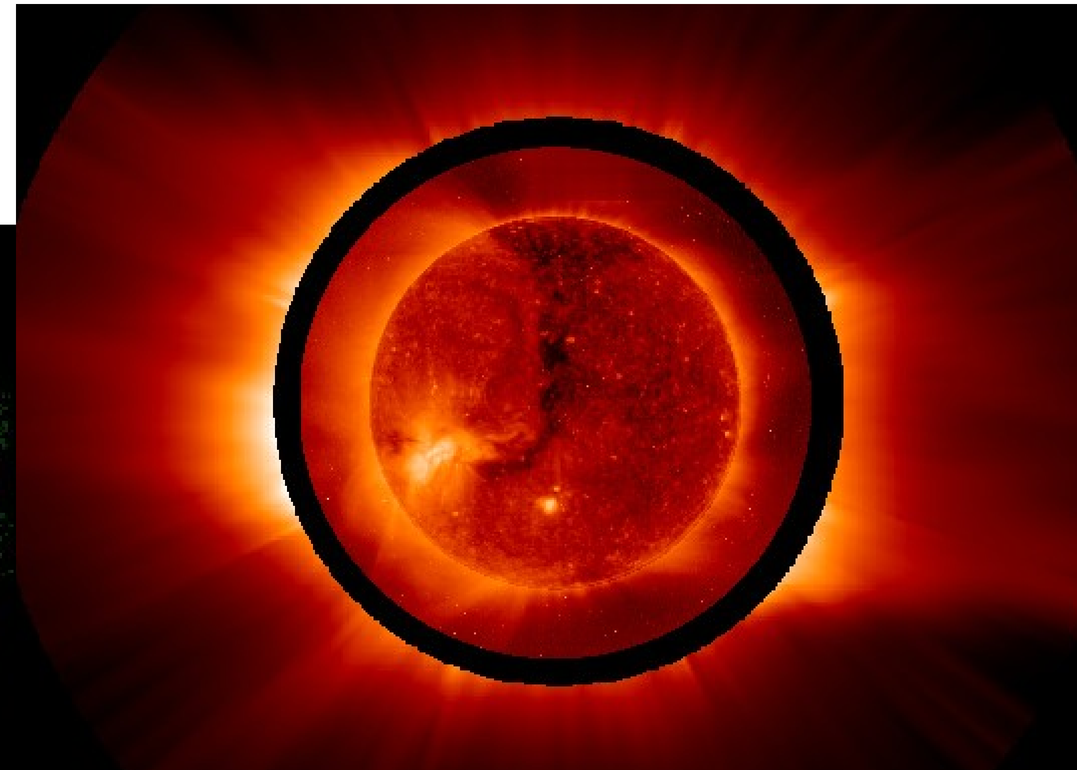
F- corona (green) and T- corona (orange) during the solar eclipse on 11.08.1999 (Shopov and Stoykova, 1999).

The solar corona

- *E – (Emission) corona* is due to a line emission spectrum of highly ionized atoms of Fe, Ni and Ca (Golub and Passachoff, 1997)



The green corona recorded by LASCO-C1 coronagraph on 7 June 1998.



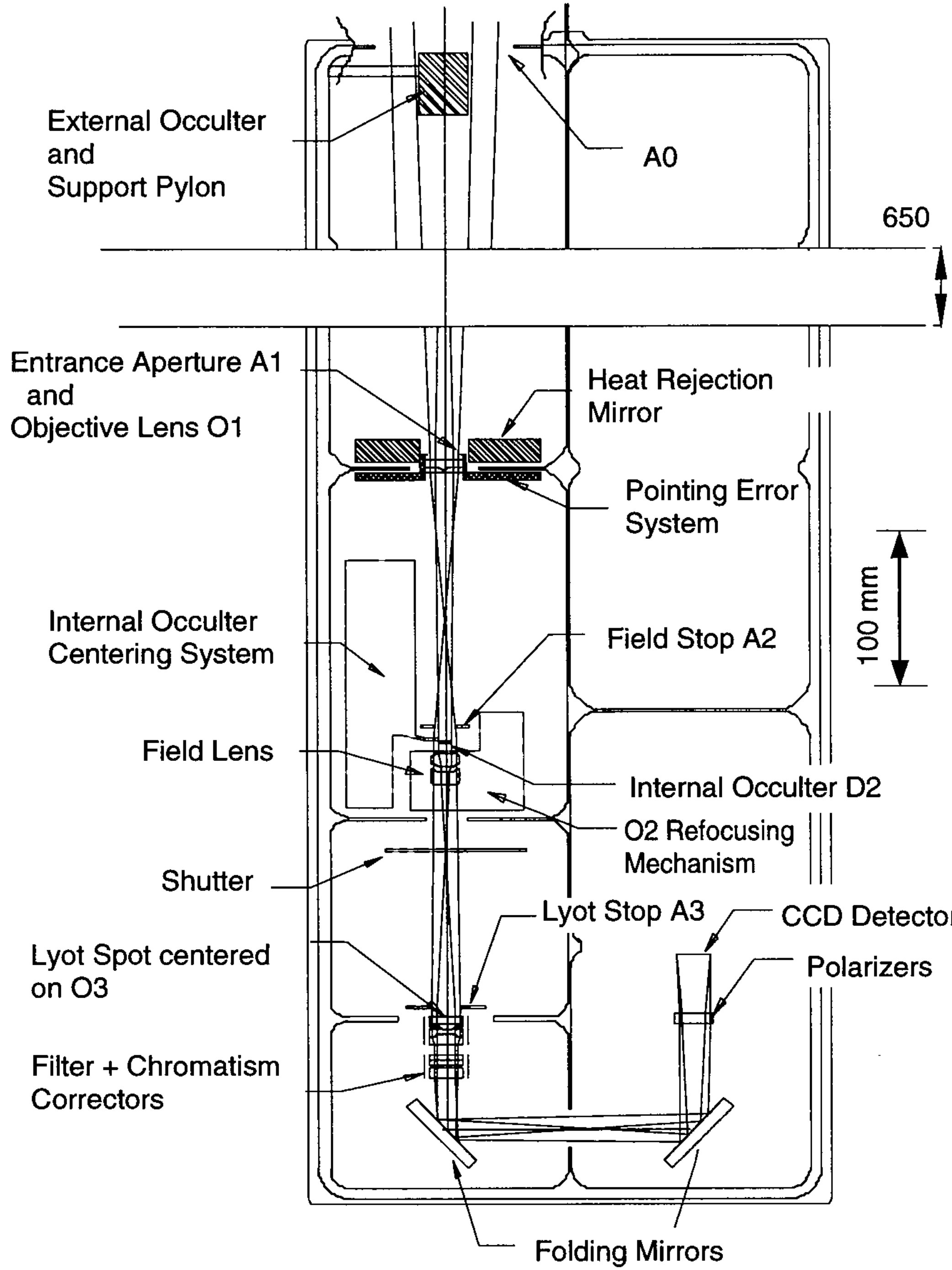
The ultraviolet Sun: The composite image, taken by EIT (inner part) and UVCS (outer part) reveals the ultraviolet light of the Sun’s atmosphere from the base of the corona to millions of kilometers above the visible disk (August 1996).

The coronagraph

- **Suppression of stray-light:**
proper optimization of the external occulter, the objective lens O1 and its apperture, and the internal occulter.
  - **External occulter:**
  a multiple (160) sharp threads diamond-machined on a cone whose Angle slightly exceeds that subtended by the Sun at the L1 Lagrangian point (rejection of 1.5×10^{-5} – Lamy et al. 1994)

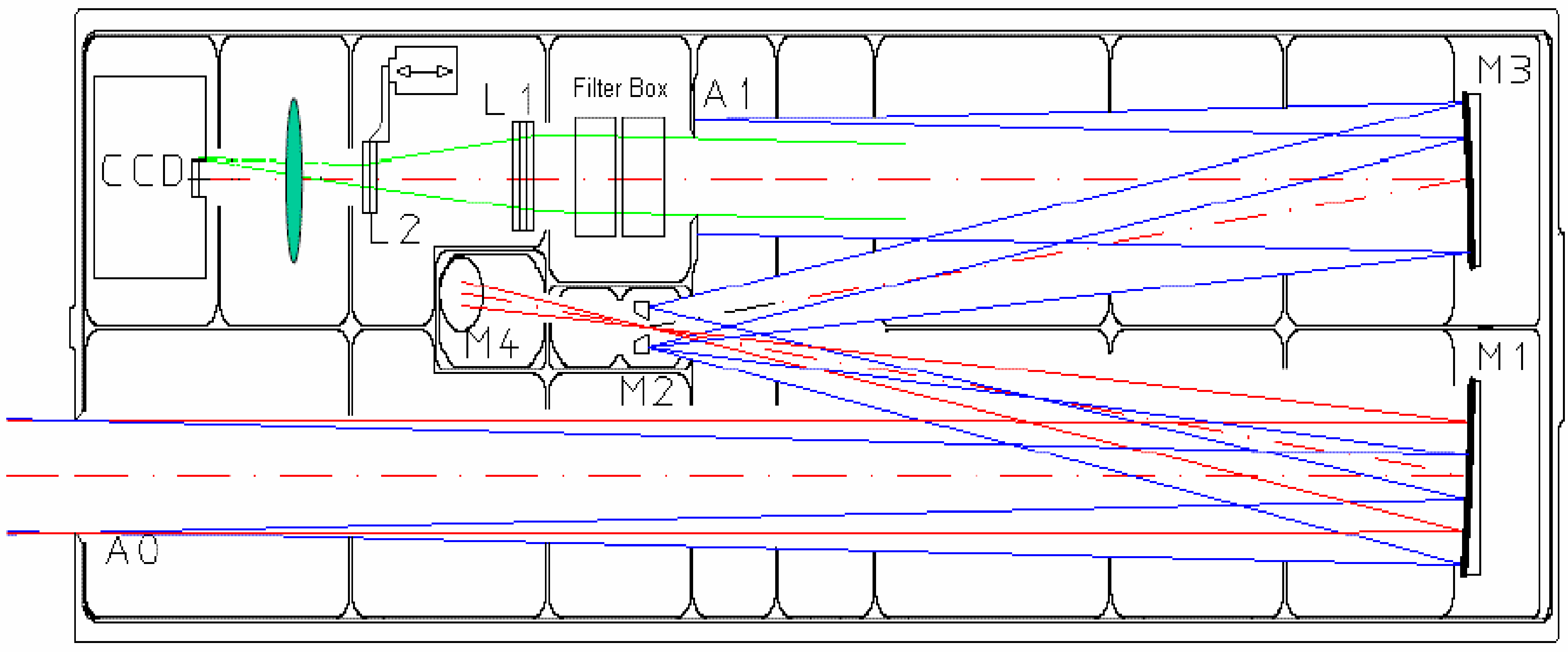
- **The light diffracted** by the entrance aperture A0 is of major concern: to minimize it introduce a serrated design whose direct diffraction avoids O1.

- **The integrated light scattered** by the O1 objective as measured at the A1 aperture: 5×10^{-5} of the illuminating source



The optical layout of LASCO-C2 coronagraph **(externally occulted)** (Brueckner et al. 1995)

The coronagraph



The optical layout of LASCO-C1 coronagraph **(internally occulted).**
Coronagraph. Red: photospheric light (solar disk), blue: diffracted sunlight at the edges of A0, green: scattered sunlight + corona light (Stenborg et al. 1999)

Stray light in LASCO coronagraphs

Mesured stray-light levels in C1 C2 and C3 versus the K+F corona. The fields of view of previous coronagraphs are indicated (Brueckner et al. 199

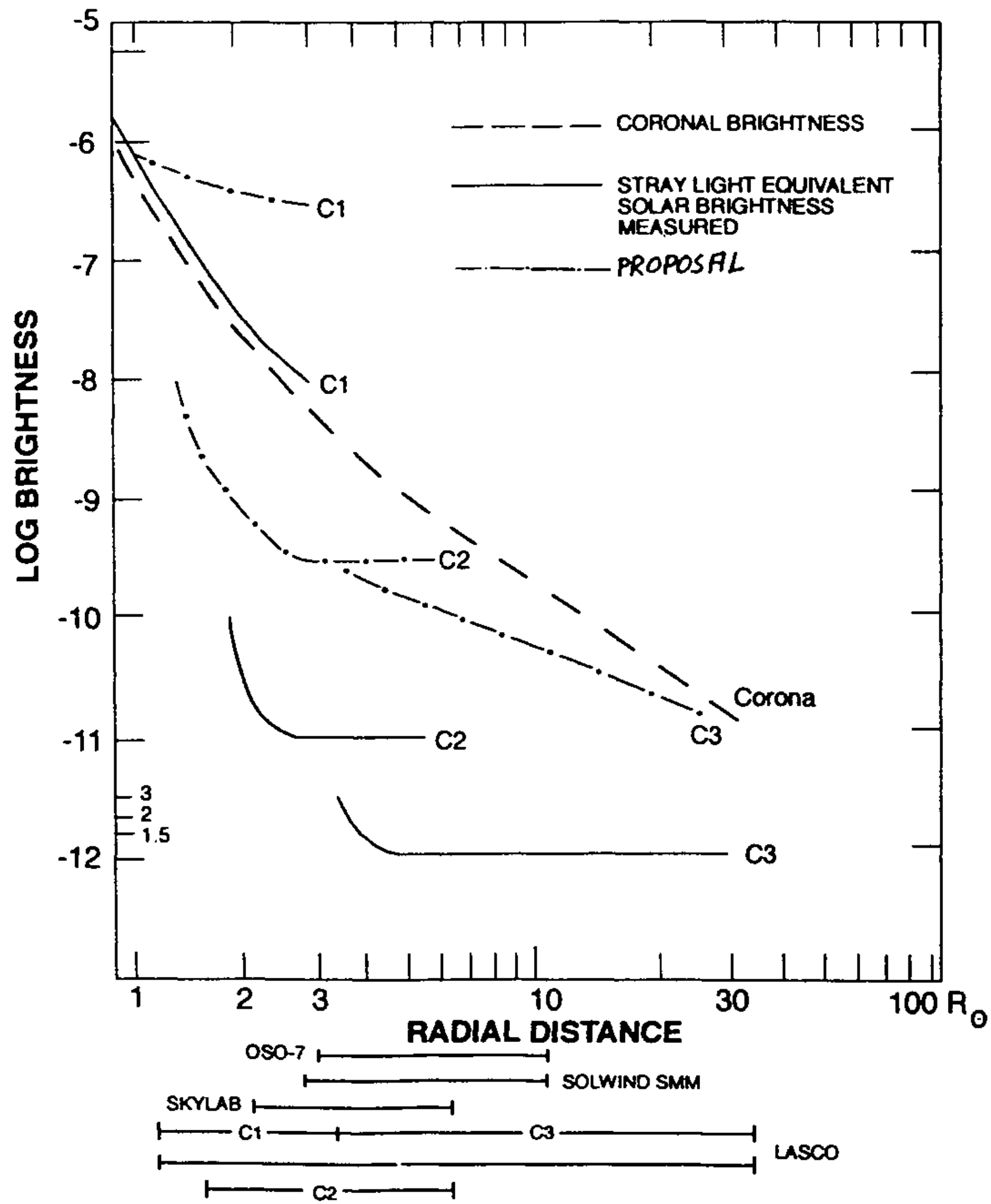


Image acquisition

The image of the solar corona is recorded on the 1024x1024 pixel CCD camera.
Thermally generated electrons are indistinguishable from photo-generated electrons **(dark current).**
The analog signal processing amplifies the output of the CCD by a factor of about 30 **(bias)**
The analogue signal is digitized to 14 bits by an analog-to-digital converter, with a quantization step of about 15-20 electrons.

edges of D1. A short distance behind D2 is a field lens O2, which collimates the primary coronal image, and also images A1 onto the Lyot stop A3. The Lyot stop intercepts diffracted light originating at the entrance aperture A1. Finally, a relay lens O3 behind A3 re-images the primary coronal image onto the 1024x1024 pixel CCD camera at the image plane F. The front surface of the O3 relay lens also carries the Lyot spot. The Lyot spot for the externally occulted coronagraphs intercepts residual diffracted light from D1, imaged on the spot by inter-reflections in the O1 objective lens. Color filters and linear polarizing filters (F/P) are carried on two wheels in front of the focal plane.

Table 1 summarizes the design parameters of the three coronagraphs.

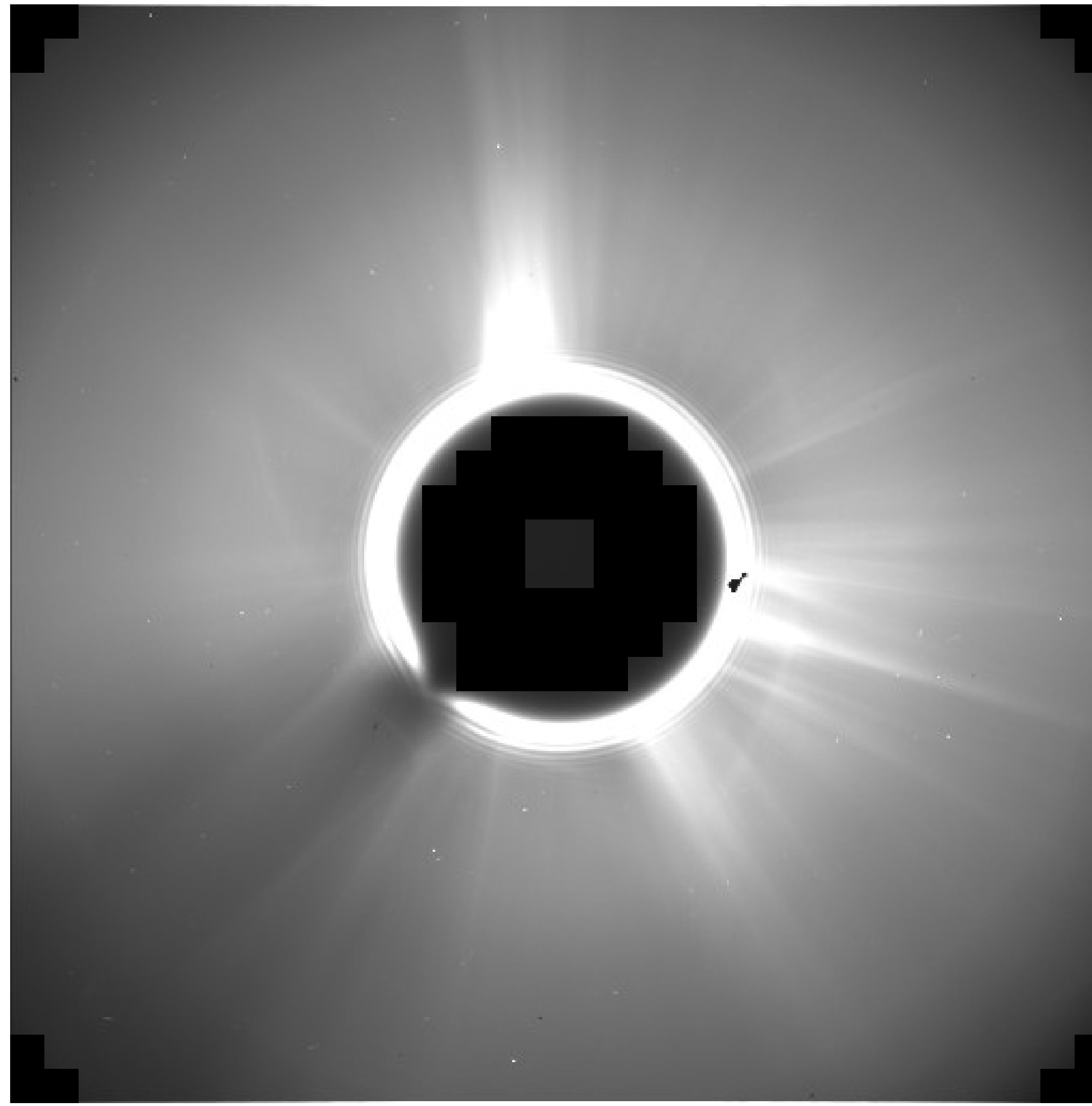
After taking, processing and compressing an image, the data are passed to a 2 Mbyte Telemetry buffer.

Brueckner et al. 1995

LASCO raw image

One raw white-light coronagraph image contains:

- -The dark current
- -The bias
- -The stray-light
- -The K-corona
- -The F-corona
- -Emission corona
- -Cosmic rays…



LASCO-C2 raw image

LASCO data pre-processing

- Subtract bias
- Divide by exposure time
- replace missing blocks
- Multiply by calibration factor (optional)
- Multiply by (inverse) vignetting function/array (divide the flat-field)
- Subtract stray light
- Distortion correction
- Rectify image to solar north up, if SOHO in upside-down position

There are SolarSoft routines which are doing all these corrections.

Visualize the CMEs

To remove the unwanted signal:

-Subtract monthly background – (streamers still there)

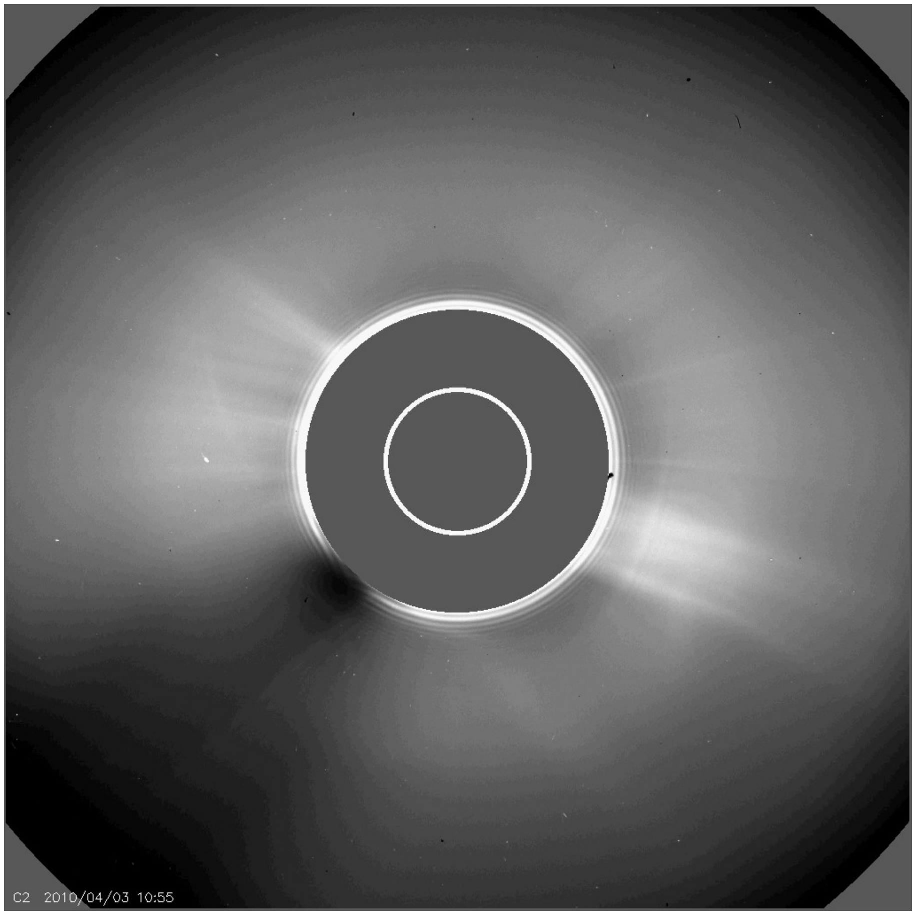
-Base difference or running difference images

-To remove cosmic rays apply median filtering

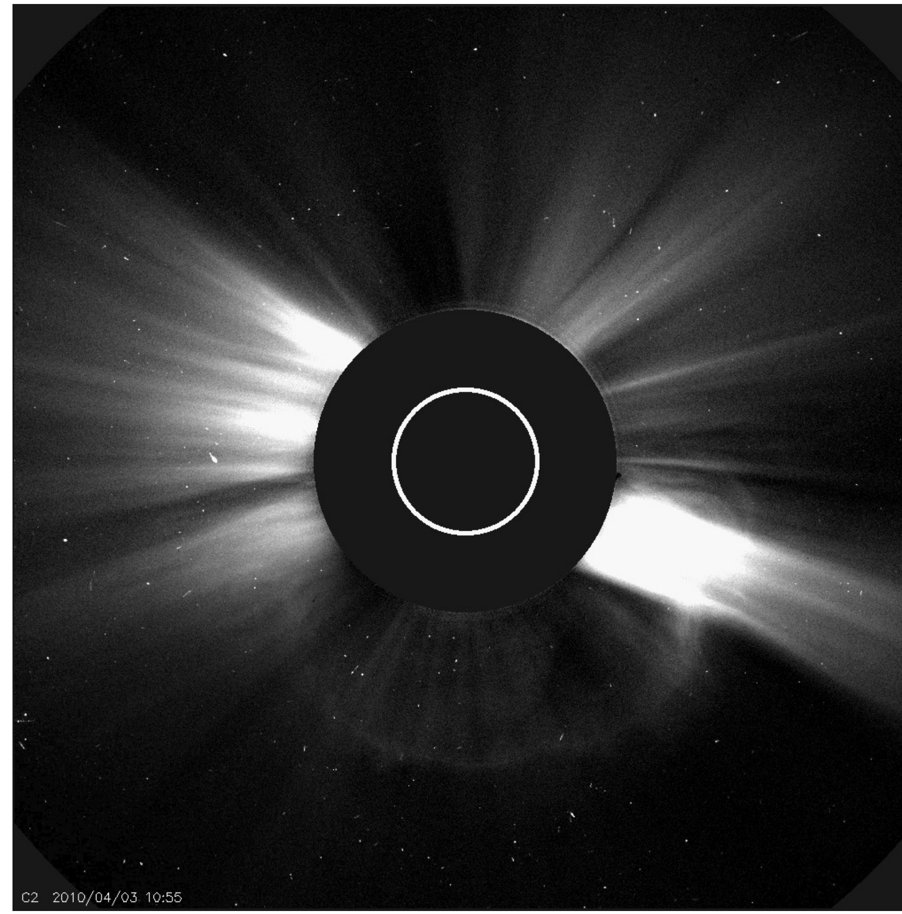
What should be left is only K-corona – but sometimes we also see H alpha emission
in the core of the CMEs – e.g. of 31 Aug 2007 event

Visualize the CMEs

- Raw image



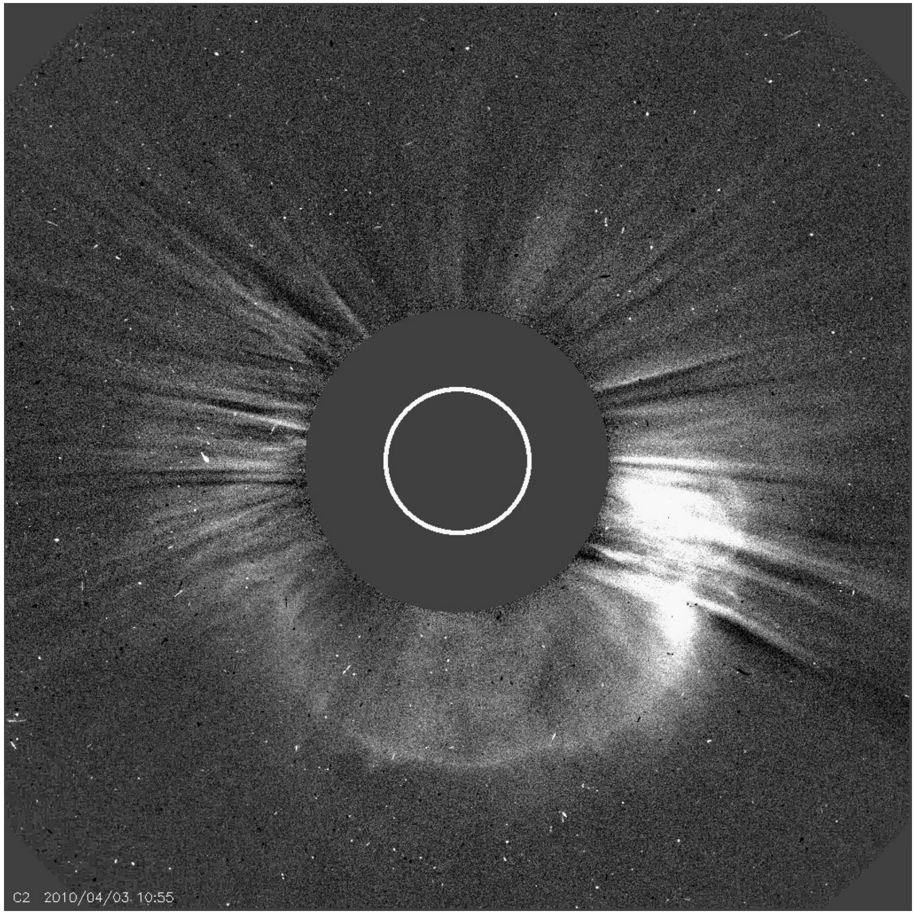
- Monthly background

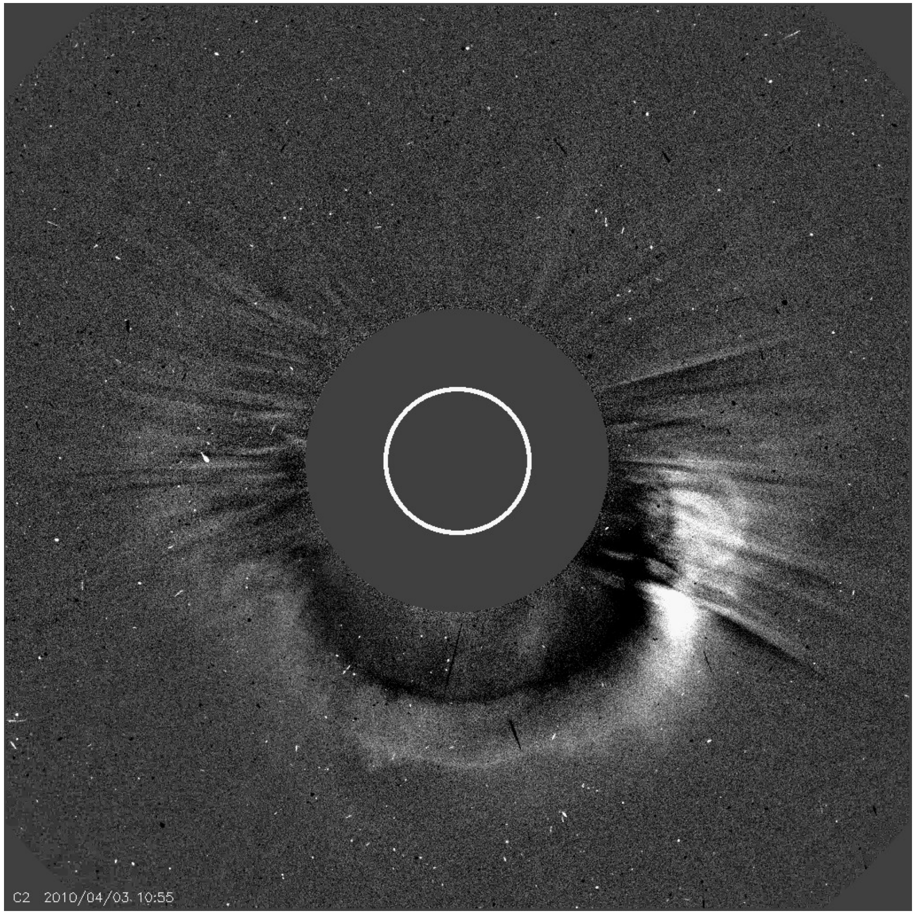


Visualize the CMEs

- Base difference

- running difference

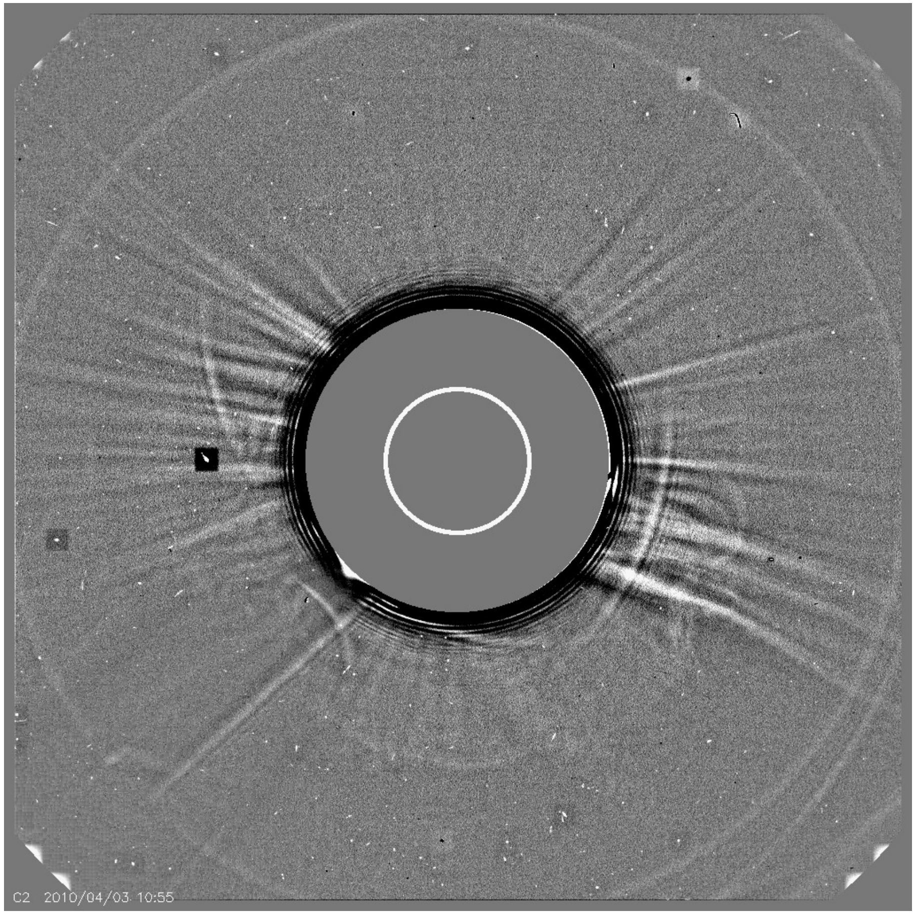


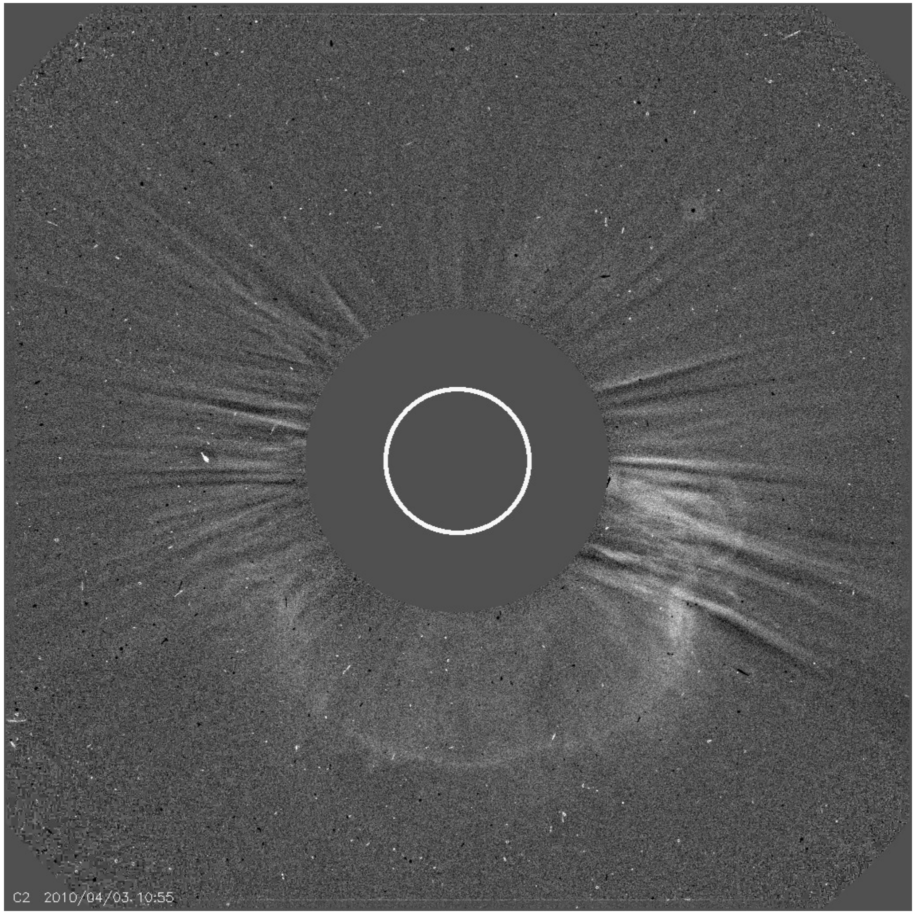


Visualize the CMEs

- Unsharp mask

- Sharpen ratio





Thomson scattering

Billings 1966

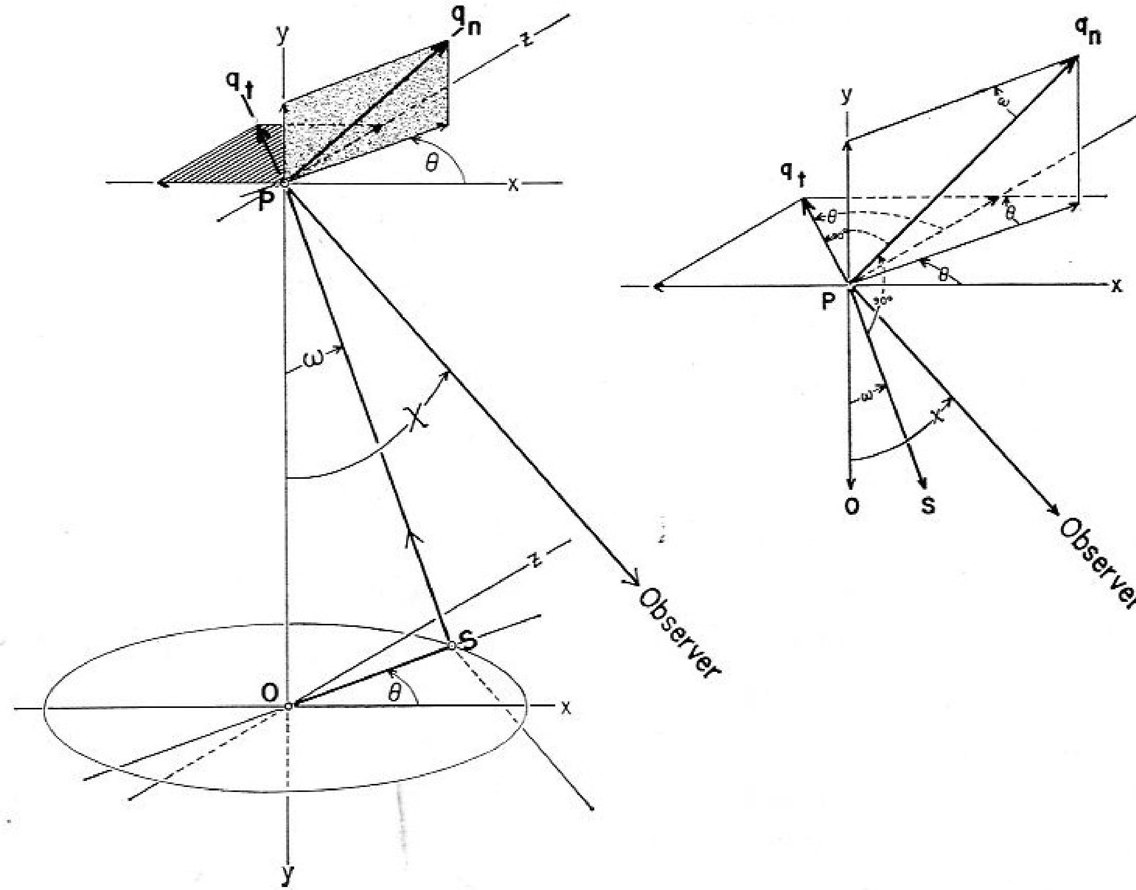


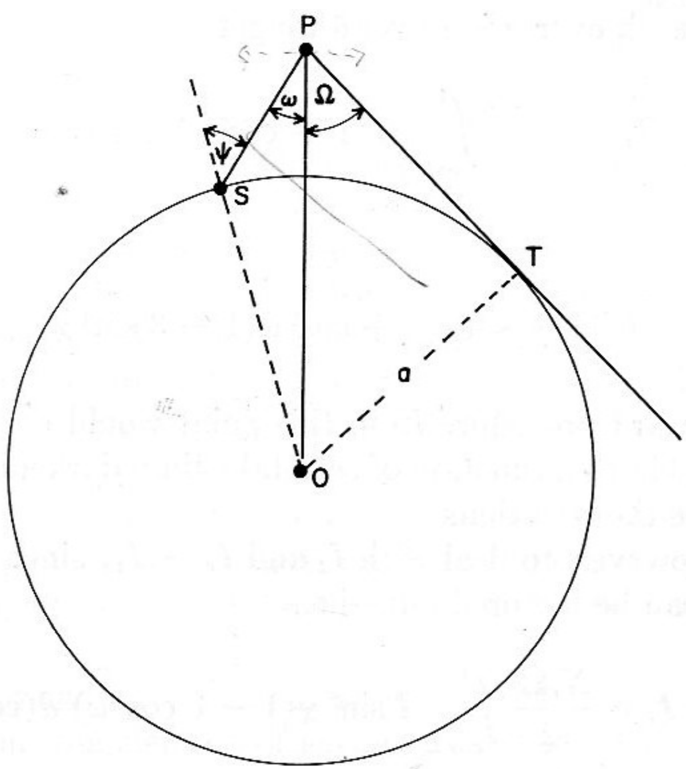
Fig. 6.1. Geometry of electron scattering in the corona. The ellipse is a circle about the y axis, on the solar photosphere, as seen in perspective. The plane of the paper, the x–y plane, also includes the line of sight to the observer. The source of radiation, S, on the photosphere, is represented as lying behind the plane of the paper in a plane OPS that makes an angle ν with the x–y plane. The radiation vector qn and its components also lie in this plane.

Thomson scattering

I_r = the intensity of the radially-electric Vector-scattered radiation
I_t = the tangential electric vector component
of the scattered radiation
u = limb darkening

$$I_t = I_0 \frac{N_e \pi \sigma}{2} [(1 - u) C + uD]$$

$$I_t - I_r = I_0 \frac{N_e \pi \sigma}{2} \sin^2 \chi [(1 - u) A + uB],$$



$$A = \cos \Omega \sin^2 \Omega,$$

$$B = -\frac{1}{8}\left[1 - 3\sin^2 \Omega - \frac{\cos^2 \Omega}{\sin \Omega}(1 + 3\sin^2 \Omega) \ln \frac{1 + \sin \Omega}{\cos \Omega}\right],$$

$$C = \tfrac{4}{3} - \cos \Omega - \frac{\cos^3 \Omega}{3},$$

$$D = \frac{1}{8}\left[5 + \sin^2 \Omega - \frac{\cos^2 \Omega}{\sin \Omega}(5 - \sin^2 \Omega) \ln \frac{1 + \sin \Omega}{\cos \Omega}\right].$$

Billings 1966

Polarization ratio (observations)

- the ratio of polarized-to-unpolarized electron-scattered emissivity (K-corona) is measured by recording coronal images through three polarizers with axes oriented at 0 (I_A), 120 (I_B) and 240 (I_C) degrees.

$$I_{\mathrm{p,cme}} = \frac{4}{3}[(I_A + I_B + I_C)^2 - 3(I_A I_B + I_A I_C + I_B I_C)]^{1/2}$$

use secchi_prep.pro

$$I_{\mathrm{p,cme}} = \frac{2}{3}(I_A + I_B + I_C)$$

$$I_{\mathrm{u,cme}} = I_{\mathrm{t,cme}} - I_{\mathrm{p,cme}}$$

where I = electron-scattered brightness

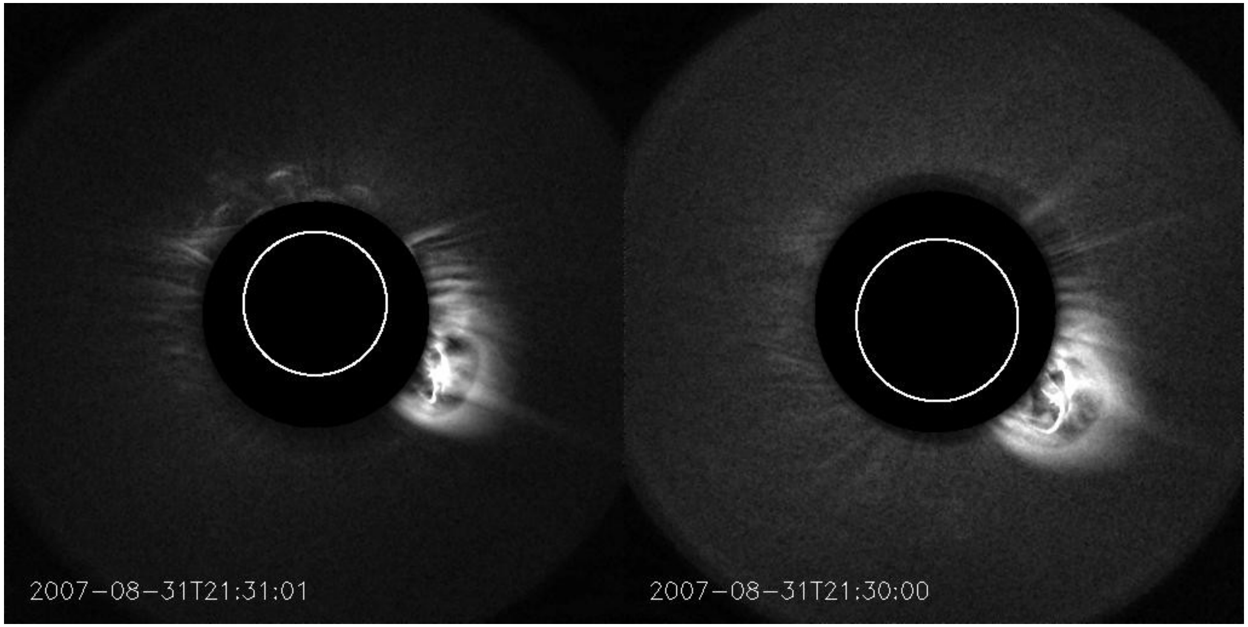
A measurement of the brightness ratio determines the LOS averaged distance from the plane of the sky (see Moran and Davila 2004).

Emission corona - Halpha

COR1 observes in a white-light waveband 22.5 nm wide centred at the Hα line at 656 nm (Thompson & Reginald 2008).

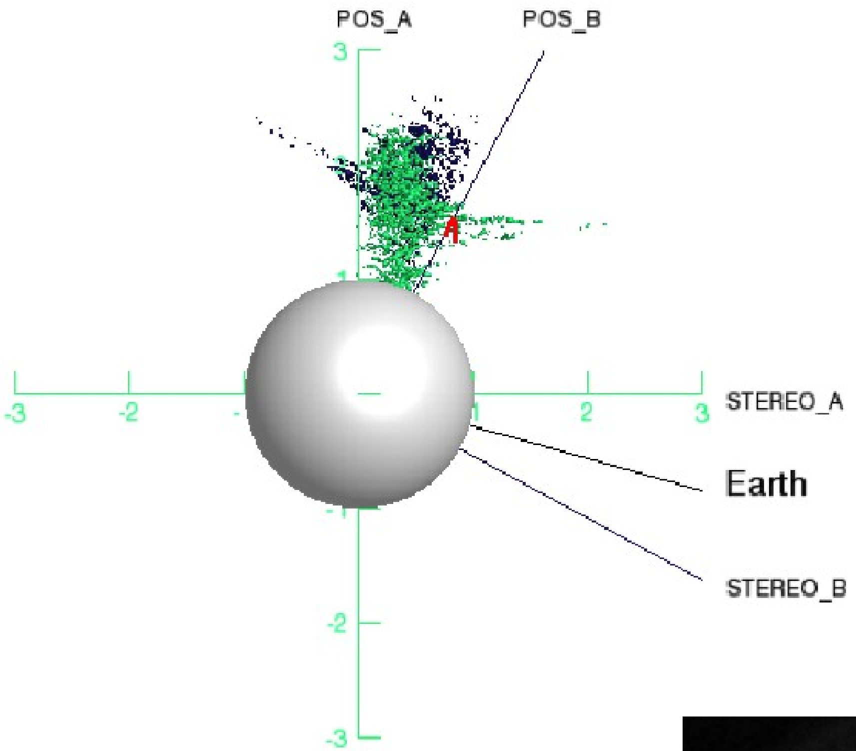
The COR1 coronagraphs take polarised images at three different polarisation angles at 0, 120, and 240 degrees.

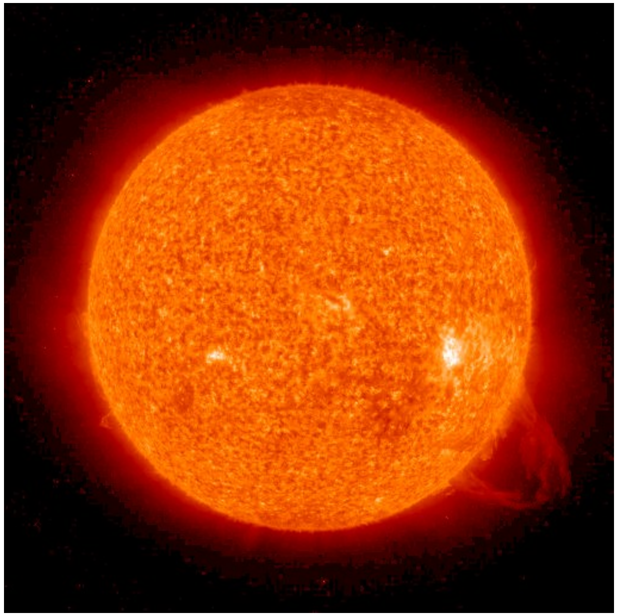
These primary data allow to derive Stokes *I*, *U* and *Q* components and finally total (*tB*), polarised (*pB*) and unpolarised brightness ($uB = tB - pB$) images.

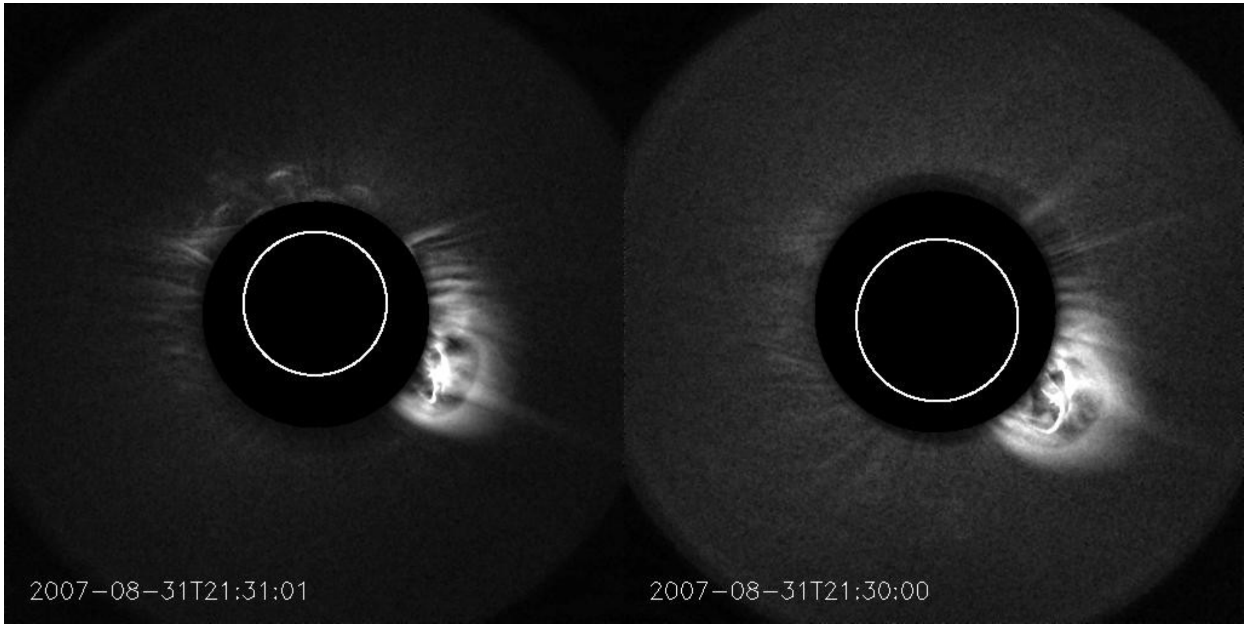


Mierla et al. 2011

Emission corona – H alpha







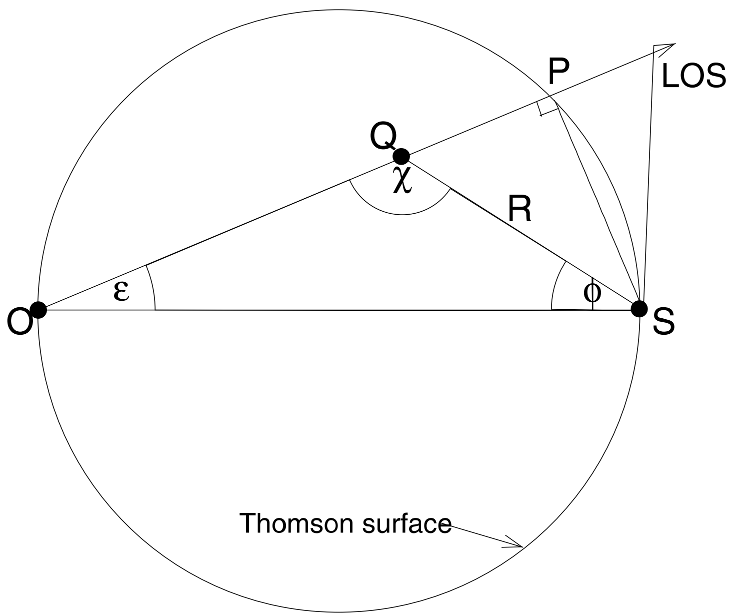
the major part of the CME core emission, more than 85% in this case, is Hα radiation and only a small fraction is Thomson-scattered light.

Mierla et al. 2011

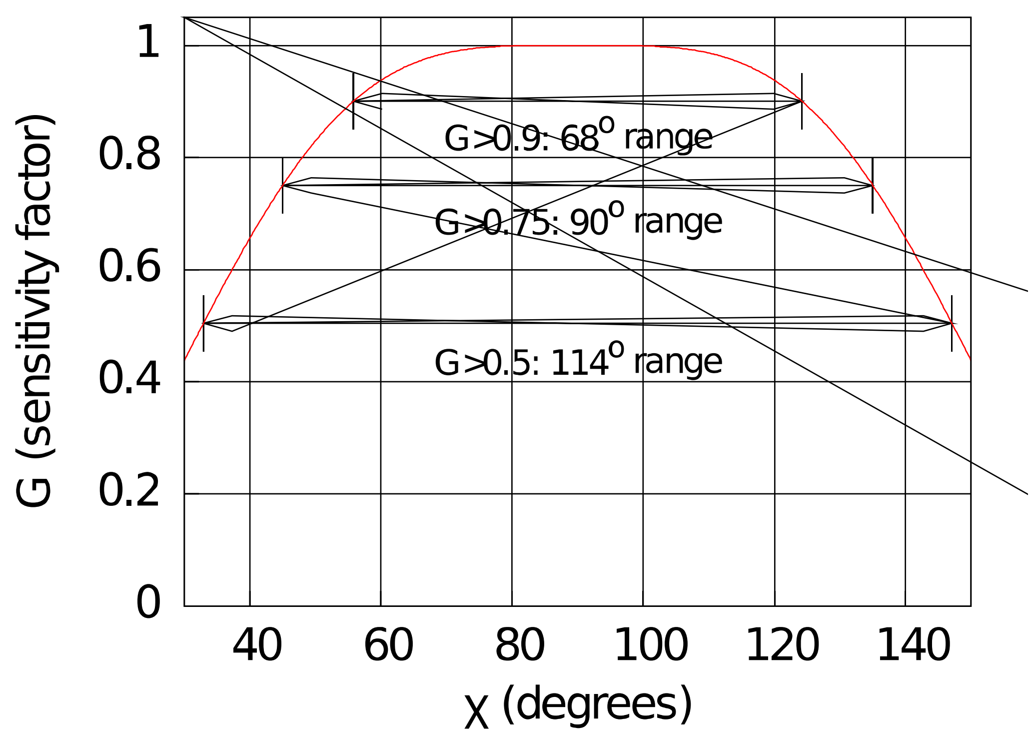
Feature visibility - Thomson sphere

Vourlidas and Howard, 2006; Howard et al. 2009

The incident light and density are maximized on the Thomson sphere along any LOS. The scattering efficiency is minimized on the Thomson sphere.

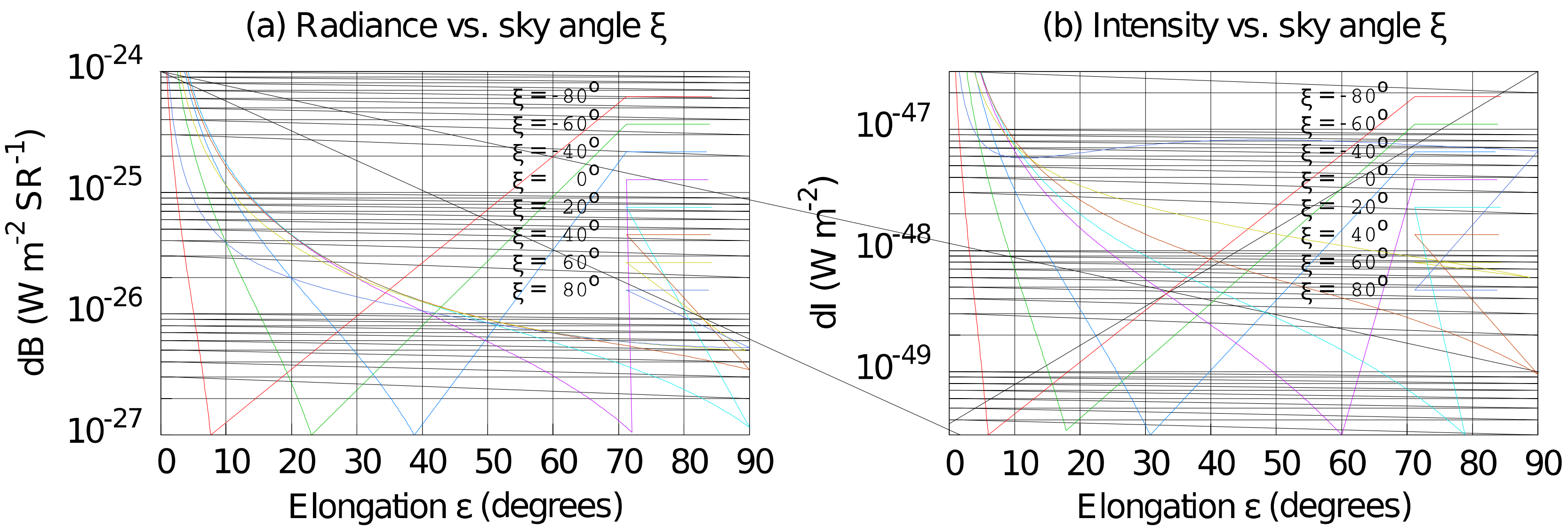


Thomson plateau (Howard and DeForest 2012)



Feature visibility in heliospheric imagers

$$dI \equiv \frac{dP}{dA} = B\,d\Omega = B\frac{dA}{z^2},$$ For small features or large distances



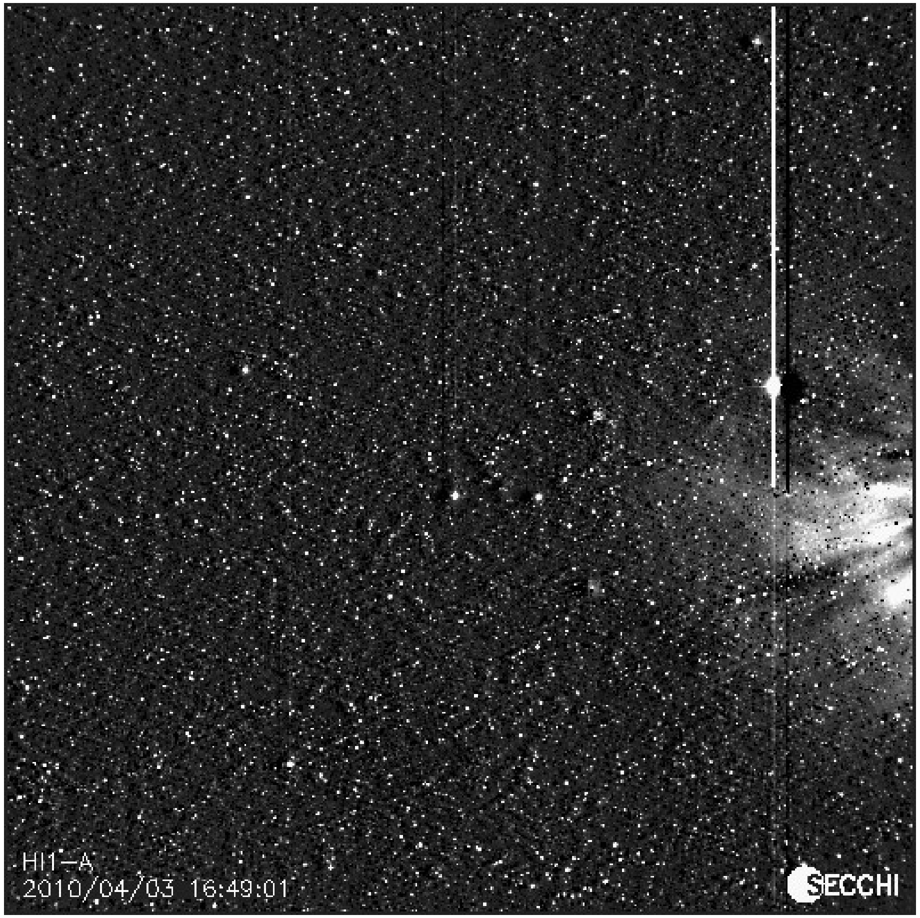
- Intensity is the correct value to use for calculating detectability of an object
- Features with larger elongation and exit angles are close to the observer and therefore subtend a larger solid angle. That proximity effect enhances the intensity of light from the feature even though its radiance is independent of distance
- “confusing intensity and radiance”: mostly irrelevant in the corona where the observer-object distance is nearly fixed, but becomes highly important in heliosphere

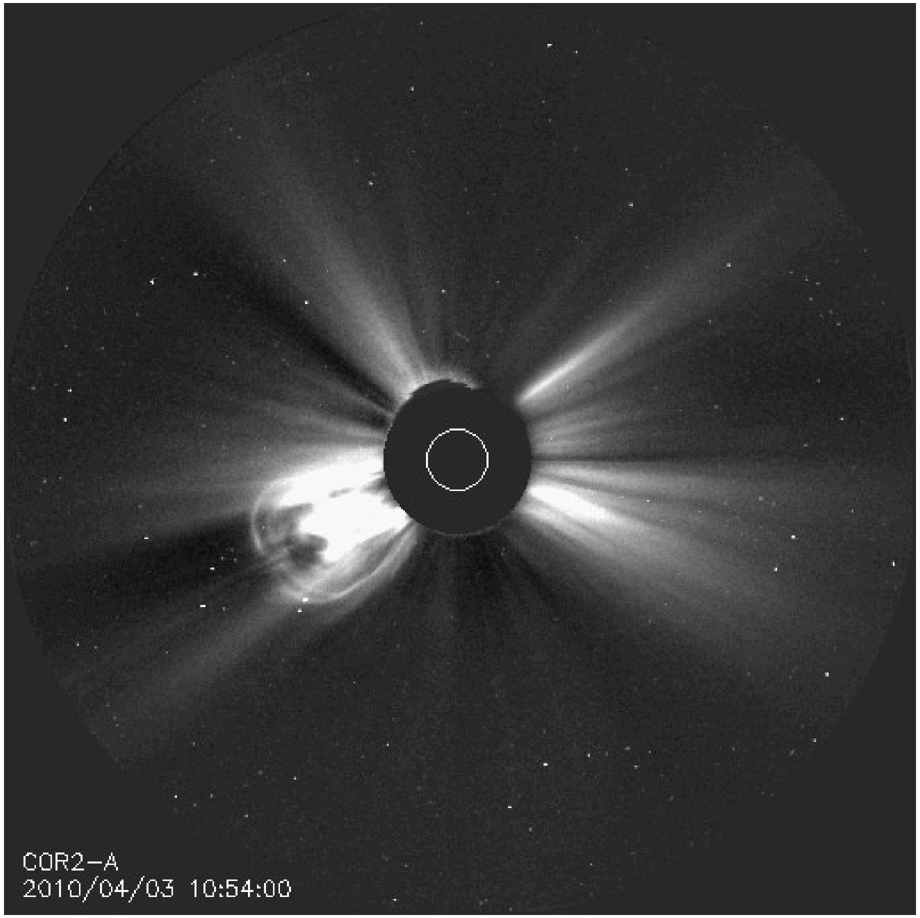
Howard and DeForest 2012)

Visualize the CMEs in heliosphere

- HI1 -A

COR2-A





What do we see in white-light coronagraph images

- Noise
- Stray-light
- Cosmic rays
- Planets, comets, stars
- Dust (F-corona)
- Streamers
- CMEs
- Outflows
- Inflows
- …