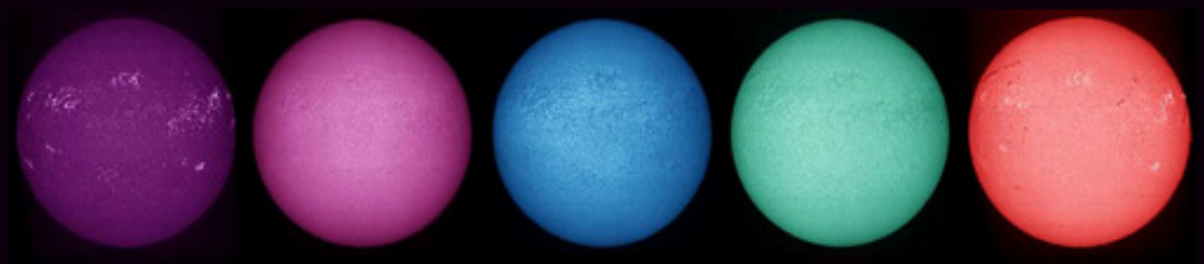
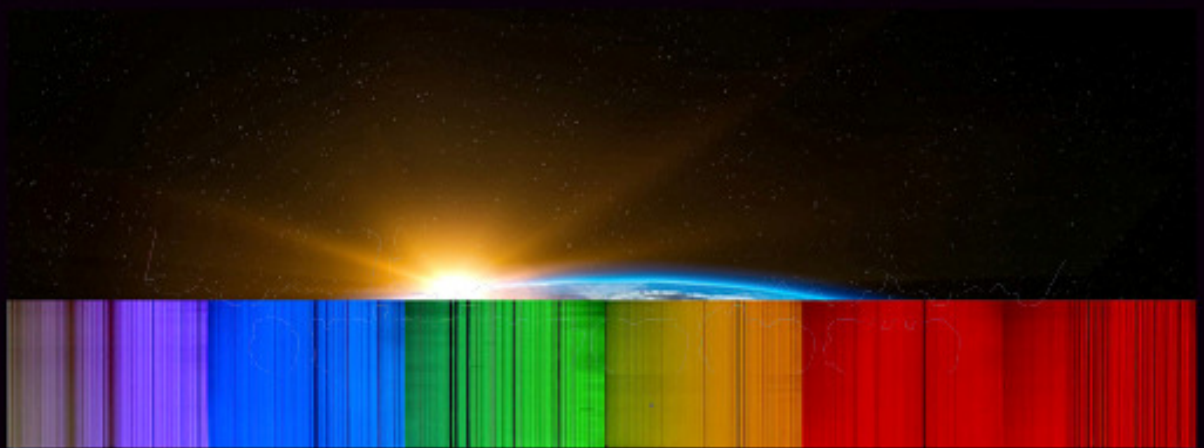


*Fulvio Mete*

# **Digital Spectroheliography** **a window on the sun**



*Light from infinity.org*

*This book is dedicated to the memory of Fabio BOCCI, an Italian amateur astronomer with great competence and personality, good and courteous, who repeatedly expressed his interest in the spectroheliography.*

### **Acknowledgments**

I would like to thank Dr. Giorgio Viavattene, physicist specialized in solar physics, for the accurate revision of this work.

A special thank to my cousin, the Italian Australian Giulio Paoletti, for his invaluable help in the translation of this text.

### **Premise**

The Sun, the closest star to us, is a gigantic laboratory where can be studied physical phenomena which, due to their scale, are not accessible to terrestrial experimentation and can not be studied in stars more distant: for this reason the study of the Sun has contributed, and contributes in remarkable way to the general progress of astrophysics. This concept is equally valid for spectroscopy and spectrography, which they find in the Sun a great opportunity for study and experimentation.

This text of amateur digital spectroheliography is dedicated to everyone, but in particular to those who already have knowledge and have had experience in the field of Spectroscopy. It is conceived not by a solar physicist, but by an amateur in favour of other amateur astronomers, with an eye to simplicity. It is therefore not an exclusive book: however, to repeat the experiences I have shown, one need a sufficient knowledge of spectroscopy, techniques, and a certain practical skill. For those, on the other hand, who do not intend to take on a considerable amount of personal sacrifice and construction work in making spectroheliographs but that however have basic knowledge and wish to deepen the study in this sector of scientific solar research I have tried to make the text as simple as possible, compressing and simplifying a discipline extremely complex in order to attract their attention and keep alive and current their passion for solar observation. This popular text of digital spectroheliography is certainly the first in Italy about the specific theme, and the second on a planetary level after that, very well done, by my friend Ken Harrison. Unlike this, in which are reported the experiences of a certain number of amateur astronomers (myself included), I have tried however to show almost exclusively my experiences, deriving from many years of study and experimentation.



For the newbies of spectroscopy, my advice is to read preliminarily my book "An outline of amateur astronomy spectroscopy" at the link

<http://www.lightfrominfinity.org/Libro%20di%205pettroscopia/Libro%205pettroscopia.htm>

The text, for now in Italian only (need translation in English) will be an excellent basis for understanding in depth the content of the present work. For all without distinction wishes of a good reading.

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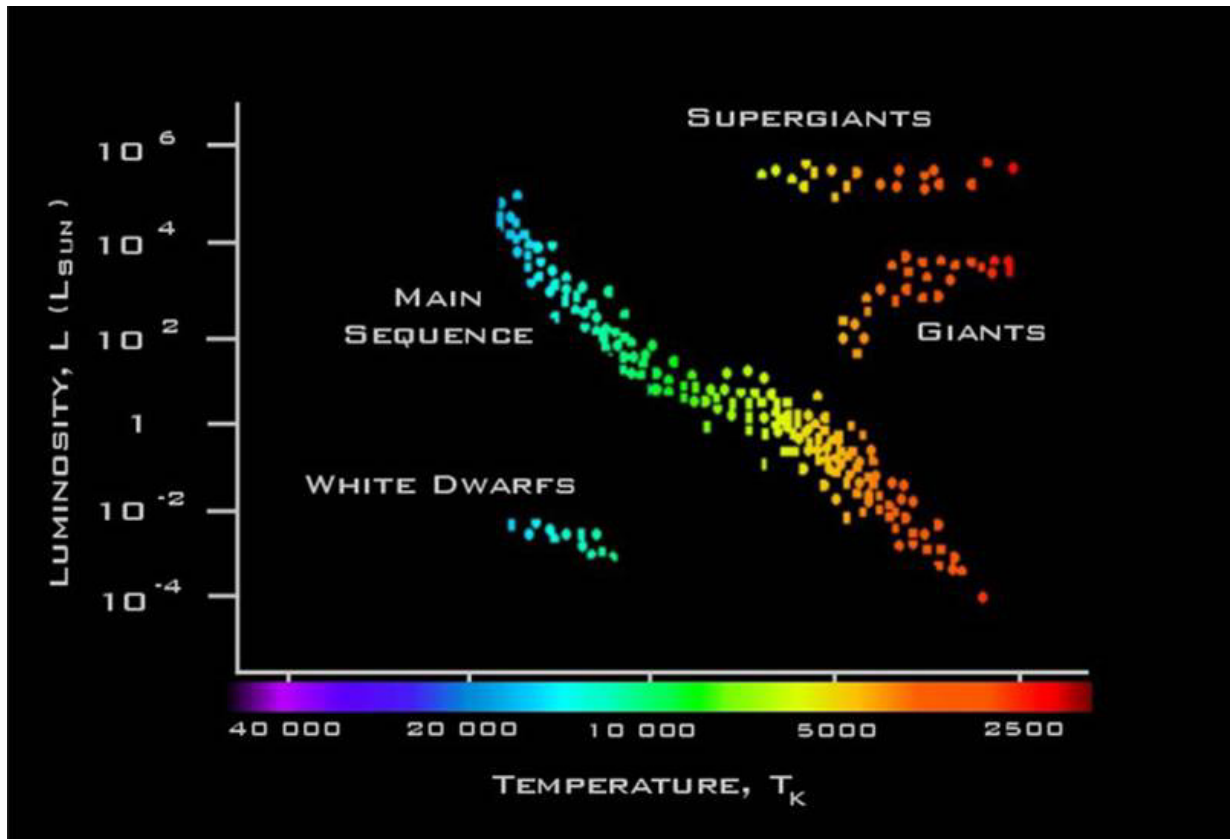
Before talking about spectroheliography it is good to provide some news on the object of interest, the Sun.

## **The sun, the nearest star**



Most of the visible light we observe is the one which comes from Sun, the star closest to us. But what is the Sun?

The Sun is a star of medium-small size, with an equatorial radius of about 696.000 Km, averagely 149.597.000 Km from the earth (according to the last one definition of astronomical unit defined by the IAU), with a mass of 333400 times the earth is made up mainly of hydrogen (about 73.46% of its own mass), and Elio (about 24.85%), to which heavier elements are added (metals) present for 1.69% (Rif Bianucci "Il Sole" - Giunti Ed.) is classified as a yellow dwarf of spectral type G2 V: G2 indicates that the star has a photosphere surface temperature of 5 776 K (The temperature is commonly measured with the Kelvin scale (K), called "absolute scale", where  $0^{\circ} = -273^{\circ} \text{C}$ . Then  $5776 \text{ K} = 5776 - 273: 5503^{\circ} \text{C}$ ), characteristic that gives to its light an extremely intense and chromatically cold white color, which however, it can often appear yellowish, due to the scattering of the terrestrial atmosphere. The V (5 in Roman numerals) indicates that the Sun, like most of the stars, is in the main sequence, or in a long phase of stable equilibrium within which the star melts, in its nucleus, the hydrogen in helium. The enormous amount of energy is then transported outwards by two means: the radiative one (emission and absorption of photons) carried out by the area that takes this name, and the convective one, through convection cells (circulation of hot and cold gas cells) more external than the first, in the solar area so named.



In the HR diagram, which links the absolute magnitude to the temperature and to the spectral class the Sun is located in the central part of the main sequence.

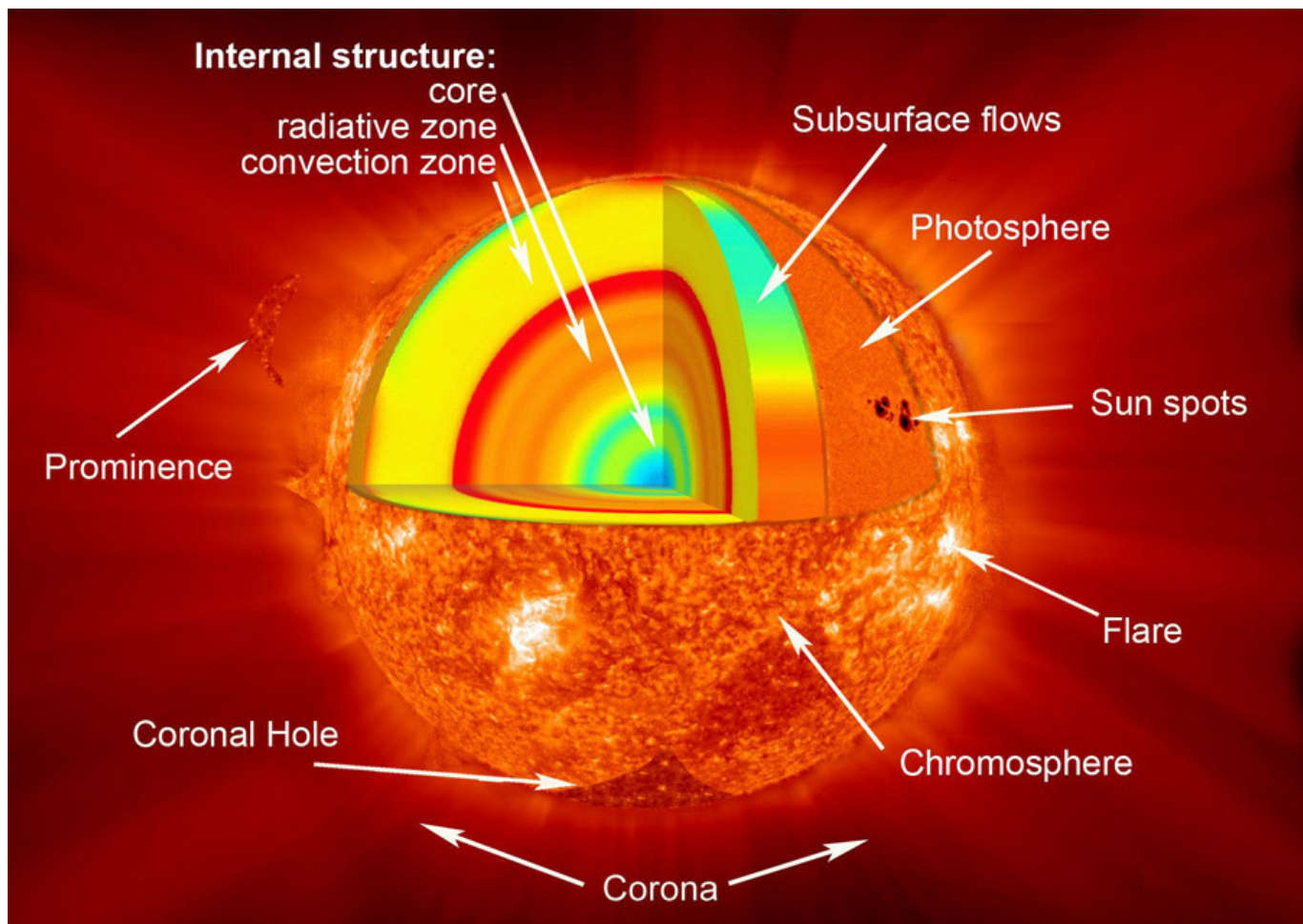
This process of nuclear fusion generates a large quantity every second of energy (equivalent to  $3.83 \times 10^{26}$  Joule per second), thrown into the space in the form of electromagnetic radiation (solar radiation), flow of particles (solar wind) and neutrinos. Solar radiation, emitted basically as visible and infrared light, allows life on Earth providing the energy necessary to activate the main mechanisms that are present to the base of life itself; furthermore, the insolation of the earth's surface regulates the climate and most meteorological phenomena. Nuclear fusion also causes the star to be in a state of equilibrium, is hydrostatic, ie it does not expand (due to the pressure of radiation of thermonuclear reactions) nor does it contract (due to the strength of gravity, to which it would naturally be subjected), and thermal. A G2 class star as the Sun employs, considering the value of its mass, about 10 billion years to completely deplete the hydrogen in its core.

The Sun is about halfway through its main sequence. At the end of this period of stability, in about 5 billion years, the Sun will enter a phase of strong instability giving life to a so-called "red giant": the moment in which the hydrogen of the nucleus will be converted into helium by about 10% the layers, immediately superior will suffer a collapse due to the disappearance of radiation pressure of thermonuclear reactions. The collapse will determine a thermal increase reaching temperatures which will trigger the fusion of hydrogen in the upper layers, causing the expansion of the star up and beyond the orbit of Mercury; such expansion will cause a cooling of the gas (up to 3500 K), explaining why the star will have coloring of a typically intense yellow. When also the hydrogen of the upper layer to the core will be totally converted into helium (within a few tens of millions of years) there will be a new collapse, which will result in an increase of the helium core temperature up to about 106 million K; this temperature will suddenly trigger the fusion of helium. Because of the very high core temperatures, the fusion of helium will soon be exhausted (some tens of millions of years) and fusion products, which can not be used in new thermonuclear cycles due to the small mass of the star, will accumulate inert in the nucleus; meanwhile, failing again radiation pressure pushing outwards, a collapse will subsequently occur which will trigger the fusion of helium in the shell surrounding it in the nucleus and of the hydrogen in the layer immediately above it. These new reactions will produce so much energy to cause a new expansion of the star, which will reach such dimensions next to 1 AU (about 100 times the current ones), so much so that its atmosphere will most likely incorporate Venus. Incert is destiny of the Earth: some astronomers believe that even our planet will come incorporated by the dying star; others instead assume that the planet will be saved, since the loss of mass by our star would widen his orbit, which would then shift to almost 1.7 AU. Our planet will be but uninhabitable: the oceans will be evaporated because of the strong heat and large part of the atmosphere will be dispersed in space by intense thermal energy. In 7.8 billion years, exhausted every thermonuclear process, the Sun will release its outer layers, which will be wiped out in the form of "superwind" creating a planetary nebula; the more internal core will collapse and give rise to a white dwarf (approx dimensions of the Earth), which will slowly cool down to become, in the course of hundreds of billions of years, a black dwarf.

## The structure of the Sun

The solar structure is divided into eight parts:

Core, radiative zone, transition zone, convective zone, photosphere, chromosphere, chromosphere-corona transition (which is not a real one zone, given that temperature and density vary in it almost continuously), corona.



In the image above (source SOHO-NASA-ESO) is shown the internal structure and some of the most important features of the solar disk.



### **The core**

represents in volume 10% of the star, in mass over the 40%. And here the reactions of nuclear fusion take place, the principal source of solar energy. With the nuclear fusion 4 nuclei of hydrogen, in conditions of extremely high temperature and pressure are converted into a nucleus of Helium and some minor particles (among which the neutrinos), whose weight is lower than the four initial hydrogen nuclei; the difference is converted into energy on the basis of the famous Einsteinian equation  $E = mc^2$ . Astrophysicists believe that the solar core has dimensions close to 0.25 solar rays (174.000 Km), with a density higher than 150,000 kg /m<sup>3</sup> (150 times that of water), a temperature that reaches 15600000 K and a pressure of around 500 billion atmospheres (on average, as it depends on the solar cycle). It is the combination of similar values that causes nuclear fusion of hydrogen in helium. The core is the only region of our star where nuclear fusion is currently taking place. These reactions release energy below form of gamma radiation which, once emitted from the core, is absorbed and re-emitted from the matter of the upper layers, helping to keep the temperature high; in crossing the layers of the star electromagnetic radiation loses energy assuming wavelengths more and more longer, passing from the gamma band to the X and ultraviolet band, finally spreading in space as visible light. Another product of the nuclear reactions are neutrinos, particles that rarely interact with matter and that therefore freely cross the space.

### **The radiative zone**

is located outside the core, extending from about 0.25 up to 0.7 solar radius (about 490,000 Km); it absorbs the energy produced by the core and transmits it by irradiation (hence the name) to the upper

layers. Pressure and temperature are still high enough to allow the transfer of the energy to the next layer

.

### **The transition zone**

It is situated between the radiative and convective part, is called tachocline and extends, according to recent helioseismological studies, from 0.7 solar radius. The astrophysicists believe that it plays a decisive role in the genesis of the solar magnetic field, as they would intervene in the solar dynamo (mechanism by which the magnetic field of our star originates) reinforcing the weak poloidal fields to create a more intense one of toroidal form.

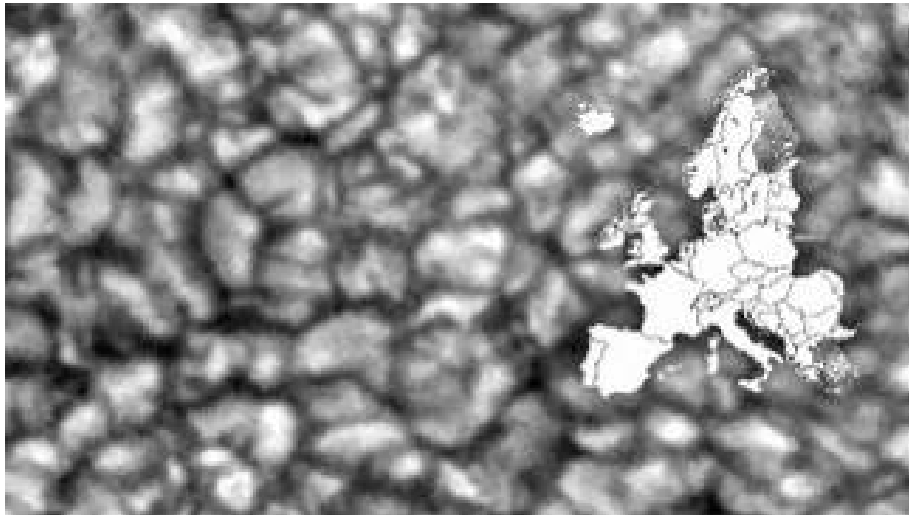
### **The convective zone**

It has a thickness of about 200 000 km and is located in the outer portion of the Sun, starting from about 70% of the solar radius, after the transition zone. The area is characterized by lower temperatures and densities than those of the underlying layers; as a consequence, energy and heat can not be transferred by radiation, but through convective motions. The warmer and less dense matter is transported to the surface, where it yields part of its thermal energy; once cooled, the matter resurfaces at the base of the convective area, where it receives again the heat coming from the radiative area. Unlike the underlying layer, therefore, in the convective area the matter is in constant movement. This constant and turbulent movement seems to be one of the fundamental causes of the solar dynamo and of the origin of the granules. The thermal columns of the convective zone leave signs on the solar photosphere which are called granules, mesogranules and solar supergranules. The turbulent motion of the plasma and of the charged particles of the convective zone generate a powerful magnetic field, characterized by paired poles (north and south) arranged along the entire solar surface. The field reverses its own direction every eleven years, corresponding to the maximum of the solar cycle. The solar magnetic field is the origin of several phenomena that collectively take the name of "solar activity"; among them are the photospheric sunspots, the flares the CME (coronal mass ejections) and the variations in the intensity of the solar wind, which spreads matter through the solar system.

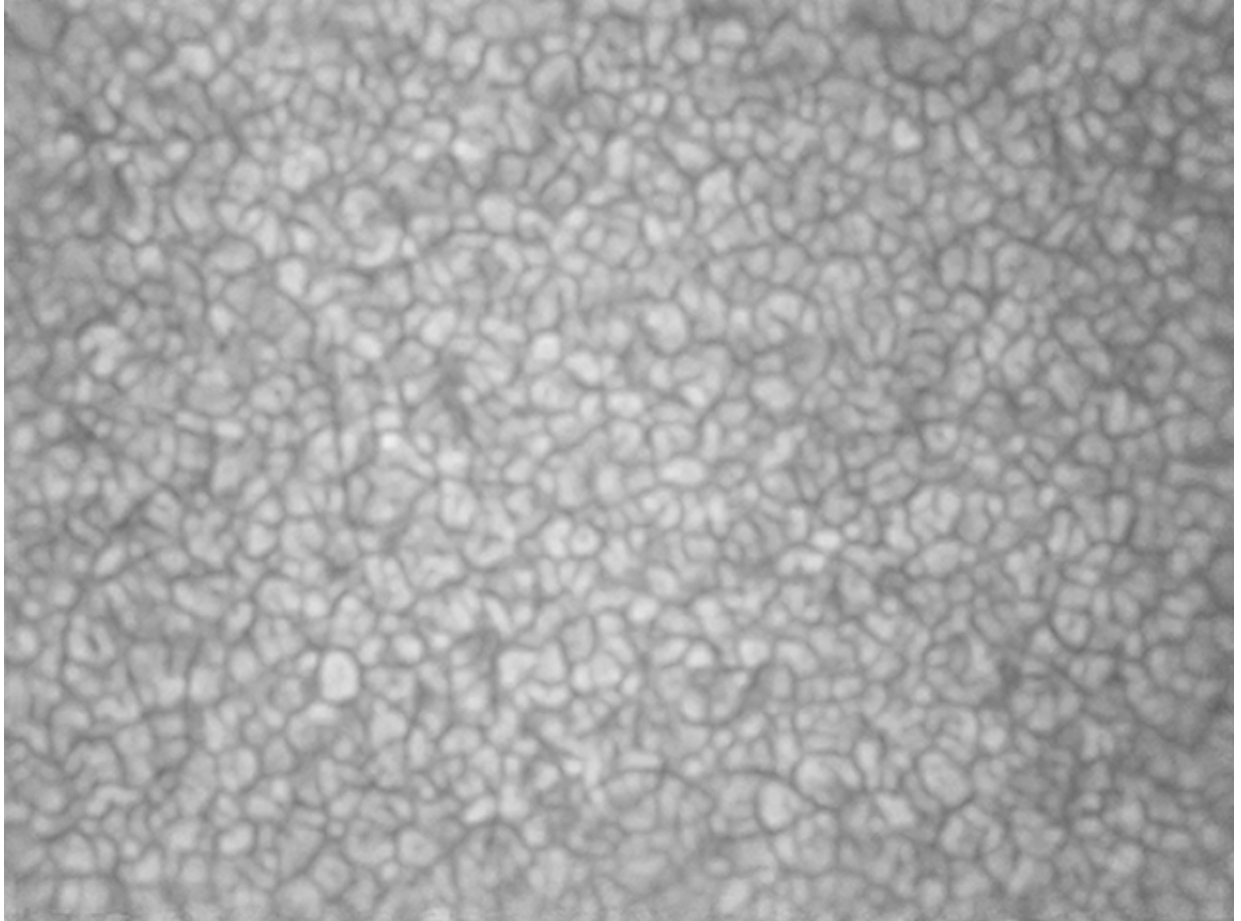
## **The photosphere**

is the surface layer of the Sun, thick on average 500 km (its thickness depends on the cycle), below which the star becomes opaque to visible light; it is therefore the first visible layer, from which the energy coming from within is free to propagate in space and constitutes the beginning of the solar atmosphere, which continues with the chromosphere and the corona. It is home to phenomena such as sunspots. The photosphere spectrum has characteristics similar to those of the continuous spectrum of a black body heated to a temperature of 5776 K, and appears interspersed with the absorption lines of the small stellar atmosphere. Direct observation of the photosphere has a grainy appearance, due to the presence of granulation. It is home to particular and complex phenomena, such as granulation and sunspots.

The photospheric granules are caused by the ascending and descending plasma columns of the convection zone, visible in their upper part in photosphere. They have a diameter of about 800-1300 Km, an average angular extension of 0.8-1.8 arcsec and last from 4 about 15 minutes: they are formed by a dark peripheral area, which is the external part of the descending plasma column and a bright, ascending, warmer central. The darker intergranular space subtends about 0.4-0.5 arcsec. In the figure ( source NST-BBSO) a zone of photospheric granulation compared to the extension of Europe.

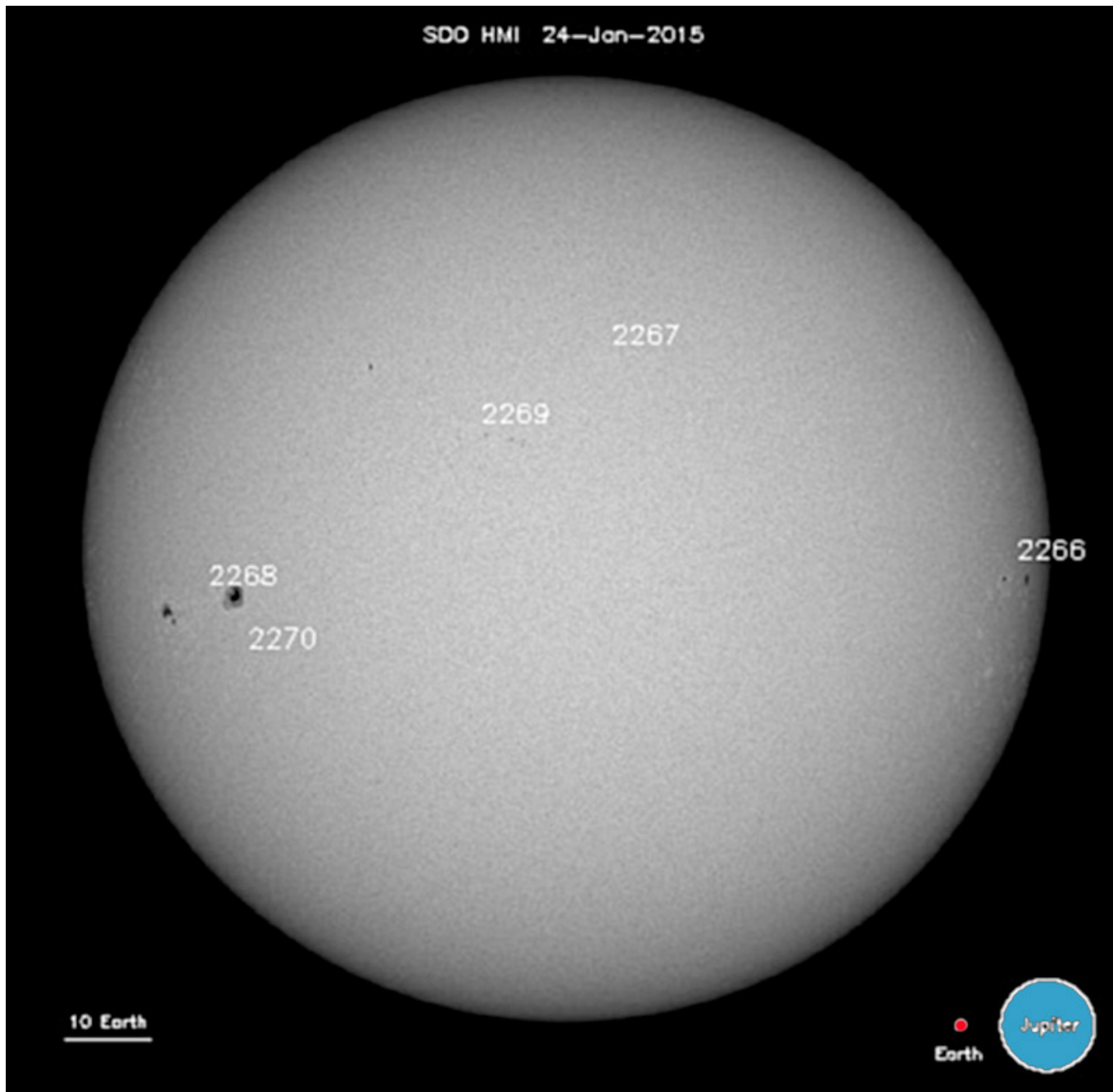


In the following image an excellent amateur photo of the photospheric granulation carried out by the amateur astronomer Salvatore Lo Vecchio with an apochromatic refractor of 150 mm at 9.6 meters of equivalent focal length and a DMK 21 camera. As we observe the granule sizes are varied, as well as their shape, which goes from round to rectangular, or composite.



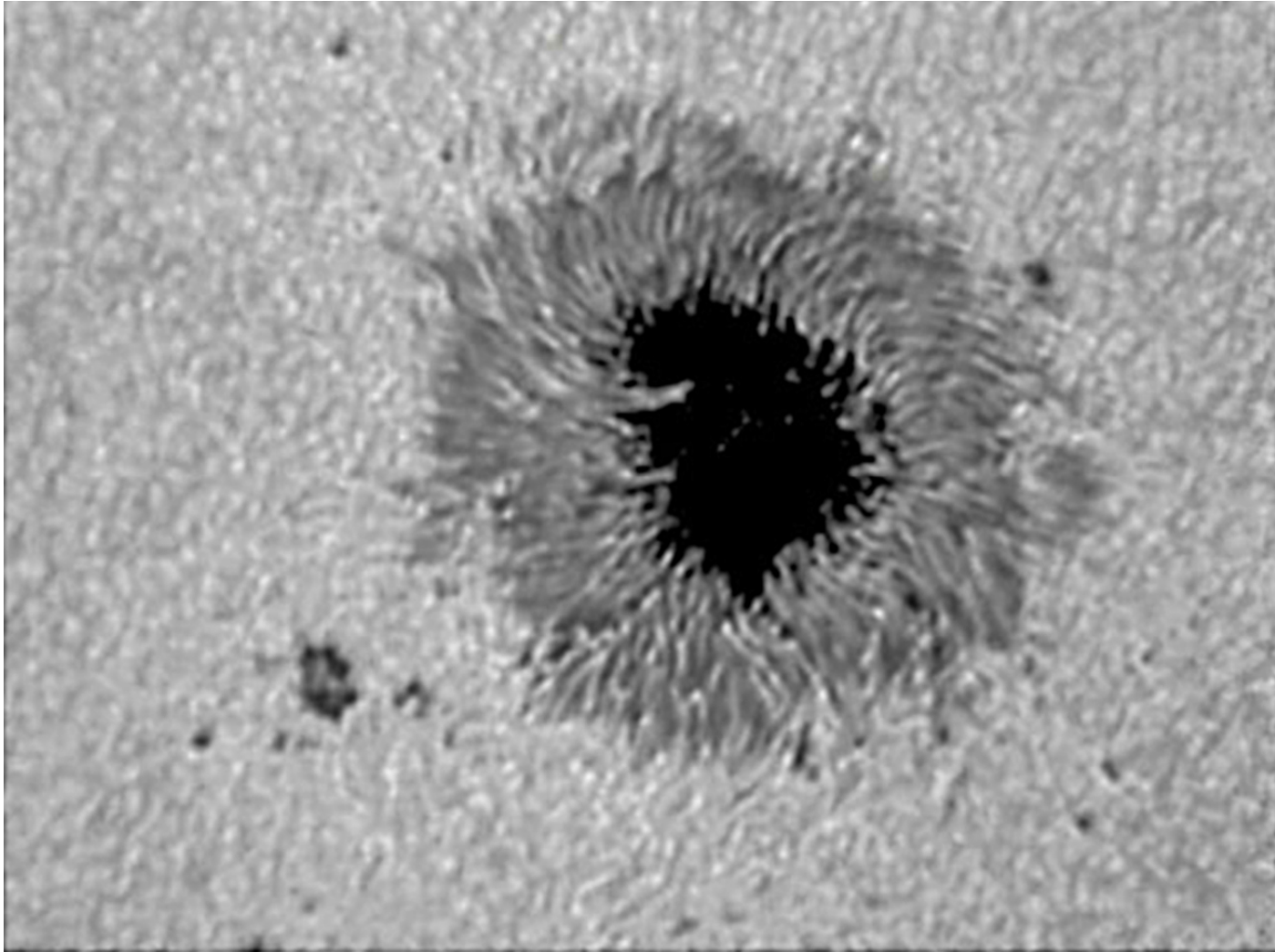
Sunspots are areas of the Sun distinct from the rest of the photosphere surface for the lower temperature and a strong magnetic activity. Despite being very hot (between 3000 and 4500 K) they appear dark by contrast with the remaining solar surface at 5776 K. They normally appear in pairs having opposite magnetic polarity. Their cause is the strong magnetic activity that inhibits the convection (in fact in the spots and in their immediate vicinity it is not generally visible the granulation) .The number of sunspots grows from a minimum to a maximum with a period of ten years (so-called "solar cycle" ).

In the following image the solar disk with some sunspots (source SOHO-SDO)

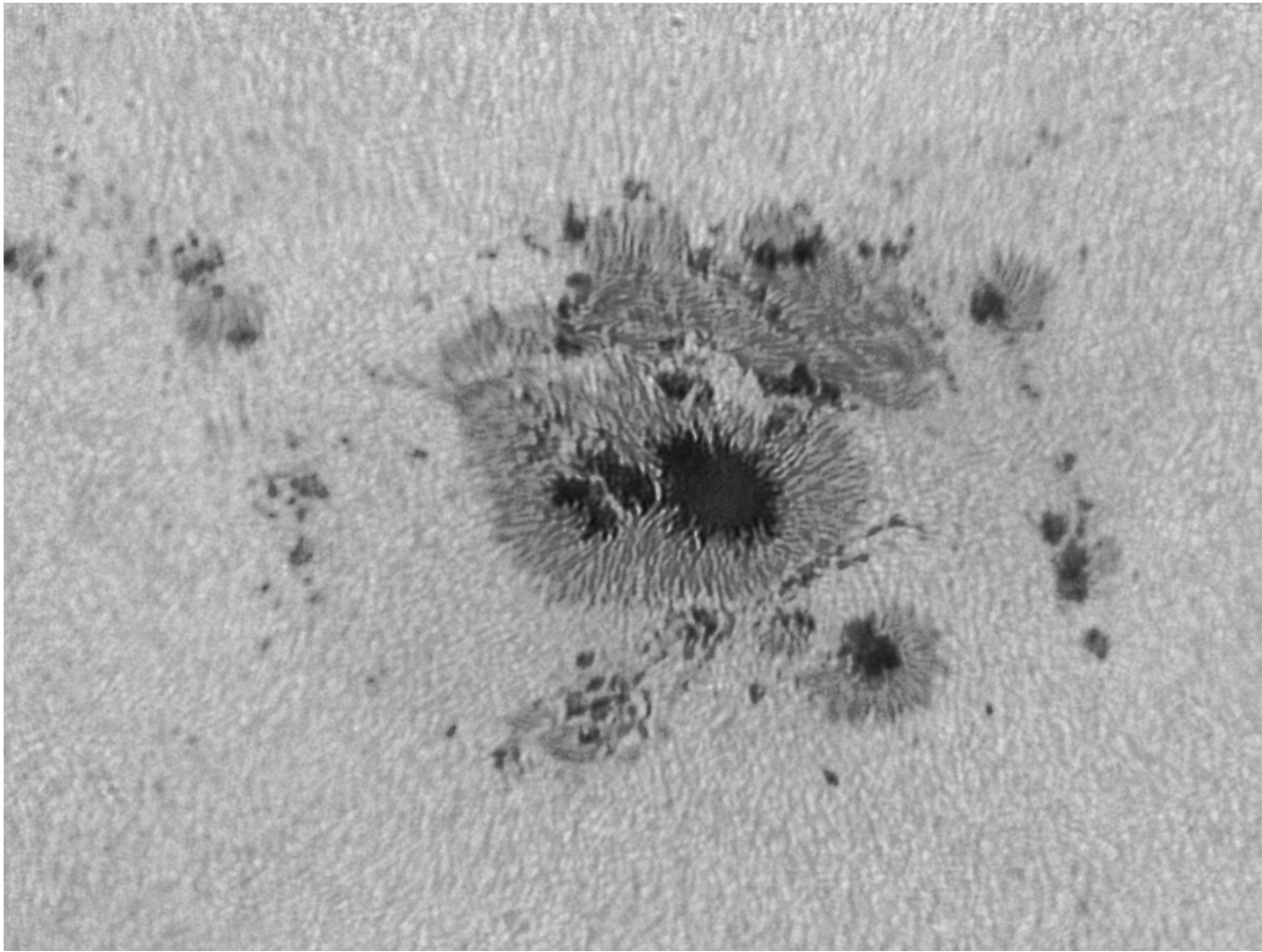


The following are photos of the author of high-resolution sunspots in white light, obtained the first with a newton solar reflector with a non-aluminized mirror of 200 mm and the other two with a 115 mm apochromatic refractor at an EFL of 4000 mm: note the granulation and the filaments of the penumbral zone, of about 1 arcsec of angular dimension. The distinction between the darkest central part, the umbra, and the lighter peripheral one, the penumbra, is also observed. The ratio of the respective areas ( $A_u / A_p$ ) ranges between 0.24 for small spots and 0.32 for large ones (see "On umbra / penumbra ratio of sunspots" - Brandt and Schmidt- 1990).

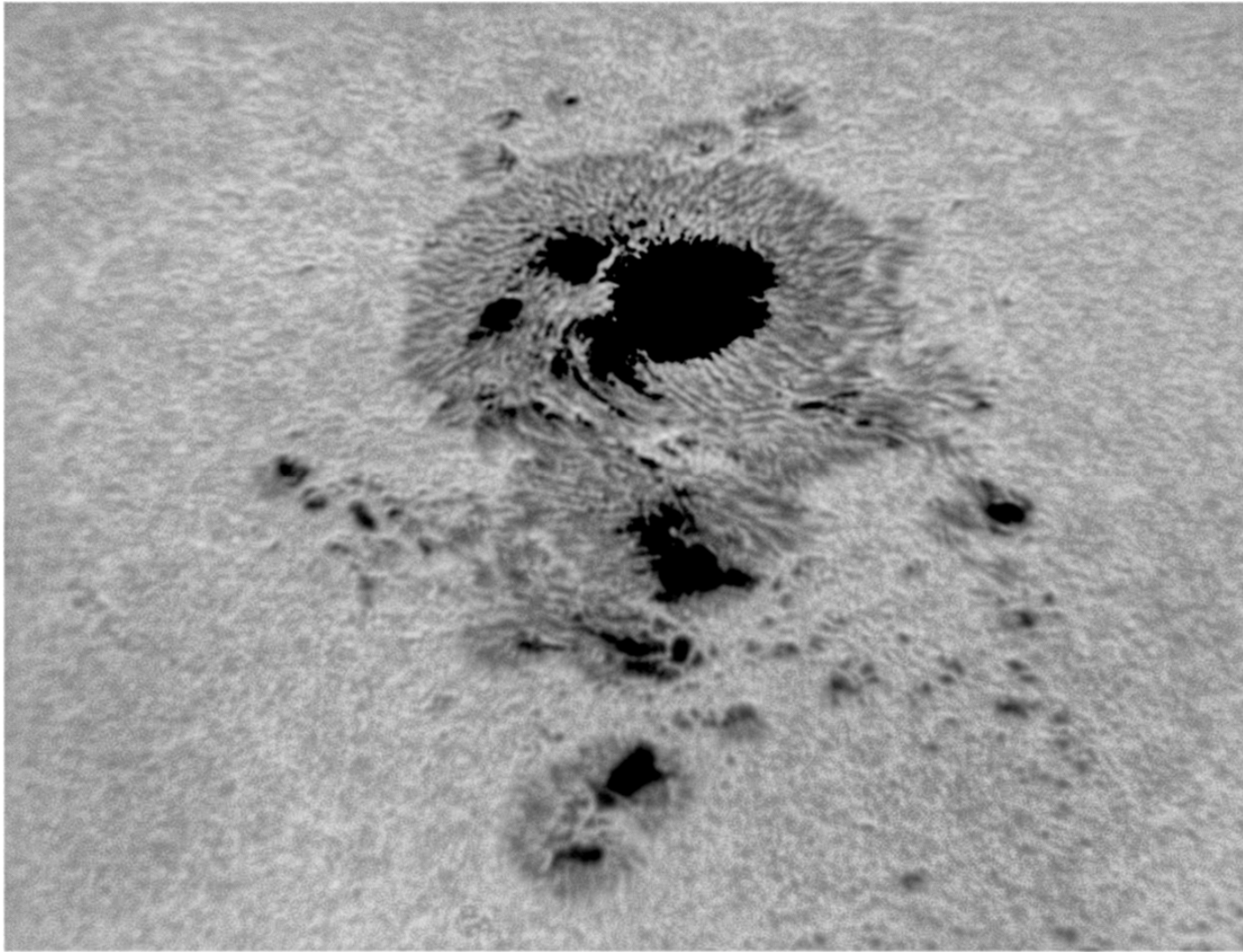




In the sunspot shown below is also visible a so-called "light bridge" a bridge of light that crosses the umbra, with plasma temperatures higher than this. It can sometimes be a symptom of an increase in activity in the chromosphere. its influence at the coronal level.



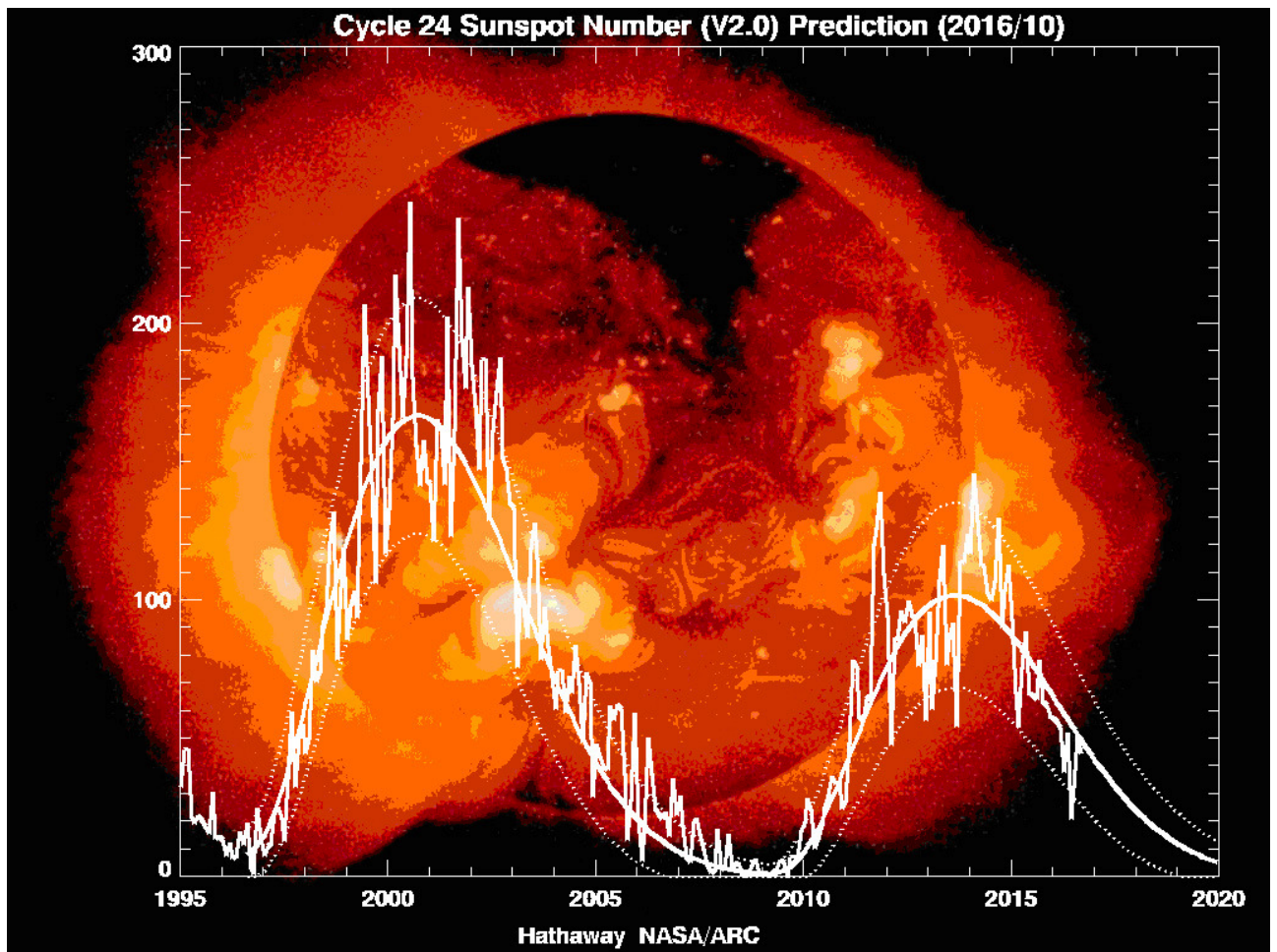
The image below was obtained by applying a 720 nm IR-Pass filter (it may seem a contradiction) after a Herschel prism, at the focus of an apo refractor TMB LZO 115/800 brought to 4000 mm EFL with a 5X barlow. Note the relief of the macular area compared to the quiet sun.



The sunspots, with their eleven-year maximum and minimum cycle, constitute the index of solar activity. The Swiss scientist Rudolf Wolf conceived in the mid-nineteenth century, a systematic method of measuring the number of spots still used today as an indicator of the cycle and solar activity.

In the following image (source NASA / ARC) the solar cycle forecast from 1995 to 2020, with the actual data up to October 2016 and the projections for the next period. As you can see it seems that the number of spots (cd number of Wolf) and therefore the solar activity is decreasing in recent years: however, this hypothesis is currently being discussed in depth, as it is still unclear whether there are cycles of solar cycle modulation.

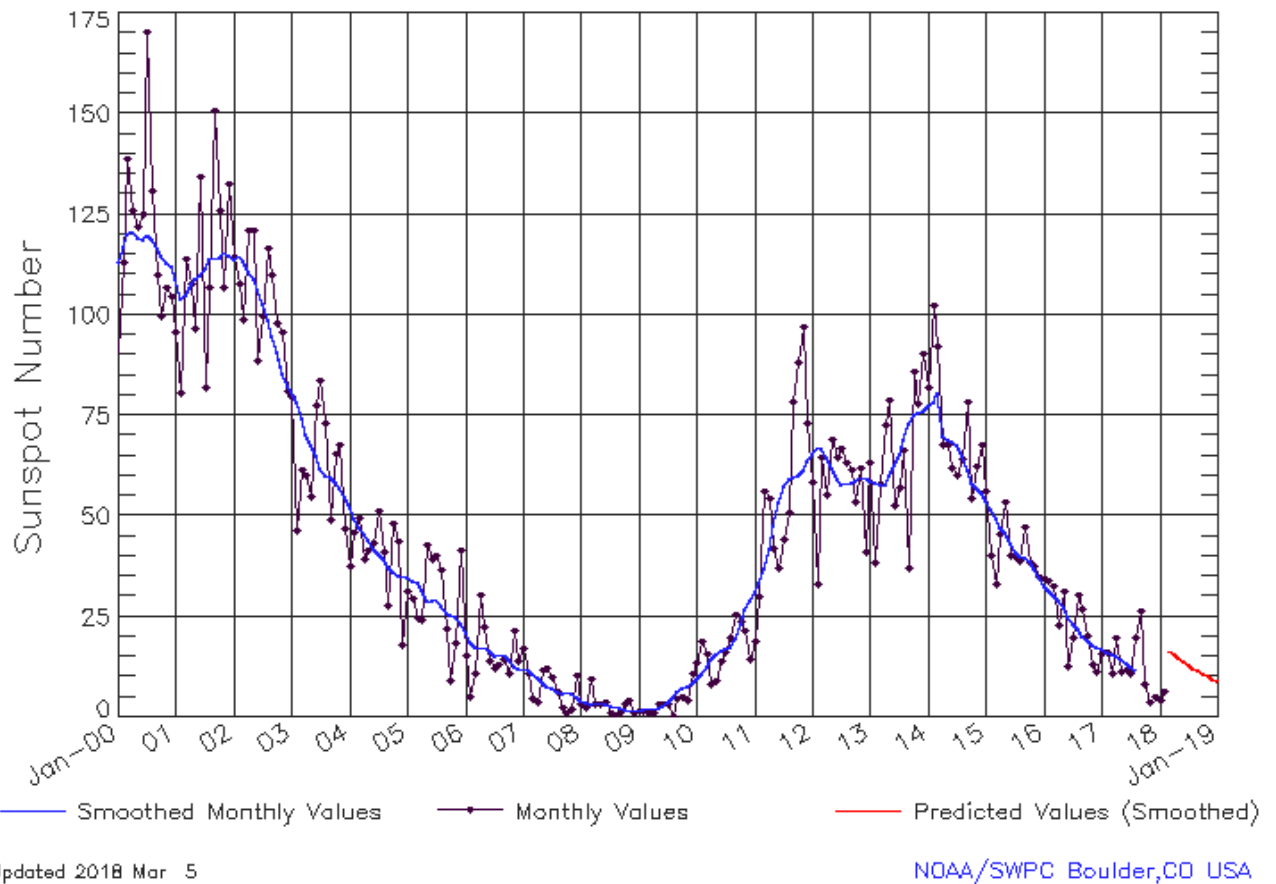




Here below the real data of the number of Wolf for cycle 24 updated to February 2018 (source NOAA / SWPC). Notice the sensible decrease of the peak of the mean curve of Cycle 24 respect to that of Cycle 23 (about 80 versus 120).

## ISES Solar Cycle Sunspot Number Progression

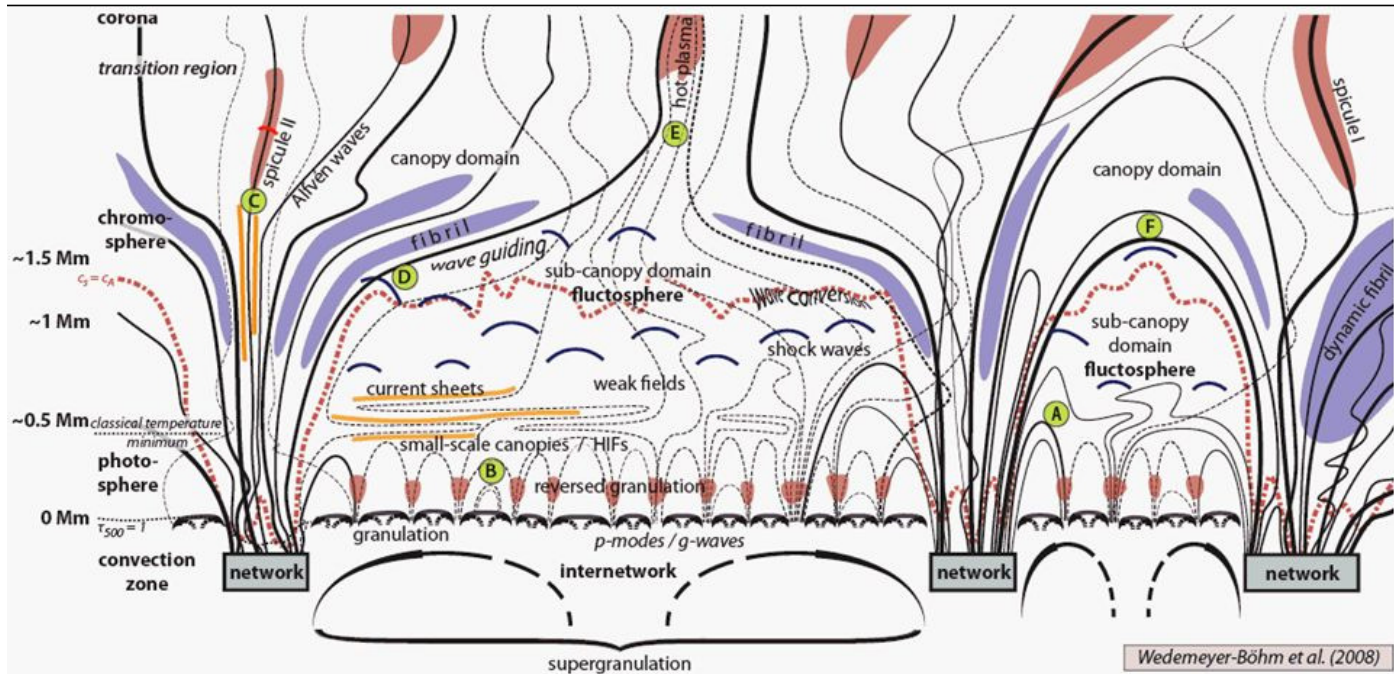
Observed data through Feb 2018



### The chromosphere

The chromosphere is a thin band about 2300 Km thick above the photosphere called (from the Greek χρώμα, χρώματος - chroma, chromatous - which means color) because of its colored flecks visible immediately before and immediately after the total eclipses of Sun, called "flash spectrum". It is a thin envelope made of rarefied gas that appears reddish in color; in reality, the layer is transparent. The reddish color is due to hydrogen atoms, in particular of hydrogen ionized alpha (H $\alpha$ ) at the wavelength of 6563 Å (deep red) that at the lowest pressures of the chromosphere emit radiation of this color. Its temperature, on average included between 10000 and 20000 K, more precisely it is about 6000 K at the border with the photosphere, begins to decrease immediately after up to 3800 K, then grow again up to 10,000 K and then 20000 K in its highest layers, reaching even 30,000 K and beyond the upper border with the transition zone to the corona. An interesting analysis of the solar atmosphere has recently been made thanks to data from the IRIS satellite, launched in 2013, whose instrumentation was specifically developed for the study of the chromosphere and the transition to the corona.

# Structure of the atmosphere



Corona  
 Transition region  
 Chromosphere  
 Photosphere

} "Interface region"  
 (=> new IRIS spacecraft)

Wedemeyer-Bohm 2004

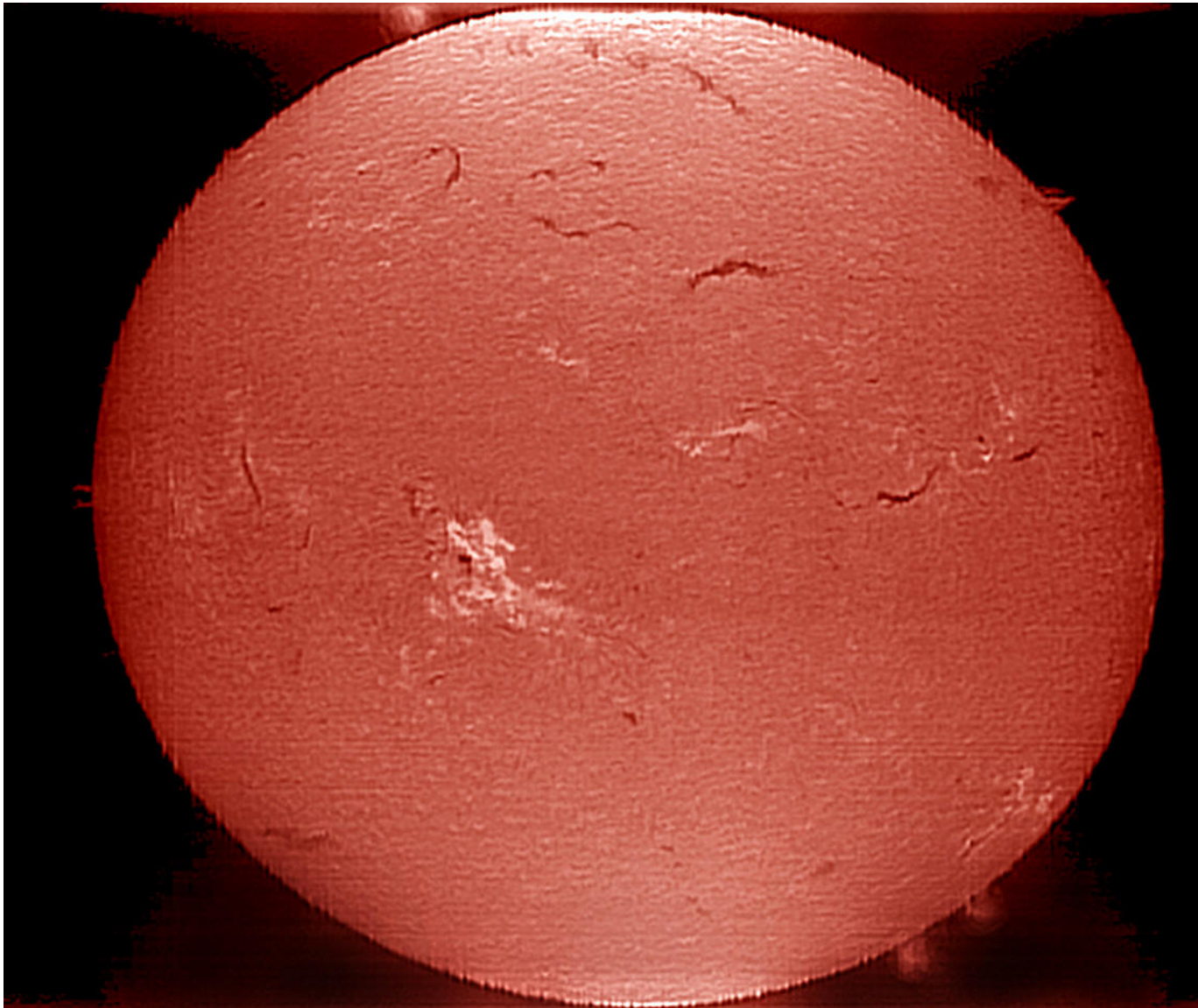
The figure above (source NASA- The cromosphere- Wedwmeyer - Bohm 2004) shows in detail the structure of the solar atmosphere. Note the magnetic loops of the granulation between the photosphere and the convention zone and the different height of spicules and fibrils.

They are particularly popular among fans of solar observations of the chromosphere and its main characteristics with narrow bandwidth filters (between 0.3 and 1 Å) for the observations in Hydrogen Alpha light at 6563 Å .

The chromosphere is not normally visible without special filters or solar telescopes; however, it is visible on the occasion of the total solar eclipses, together with the protuberances, as observed in this beautiful image of Danilo Pivato, an Italian amateur astronomer , in which is visible both the chromosphere (thin red strip surrounding the solar disk), and the protuberances, both ( in part) the corona.



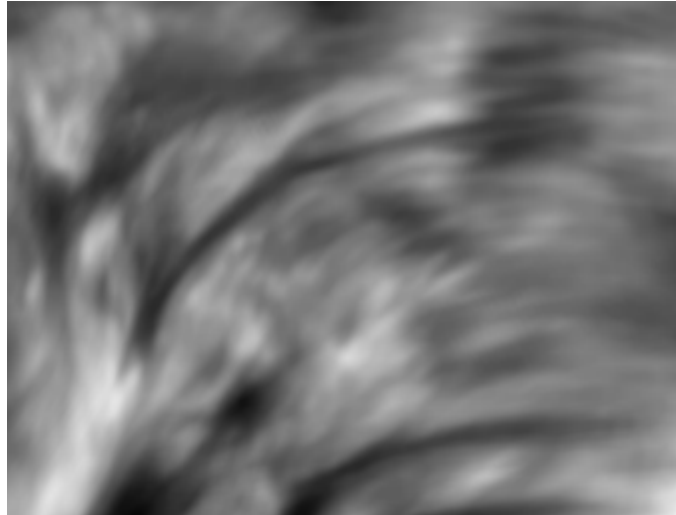
In the images taken with chromospheric filters centered on the H alpha line of the Hydrogen or with telescopes or spectroheliographs, the chromosphere shows all its features, as in the following picture, realized by the writer with a self-constructed spectroheliograph.



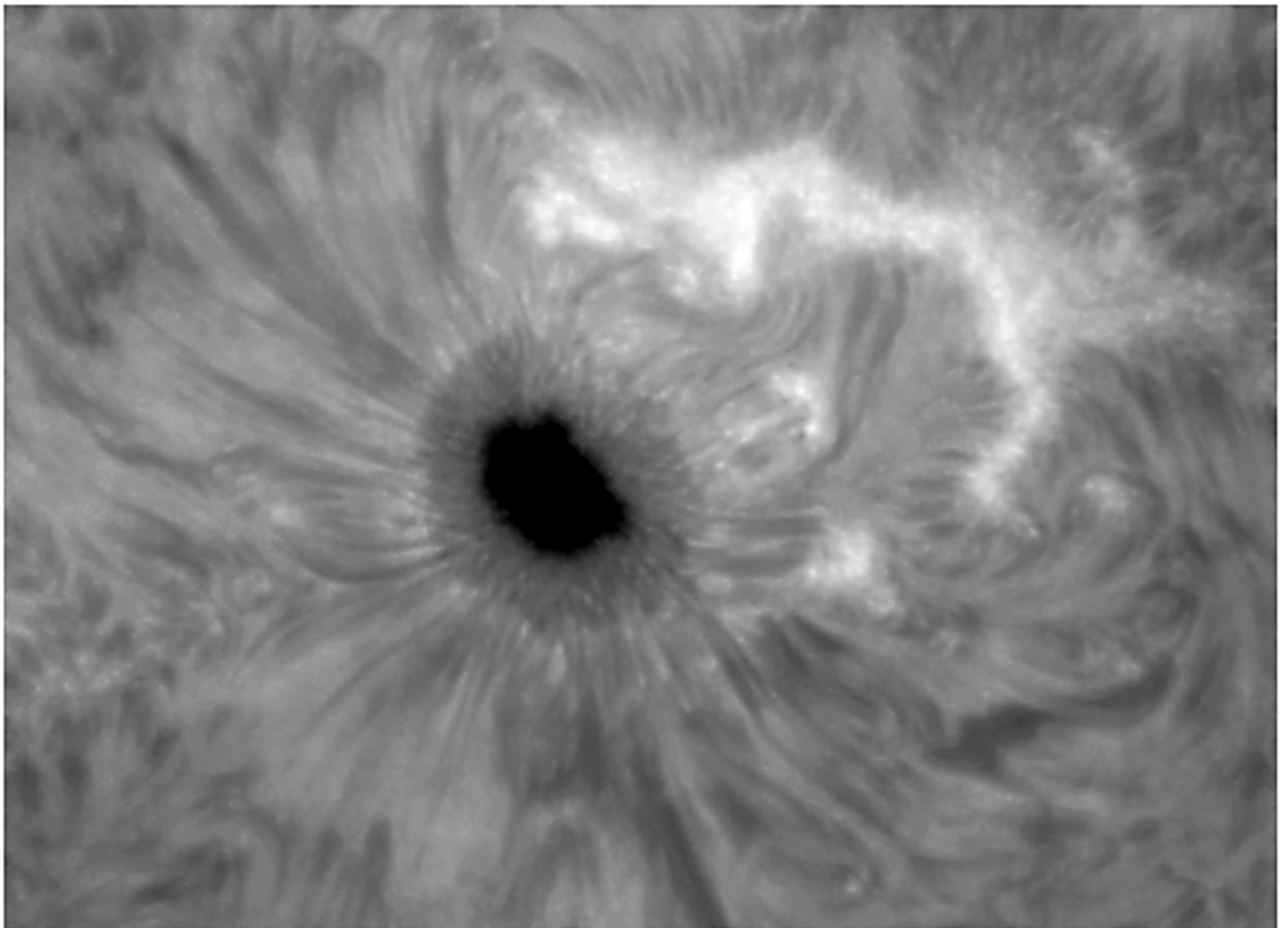
The most important features of the Chromosphere are the following:

The so called "*Cromospheric Network*" that shows supergranulation, better visible in Hydrogen Alpha and ionized calcium light, with supergranules of diameter of about 30000 Km., therefore much larger than the photospheric granules.

The "Plages", brilliant structures around the photospheric sunspots, due to the concentration of magnetic activity in these "Active" areas, as in the following image. In light CaII K the bright areas, corresponding generally to the active regions, take the name of chromospheric faculae. Around them, structures called *fibrils* are often observed, as in the following image (source DOT, H alpha) in which they appear evident.



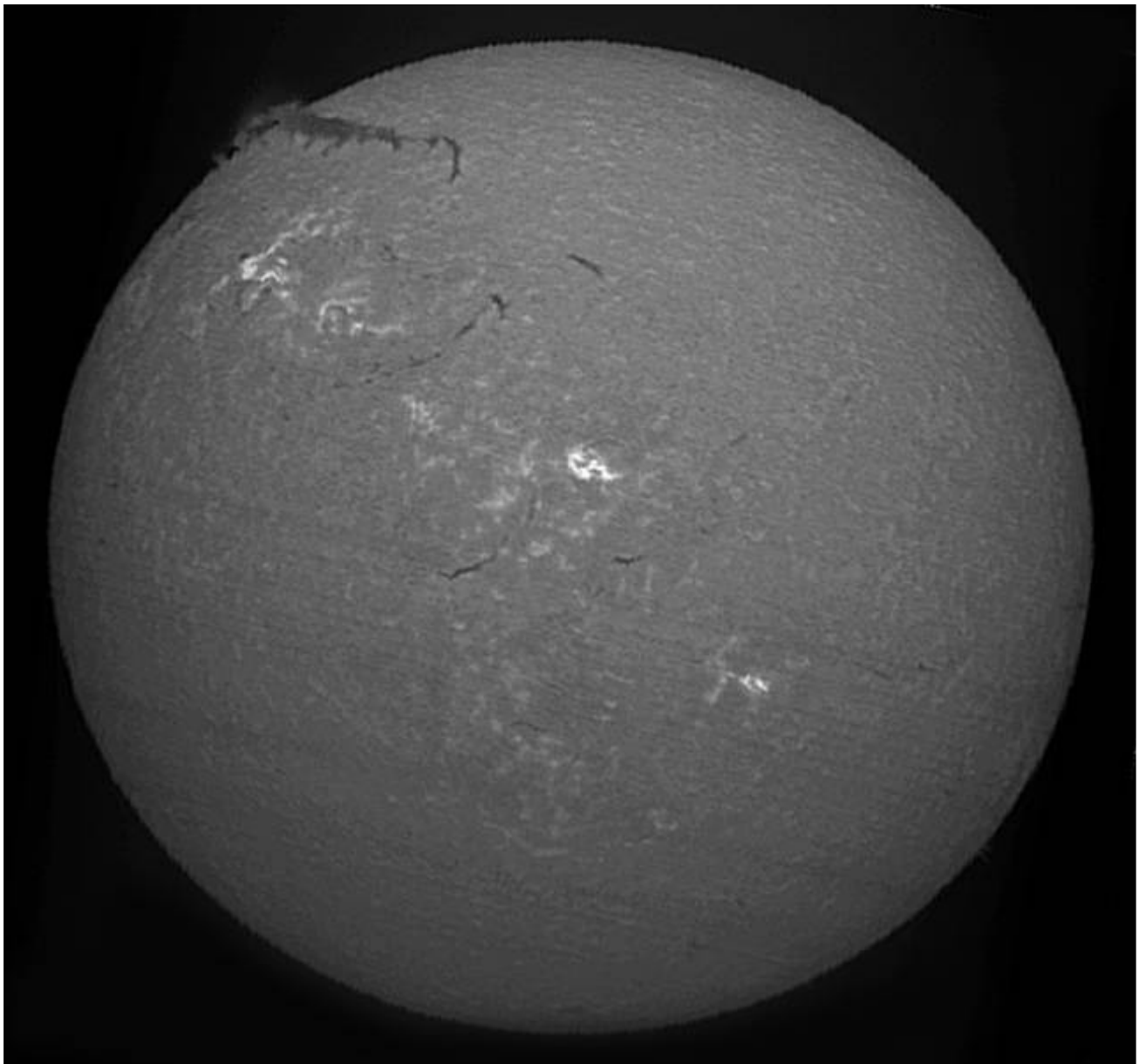
Chromospheric sunspots, plages and fibrils in a H-alpha light image by the author.



The *mottles* constitute the elements of chromospheric supergranulation, and appear dark or light in light H $\alpha$  (absorption) and bright in light CaII K and H (emission).

The *prominences*, jets of matter that extend beyond the solar surface due to strong magnetic fields. They appear bright on the edge of the solar disk.

The *filaments*, dark colored striae, are nothing but the same prominences projected on the disc, which appear dark by contrast, as we can see in the following image (a photo of the author with VHIRSS) in which there is a large protuberance on the edge that becomes filament when viewed on the disk.



The "Spicules", the grass of the chromosphere, small plasma ejections based on the chromosphere; these are visible in the image that follows, in high resolution, which shows the edge of the chromosphere with the spicules and a big prominence (photo of the author with a modified Coronado Pst ).

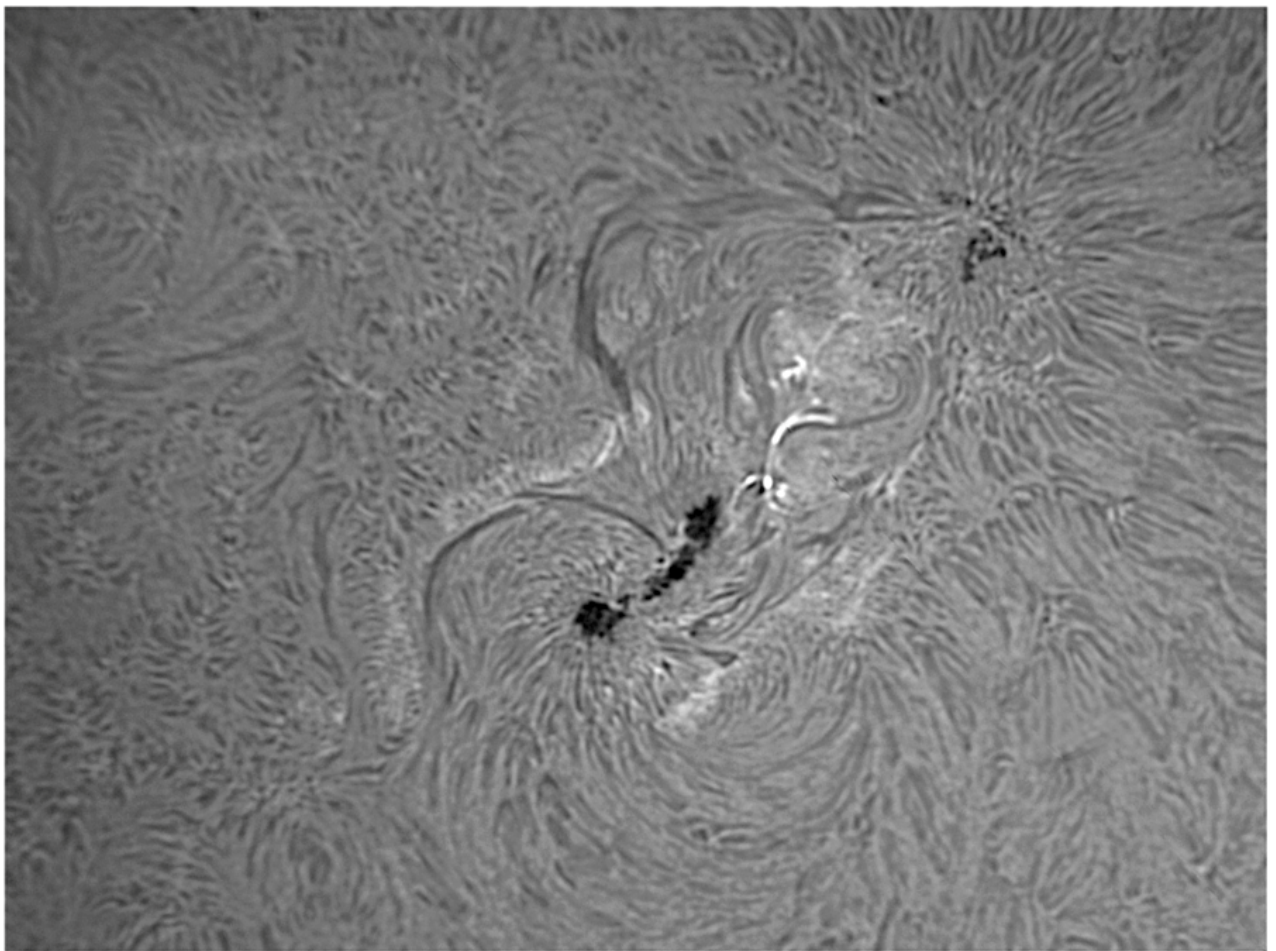




Other phenomena occurring in the chromosphere:

### Flares

In some conditions, in the chromosphere, near the active regions, phenomena of particular intense energy develop, called flares, which reach up to the equivalent of 160 billion megaton! They take place by phenomena of magnetic reconnection which accelerate charged particles and bring them into collision with the plasma. They can be associated, though not always, with coronal mass ejection (CME) phenomena. The temperature of plasma ejected can reach more than 10 millions K.



A small, but extended flare in the AR 1302 of 2011: photo of the author

## Ellerman bomb

The "Ellerman Bomb" are small, brilliant structures, similar to flares but much smaller, and resembling bright, short-lived (less than 5 minutes) moustaches that appear in active regions, on the edges of the sunspots.

## **The transition to the corona**

This area is located above the chromosphere, and in it the temperature rises rapidly from about 100000 K of the outer layers of the chromosphere, up to over a million kelvin of the corona; this increase causes a phase transition of helium, which here becomes completely ionized due to the high temperatures. The transition can not be properly defined as a zone because it does not have a defined altitude limit: it forms a sort of halo around the formations of the chromosphere like the spicules and filaments and is in constant and chaotic motion.

The transition is not easily visible from the Earth, but is detectable from space through instruments sensitive to the distant ultraviolet wavelengths: this is also one of the reasons for which satellite instruments, such as the EIT of SOHO, make images in the extreme UV wavelengths.

## **The corona**

The corona is the outer part of the solar atmosphere, has no definite limits and extends into space for tens of millions of kilometers in a very tenuous way. It consists of very high-temperature plasma (over one million kelvin). Since the plasma is very rarefied, the temperature is not to be understood in the conventional sense; in this case we speak of kinetic temperature.

The inner layers of the crown have a density of  $10^{14}$  -  $10^{16}$  particles per cubic meter (the Earth's atmosphere at sea level has a density of  $2 \times 10^{25}$  particles per cubic meter) and is home to numerous phenomena of magnetic type, such as coronal mass ejections (CME) and coronal rings.

Astrophysicists have long wondered why the corona has such a high temperature; they believe that part of the heat originates not only from the reconnection of the solar magnetic field lines, but also from the acoustic waves and, even more so, from the magnet-acoustic waves.

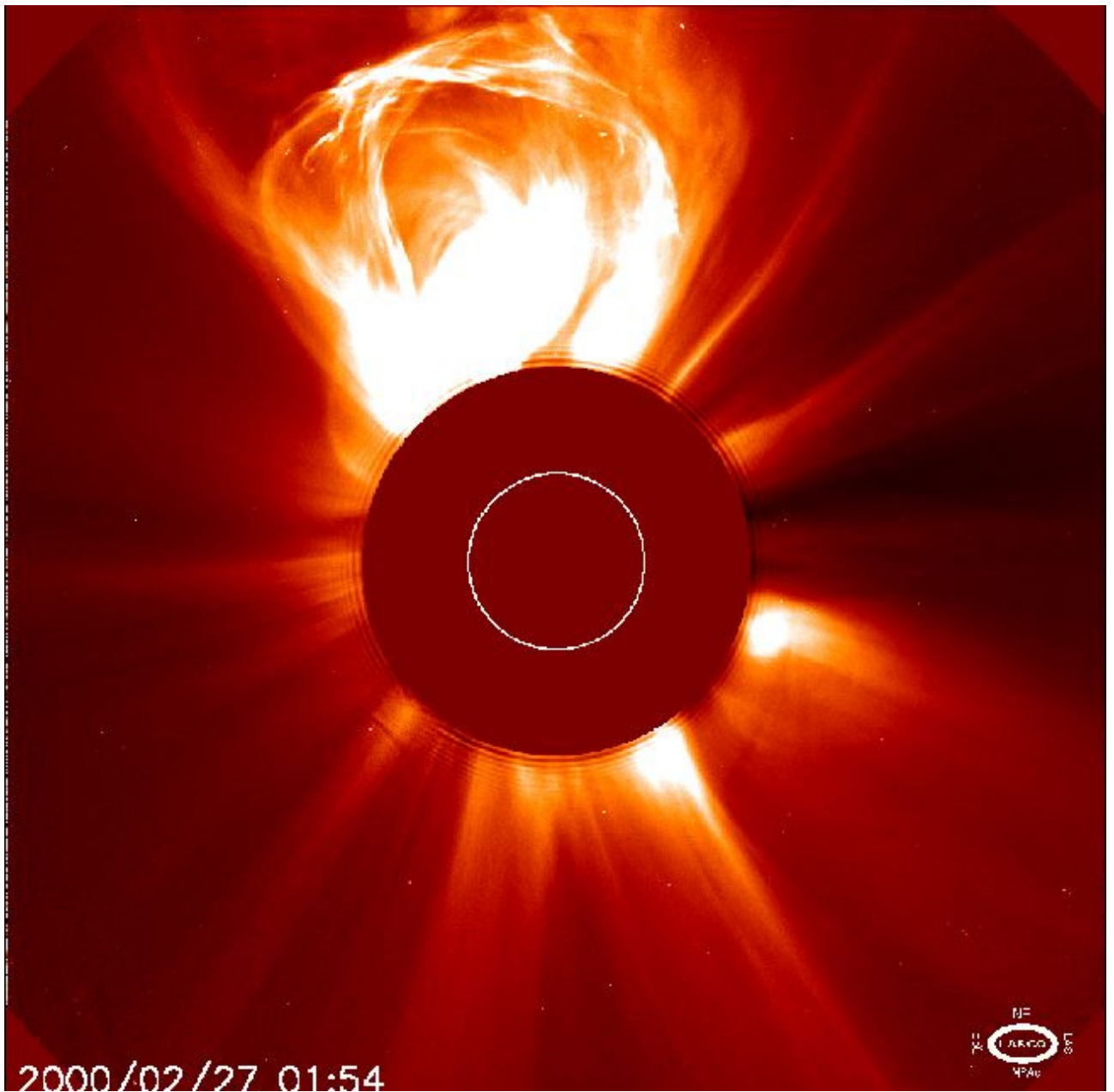
The corona is not normally visible, but it is on the occasion of the total eclipses of the sun, or with a special instrument called coronagraph, which simulates an eclipse by concealing the solar disk.



Below a beautiful image of the solar corona as it appears in the period of the cycle close to the minimum realized by the amateur astronomer Danilo Pivato on the occasion of the total eclipse of the sun of 21 August 2017 from Wyoming (U.S.A).



It should be noted that during the minimum period the crown extends along the entire solar perimeter, while near the maximum of the cycle it extends only in the equatorial latitudes.



A gigantic CME (source SOHO-LASCO)

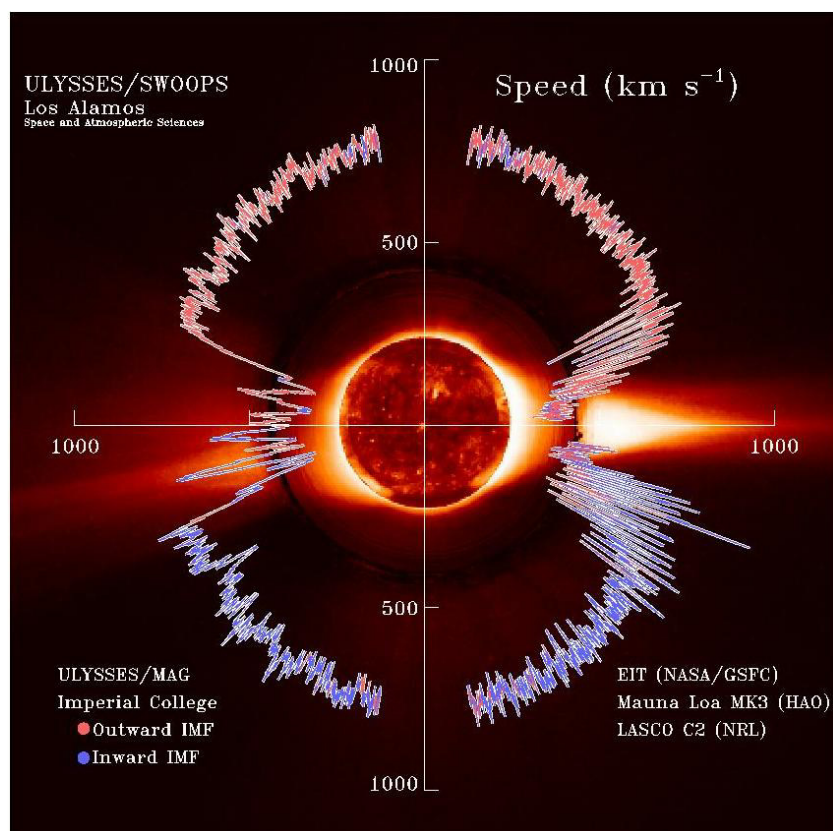
Synthesizing, chromospheric and coronal activity has the following main explosive features:

- Prominences
- Flares
- Coronal mass ejections (CME)

All are caused by the interaction between the ionized gas (plasma) and the solar magnetic field.

## The solar wind

The solar wind is a flow of charged particles emitted by the high atmosphere of the Sun: it is generated by the continuous expansion in the interplanetary space of the solar corona; said flow is normally composed of electrons and protons with high energy. In practice it is an extremely tenuous plasma, of speed ranging from 200 to 450 km sec (slow solar wind) and from 450 to 900 km sec (fast solar wind). The speed is greater in the areas of the so-called "coronal holes" in which the corona appears dark. It takes from 2 to 9 days to interact with the Earth's magnetosphere, sometimes perturbing it seriously and originating the polar aurora. The solar wind is not uniform, both in terms of direction and speed, as can be seen from the following image (Source NASA).



## **The professional instruments for solar observation**

Instruments for solar observation are subdivided into terrestrial and satellite instruments.

Earth instruments: telescopes

The main telescopes operating at the solar observatories include:

- Mc Math Pierce solar observatory KPO (161 cm) (Arizona-USA)
- Big Bear Solar Observatory GST (160 cm) (USA)
- Swedish solar telescope (100 cm) La Palma, Canary - Spain
- Themis Solar telescope Tenerife- Spain

### Terrestrial instruments: Solar towers

The solar towers, now unfortunately in disuse in most of the European Observatories as exceeded by the instrumentation on satellites, consists of a structure of a certain height (20-50 meters) on top of which there is a celostate, or a flat mirror on a motorized mount that follows the apparent path of the sun on the sky and that sends the image back to a second mirror, also flat, which in turn reflects the solar image towards a third mirror, parabolic or spherical, of very long focal length. This image of the sun is then focussed through another system of mirrors on the instrumentation at the base of the tower, generally a spectroheliograph, ie a high resolution spectroscope from which images of the Sun are obtained in the various wavelengths.

Among the main operative solar towers we mention:

- The 150-foot (45-meter) tower of Mount Wilson (USA)
  - The solar tower of the Meudon Observatory, in Paris
- The beautiful solar tower of the Rome Observatory (34 meters) and that of Arcetri are now intended for educational needs.

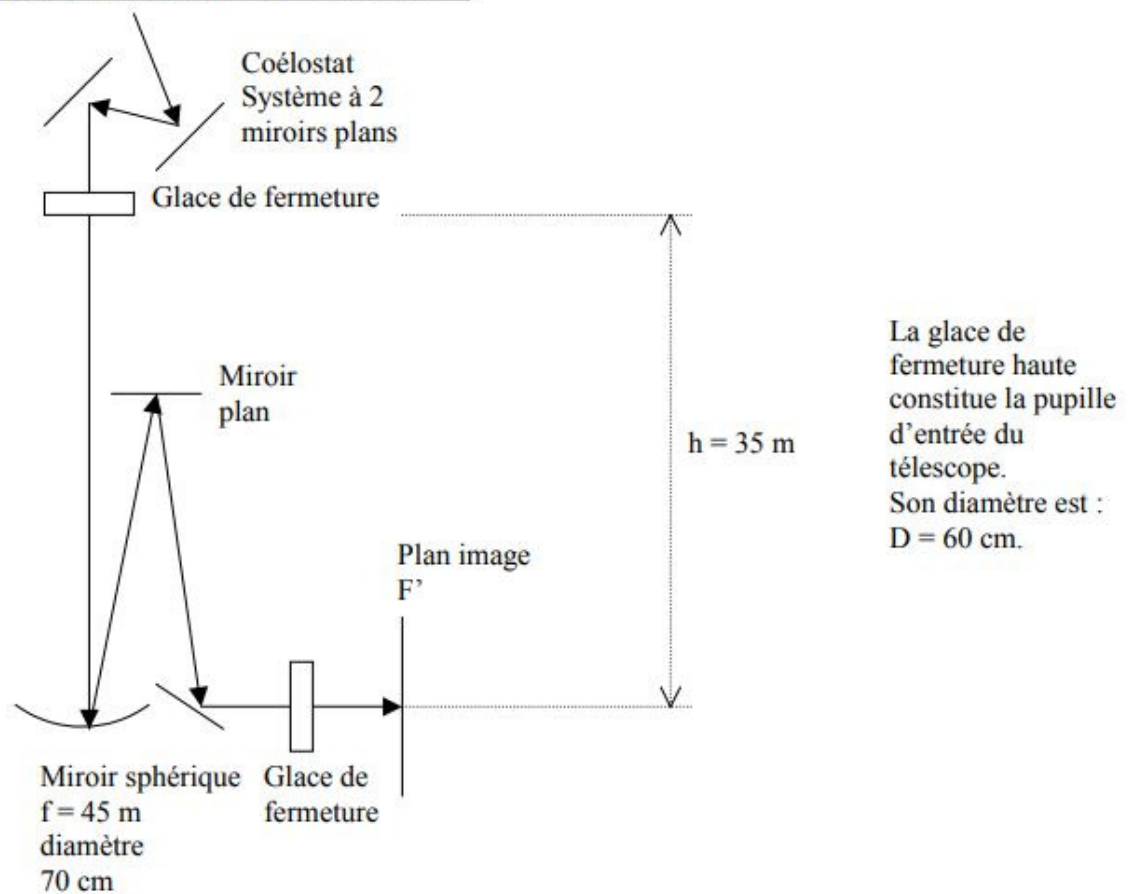




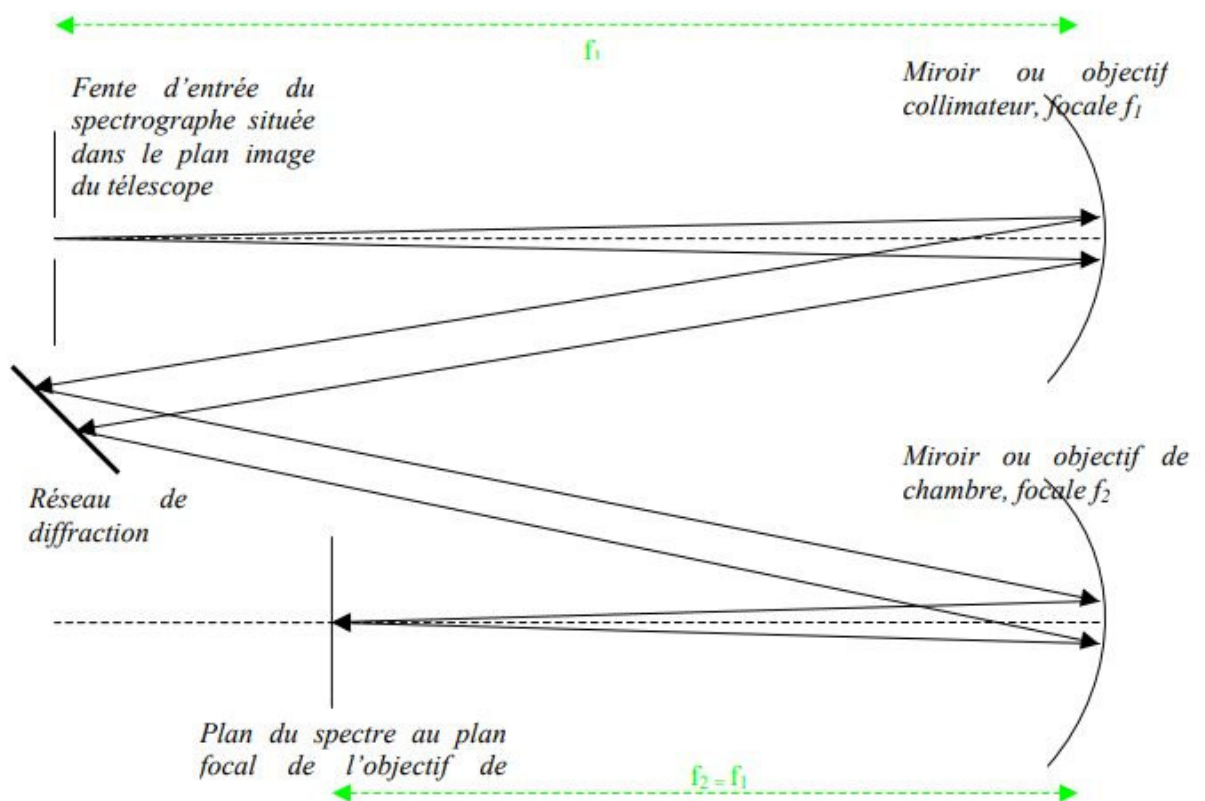
The solar tower of Rome Observatory, on the hill of Monte Mario  
(source : INAF, Osservatorio di Roma)

In the images that follow the layout of the telescope and the spectrograph of the solar tower of Meudon (Paris) (source JM Malherbe, 30.1.2013, PDF "Fiche spectrographe tour solaire simple passage" - BASS 2000), moreover in principle similar to almost all the instruments of this kind still existing.

### 1 - Tour solaire de Meudon : le télescope

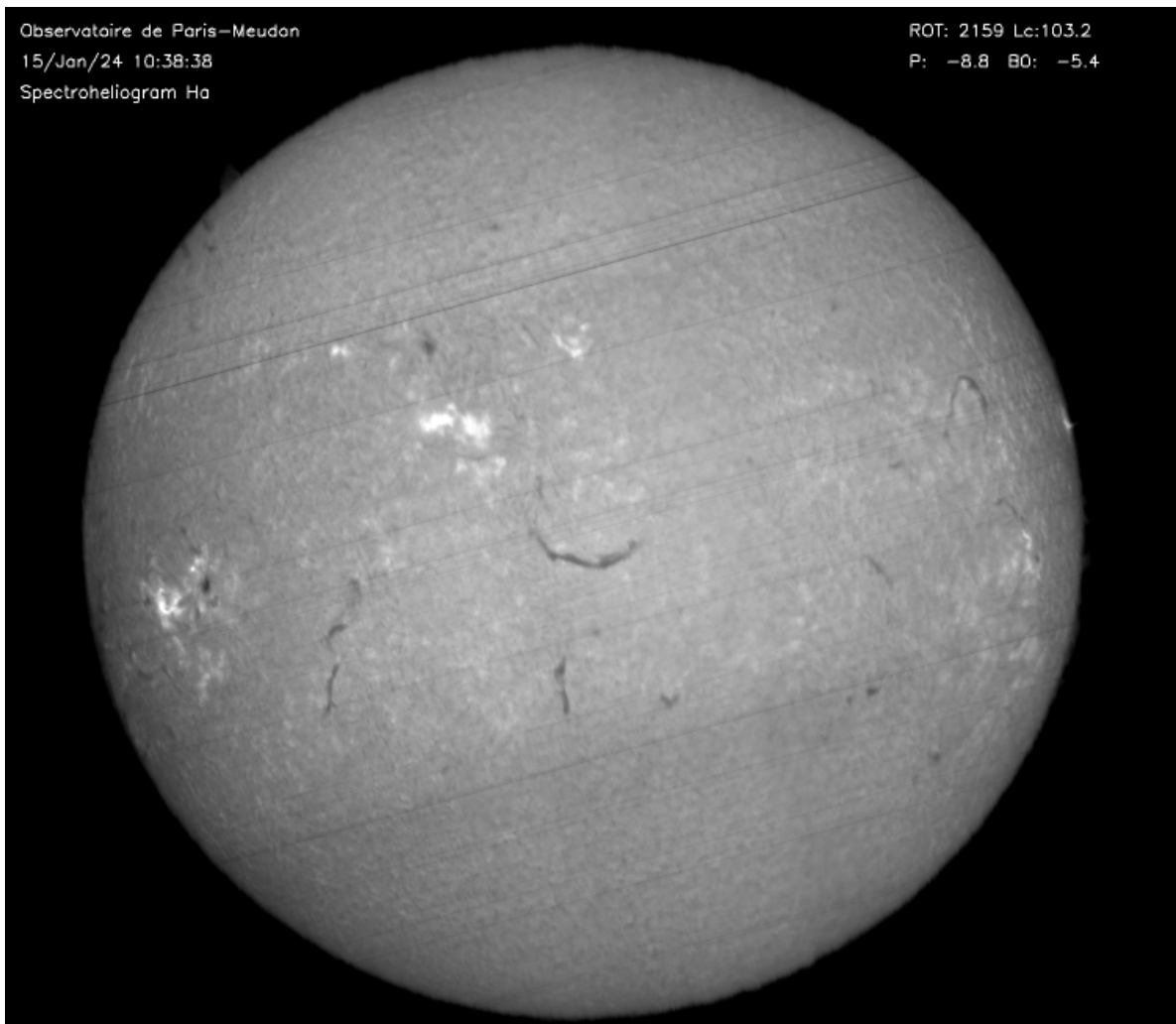


Layout of the telescope of Meudon solar tower: note the focal length of the main mirror of 45 meters.



Layout of the spectroscope of Meudon solar Tower

A solar image in H $\alpha$  light at 6563 Å obtained with the spectroheliograph of Paris-Meudon Observatory (source BASS 2000).



## The main satellite observation systems: SOHO, SDO, STEREO, IRIS

-

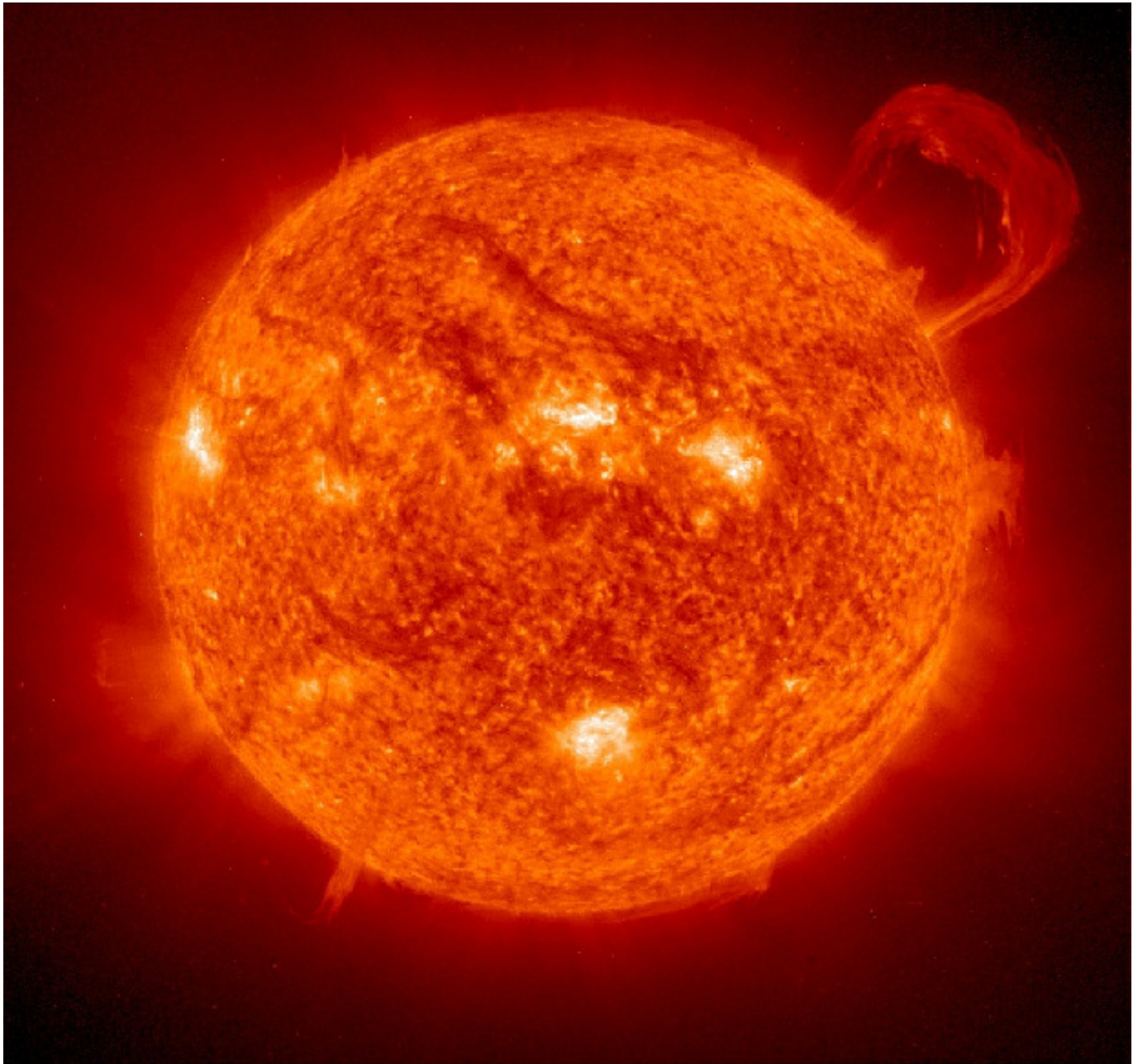
### 1- SOHO (Solar and Heliospheric Observatory)

SOHO is a collaborative project between ESA and NASA for the study of the structure of the Sun, from its core to the corona and the solar wind. The satellite was launched on December 2, 1995, with a package of twelve European and US construction instruments. NASA was responsible for launching and monitoring the mission. Soho has provided unprecedented and primary data on solar structure and dynamics, such as:

- Images of the Convection structure below the photosphere
- data on internal rotation and gas flow
- fundamental data on the solar wind
- the discovery of coronal waves



The SOHO EIT (Extreme ultraviolet Imaging Telescope) produces images at wavelengths of 304,284,295 and 171 Å, to which correspond, in order, ever higher layers of the solar atmosphere and temperatures ranging from 60,000 to 2 million K.



An exceptional prominence imaged by EIT of SOHO in 304 Å wavelength (source SOHO-NASA)

## 2-STEREO (Solar TERrestrial RELations Observatory)

STEREO is the second recent years mission of the NASA solar program (October 2006). It employs two almost identical spatial observatories - one in front of Earth in its orbit (Stereo A), the other in a different position (Stereo B) to provide the first time stereoscopic measurements to study the Sun and the nature of its coronal mass ejections , or CME. The scientific objectives of STEREO are:

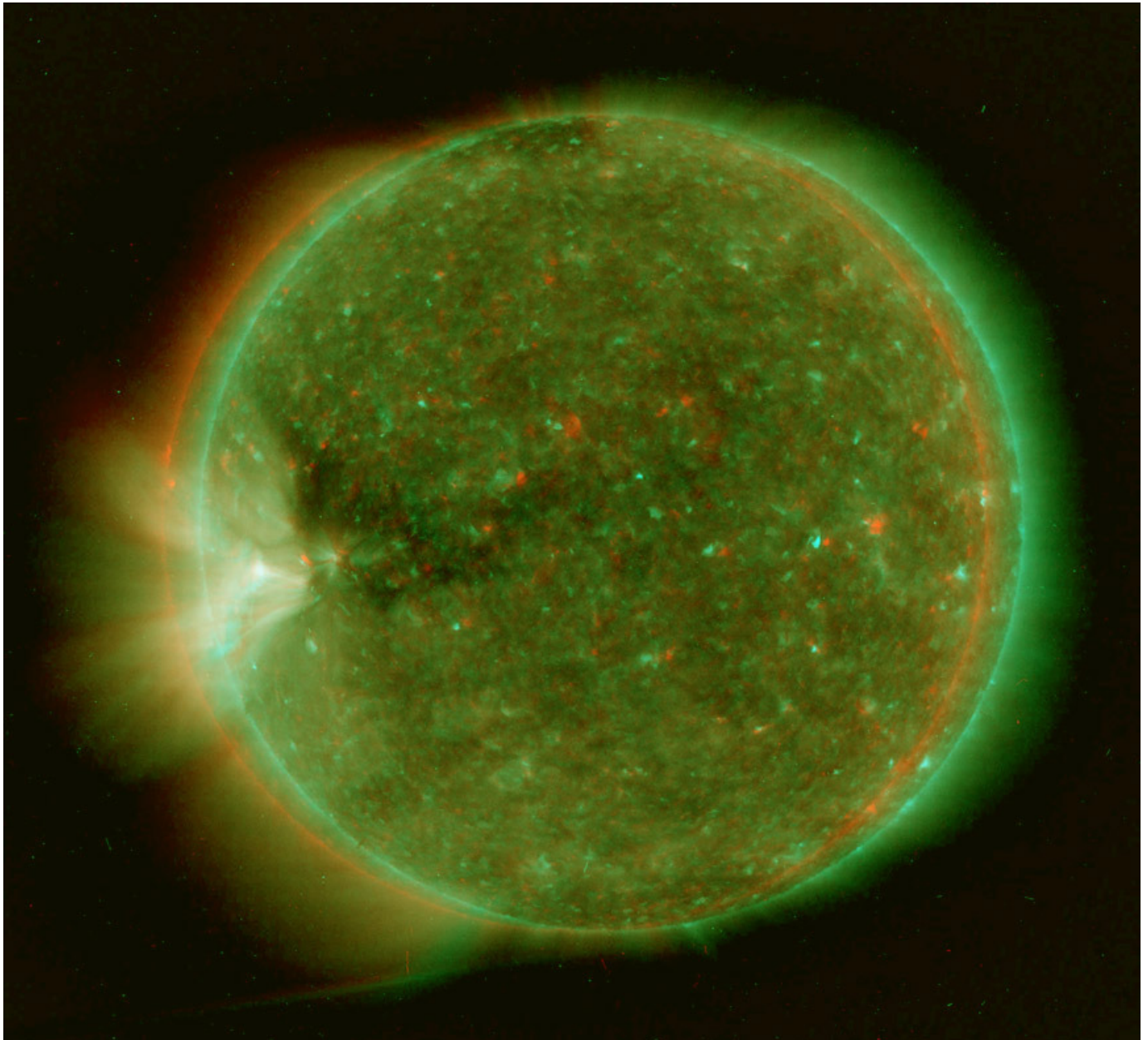
Understanding the causes of coronal mass ejection mechanisms (CME).  
Characterize the propagation of the CME through the heliosphere.  
Discover the mechanisms and sites of acceleration of energy particles in the lower corona and the interplanetary medium. Improve the knowledge of the solar wind structure.

From 1 October 2014, communications with STEREO B were interrupted and were not resumed, predictably due to a technical anomaly. Subsequently the anomaly was corrected and the Stereo survey resumed its functionality until September 23, 2016, when the communications ceased again and remained so.

The instrumentation consists of an ultraviolet Imager (LMSAL), two coronagraphs, and a heliospheric imager on both satellites.

Among the most recent research:

- Stereo images and processing system have been used to identify the finer structures of the outer ring.
- The solar wind and accelerated particles were examined, contributing to the identification of the sources.



A 3D stereo image by Stereo in the far UV a 284 Å

### 3- SDO (Solar Dynamics Observatory)

The Solar Dynamics Observatory was the first mission of NASA to be launched on the basis of a program designed to understand the causes of solar variability and its impact on terrestrial life.

SDO has been designed to better understand the influence of the Sun on the Earth and in the space close to the Earth by studying the solar atmosphere on small scales of space and time and simultaneously in many wavelengths. The goal of SDO is to understand, with a predictive ability, the solar variations that influence the technological systems of the Earth and the life of humanity by determining:

- how the solar magnetic field is generated and how it is structured
- how the stored magnetic energy is converted and released into the heliosphere in the form of solar wind, energetic particles, and irradiation variations.

- SDO was launched on 11 February 2010 on an Atlas V from SLC 41 from Cape Canaveral.

SDO uses three instruments to perform three main scientific experiments:

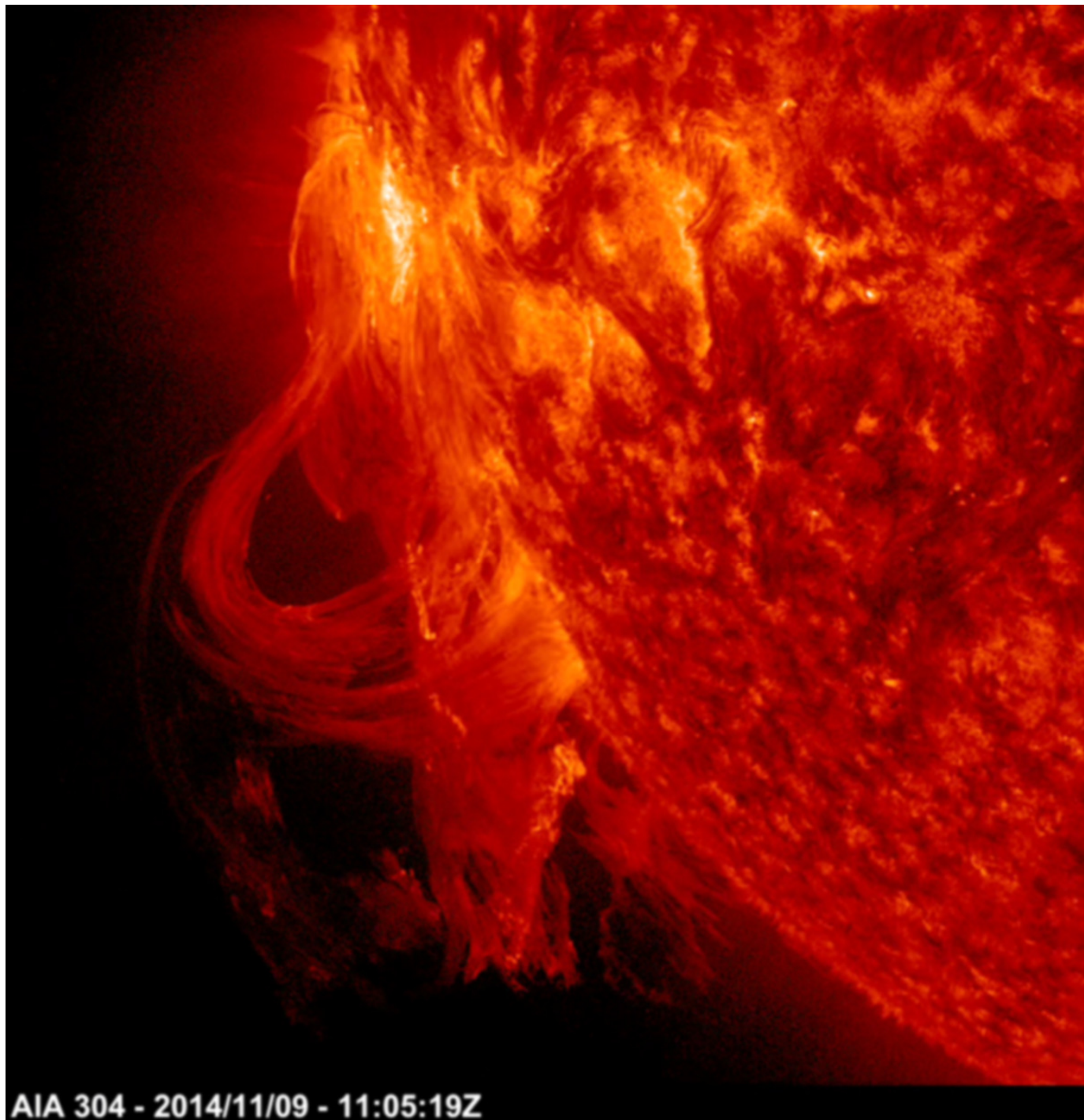
- Helioseismic and magnetic Imager (HMI)
- Atmospheric Imaging Assembly (AIA)
- EUV Variability Experiment (EVE)

Each of these instruments performs different measurements to explain how and why the Sun varies. They can also observe the Sun simultaneously, performing the full range of measures necessary to understand solar variations and their impact on the earth.

In particular, HMI (Helioseismic and Magnetic Imager) extends the SOHO-MDI capabilities to the continuous coverage of the solar disk at a higher resolution, as well as to the vectorial magnetography of the sun, or to the measurement of solar magnetic fields. Atmospheric Imaging Assembly) obtains UV images at resolutions 4 times higher than those of SOHO-EIT and 2 times those of STEREO-Secchi. It performs scans and images of the sun in 10 wavelengths every 10 seconds. EVE (Extreme Ultraviolet Variability Experiment) measures solar irradiation in the ultraviolet (EUV) extreme with a resolution never experienced before. Currently SDO is the reference mission for all solar researchers on a planetary scale. The observations of the ADO SDO tool at 304 Å and many others can be consulted on the Helioviewer website:

<https://www.helioviewer.org/>

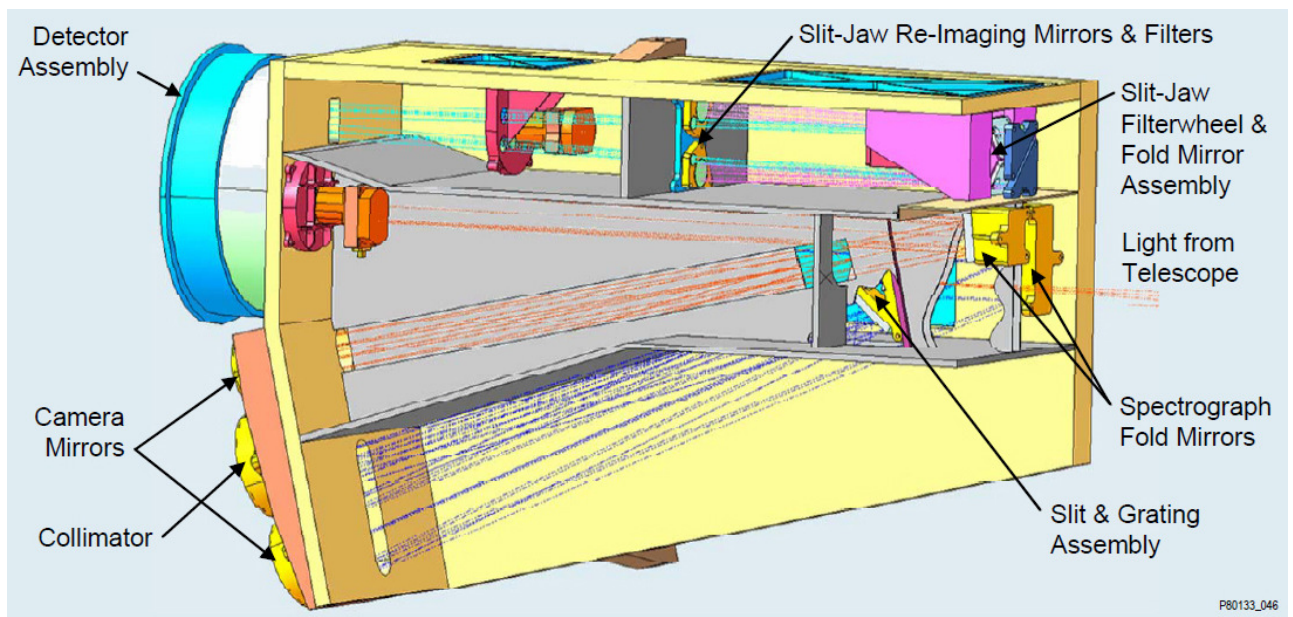




An exceptional solar eruption imaged by SDO-AIA in UV light at 304 Å

#### 4- IRIS

The instrumentation of the IRIS satellite (Interface Region Imaging Spectrograph) is aimed at observing, at a resolution never seen before, the solar atmosphere above the photosphere in order to deepen the mechanisms that cause the enormous increase in temperature between the photosphere and the corona. For this IRIS observes in particular the chromosphere and the transition to the corona to give an answer to the numerous questions on the genesis of gigantic solar explosions such as the flares and CMEs. It uses an ultraviolet telescope and a very high resolution spectrograph-spectroheliograph, able to record both images and spectra, of which hereunder is shown the layout (source NASA / LMSAL).



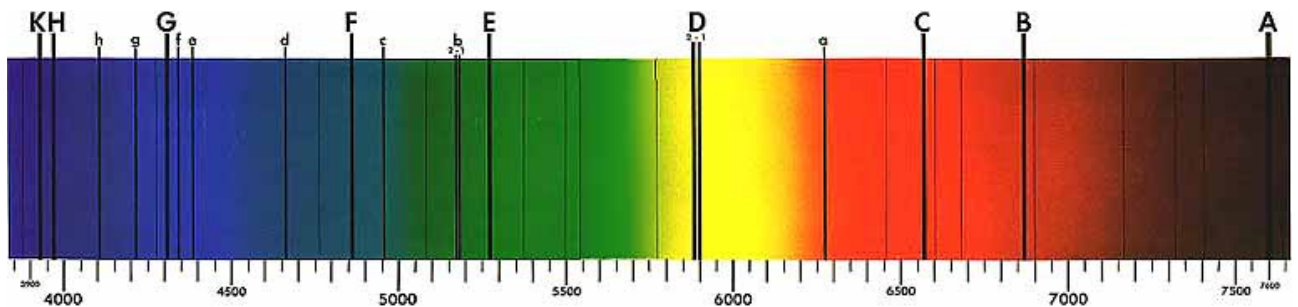
Iris constitutes the state of the art and the most modern and advanced expression of the spectroheliography, which is now the case to get to the heart.



## The solar spectrum

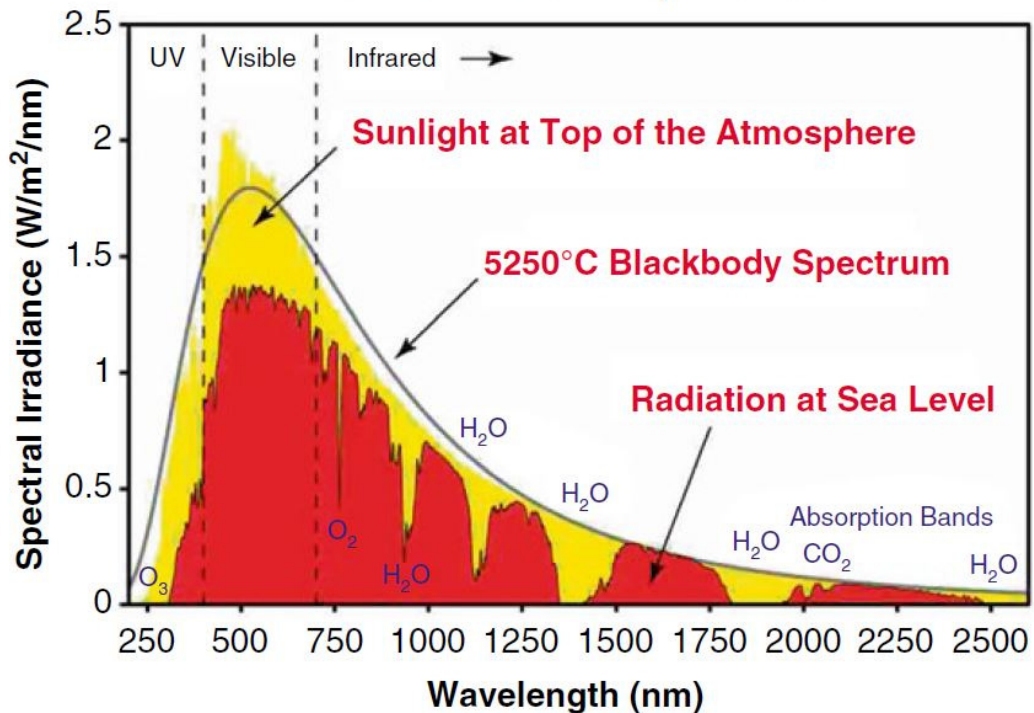
Of the solar spectrum I have already spoken in my spectroscopy text; however, it seems appropriate to recall here some aspects of the study of the solar spectrum, fundamental from the point of view of spectroheliography and spectroheliography.

The spectrum of the sun was observed and studied since the time of Newton, but, after William Wollaston's first experience of looking at its dark lines, it was Joseph Von Fraunhofer, a German physicist and astronomer, to observe and classify the major absorption lines for the first time, which took the name from him. He cataloged 574 dark lines of the solar spectrum, assigning a letter to the most obvious (the famous H and K of Calcium and the C and F of Hydrogen).



Von Fraunhofer was unable to give an explanation of this phenomenon. Only in 1859 Gustav Kirchhoff interpreted it as a selective absorption of light by the chemical elements present in the solar atmosphere. Fraunhofer also demonstrated that the distribution of energy of the Sun varies according to the wavelength, with a peak in the green, around at 500 nm. It is therefore no coincidence that the sensors of digital cameras have a higher quantum efficiency in this area of the spectrum, in which, among other things, the human eye also has the maximum sensitivity.

## Solar Radiation Spectrum

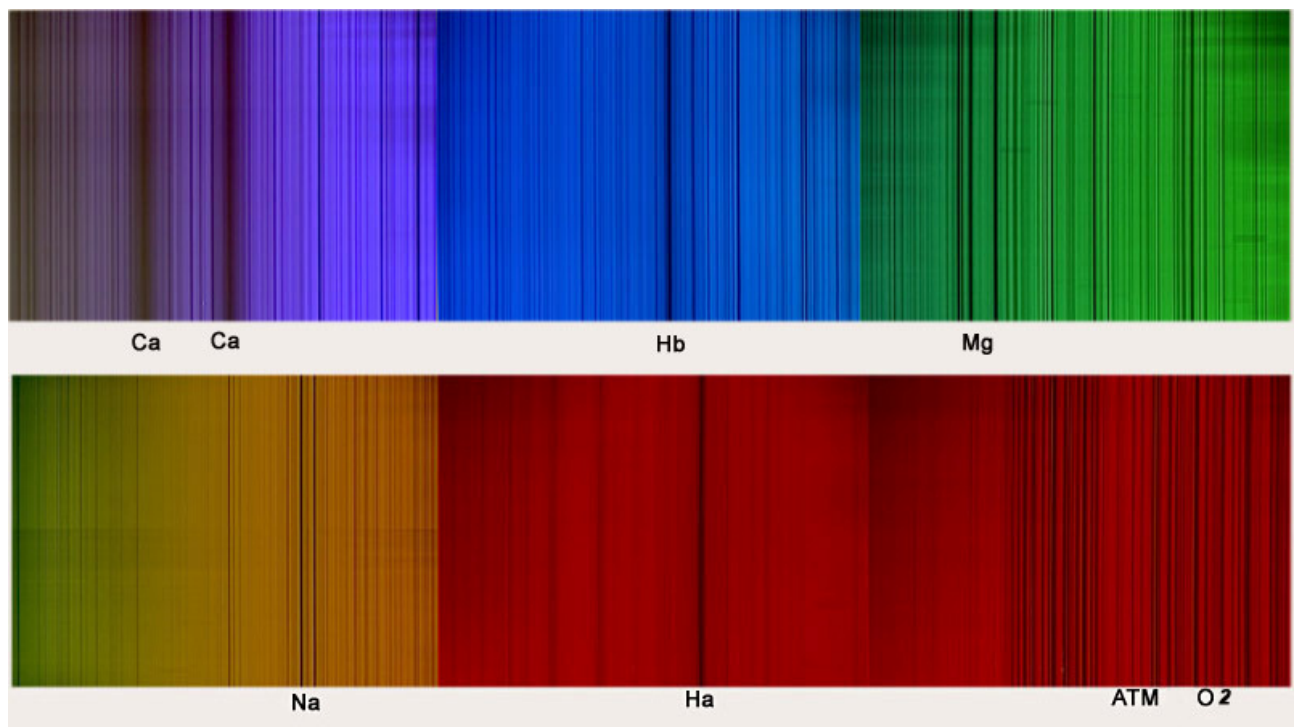


Distribution of the energy of the Sun according to the wavelength, with the black body spectrum and the radiation at sea level (WIKI).

From the above graph we can also deduce data on the relative distribution of this energy with 7% in UV ( $< 3800 \text{ \AA}$ ), about 53% in visible ( $3800\text{-}7000 \text{ \AA}$ ) and 40% in infrared ( $> 7000 \text{ \AA}$ ), which demonstrates the absolute need to observe the sun with filtering systems safe for sight. Since the Sun can be observed at high spatial resolution, it is obvious that there is no single solar spectrum, but there are many different spectra that depend on the point on which the telescope is pointed. It is therefore possible to distinguish between the spectrum of a granule, the spectrum of an intergranular zone, the spectrum of the penumbra and umbra of a sunspot, etc.

Moreover, in the solar spectrum there is a phenomenon of variation with the heliocentric angle for which a spectrum obtained at the center of the Sun differs, even if not in a very pronounced way, from a spectrum obtained at the edge of solar disc. The "standard" solar spectrum can be obtained in two ways: or taking it at the center of the disk, taking care that there are no sunspots in the shooting field, ie shooting the sun like a star, and precisely a G2V class star. Also characteristic of the Sun, like other stars, is the abrupt decrease of the spectral intensity towards the violet at the wavelength of  $3646 \text{ \AA}$ , the so-called "Balmer jump" or discontinuity of Balmer.

The spectrum of sunlight appears rich in absorption lines even with a modest spectroscope: some of them are actually caused by the Sun, while others belong to the Earth's atmosphere (telluric lines): most of the weak lines belong in fact to water vapor ( $H_2O$ ) and they change in intensity according to the degree of humidity, while others belong to the Diatomic Oxygen ( $O_2$ ), the latter mostly concentrated in deep red at the borders of the IR. The real solar spectrum however constitutes a unique laboratory for fans of physics and, why not, also for fans of astronomical spectroscopy. The lines of the Balmer series of Hydrogen, Calcium, Magnesium and Diatomic Oxygen are evident and appear, in medium resolution, as in image below (TSA spectroscope), photo of the author:



But the observation of the lines and colors of the solar spectrum is not an end in itself. It provides us with precious elements of knowledge and information on:

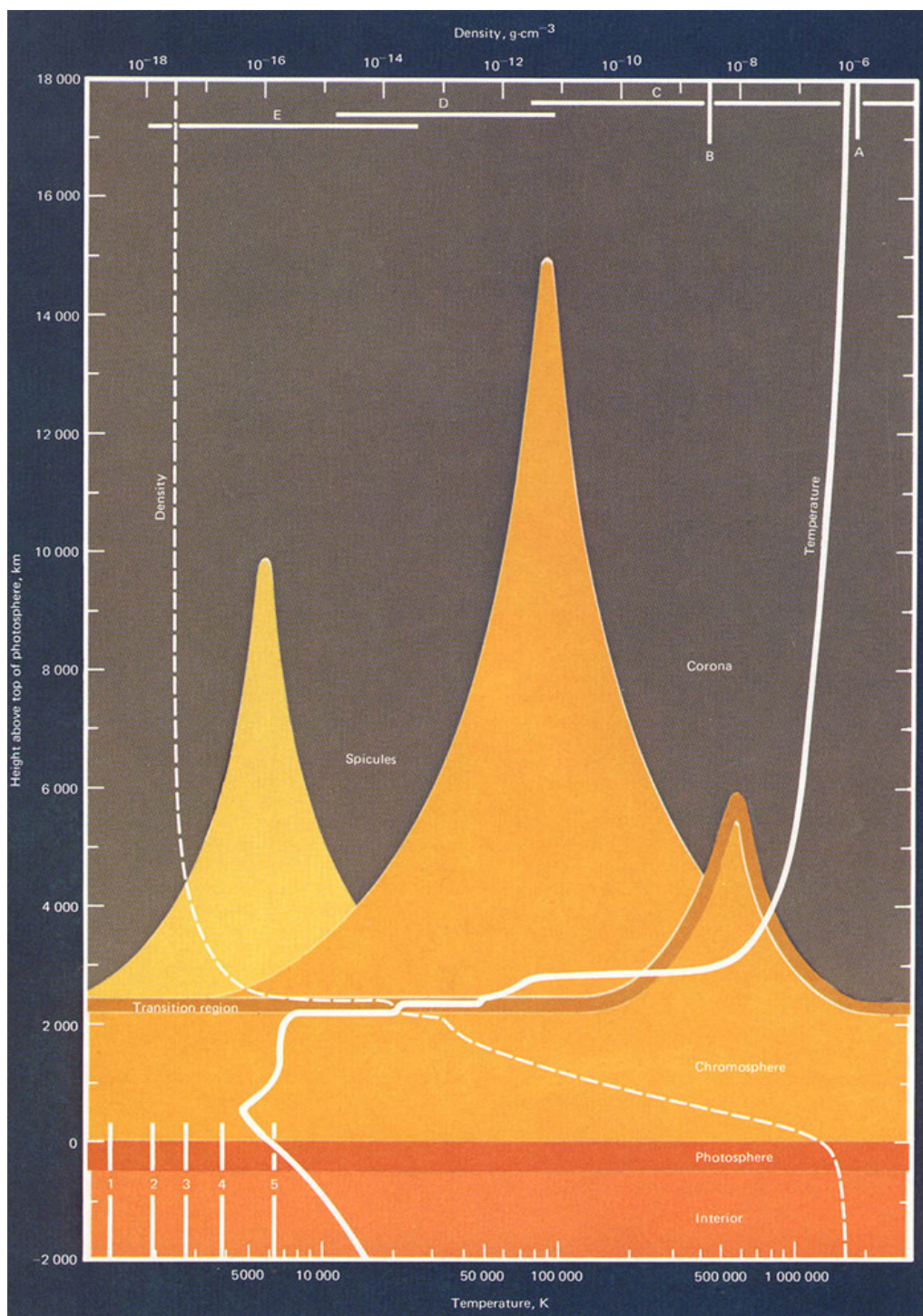
- 1-The chemical elements present on the Sun, given that the lines associated with a given wavelength constitute true digital fingerprints characteristic of each single element.
- 2-The atomic abundance of the element, deduced from the intensity of the lines.
- 3- The temperature at which the elements related to the line or their atomic transitions are located, since the transitions at different atomic levels occur at different temperatures. The temperature is also derived from the width of the line.



4-The magnetic field of the region of the sunspot studied thanks to the Zeeman effect which causes splitting (division in 2 or 3 parts) of the lines sensitive to magnetic fields.

5-The motion of the solar plasma with respect to the observer by Doppler effect.

In the following figure (source NASA-Skylab) is shown the diagram of the photosphere, chromosphere, and solar corona according to height, temperature and density. From it we can observe the point in which take place certain phenomena and the atomic populations of data elements.

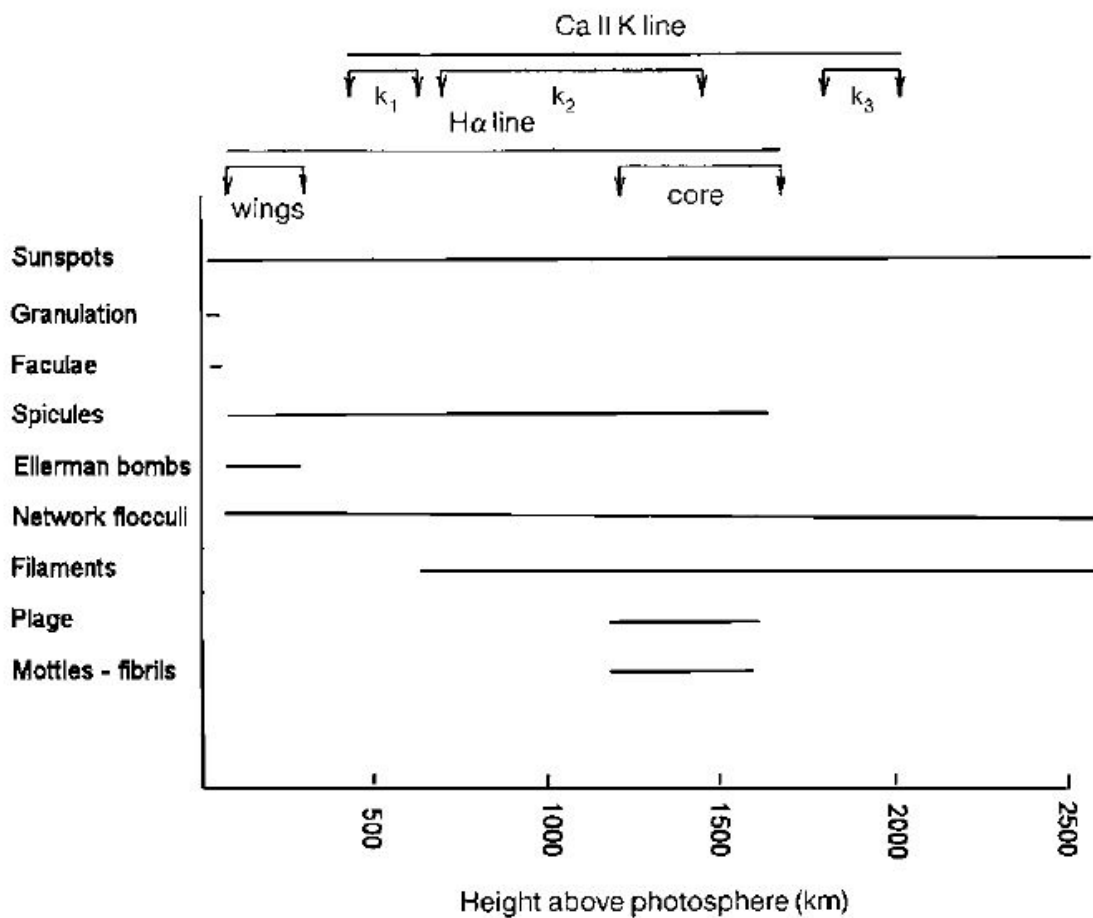


In the table below (<https://solarnutcase.livejournal.com/9556.html>) are instead reported, for the main lines, the related element, the EW (Equivalent width) and their location in the solar atmosphere, with data on the height and the temperature.

Wavelength (nm)	Name	Species	Equivalent width (nm) Disk Centre	Region	Height above Photosphere (Km)	Temp (K)
Soft X-rays				Corona	>5000	2,000,000
121.57	Lyman a	H		Upper chromosphere	2200	20,000
155		C IV		Transition region	2500	100,000
279.54	k	Mg II	2.2	UV emission, high chromosphere	500-1600	
280.23	h	Mg II	2.2			
388.36	(CN band head)	CN	0.03 (index)	Photosphere, magnetic field tracer		
393.36	K	Ca II	2	Chromosphere, flares, prominences	600-1500	
396.85	H	Ca II	1.5	Chromosphere, flares, prominences	1000-2000	
430.79	G band	CH (Fe I, Ti II)	0.72	Photosphere, flares, magnetic field tracer		
517.27	b2	Mg I	0.075	Low chromosphere		
518.36	b1	Mg I	0.025			
525.02		Fe I	0.007	Photosphere, magnetic fields (g=3)		
537.96		Fe I	0.0079	Medium photosphere		
538.03		C I	0.0025	Low photosphere		
557.61		Fe I		Photosphere, velocity fields (g=0)		
587.56	D3	He I		Chromosphere, flares, prominences		
589	D2	Na I	0.075	Upper photosphere, low chromosphere, prominences		
589.59	D1	Na I	0.056	Upper photosphere, low chromosphere, prominences		
612.22		Ca I		Photosphere, magnetic fields (g=1.5)		
630.25		Fe I	0.0083	Photosphere, magnetic fields (g=2.5)		
656.28	C (Ha)	H I	0.41	Chromosphere, prominences, flares	1250-1700	
676.78		Ni I		Photosphere, oscillations		
769.89		K I		Photosphere, oscillations		
777.42		O I	0.0066	High photosphere		
849.8	Calcium 'infrared triplet'	Ca I	0.13	Low chromosphere, prominences		
854.21	Calcium 'infrared triplet'	Ca I	0.37	Low chromosphere, prominences		
866.2	Calcium 'infrared triplet'	Ca I	0.27	Low chromosphere, prominences		
868.86		Fe I	0.014	Photosphere, magnetic fields (g=1.7)		
1006.37		FeH		Umbral (only) magnetic fields (g=1.22)		
1083.03		He I	0.003	High chromosphere		
1281.81	H Paschb	H I	0.19	Chromosphere		
1564.85		Fe I	0.0035	Photosphere, magnetic fields (g=3)		
1565.29		Fe I	0.003	Photosphere, magnetic fields (g=1.8)		
2231.06		Ti I		Umbral (only) magnetic fields (g=2.5)		
4652.55	H Pfundb	H I		Chromosphere, electric fields		
4666.24		CO		High photosphere, thermal structure		
12318.3		Mg I		High photosphere, magnetic fields (g=1)		

To further clarify the concept, the following diagram shows us how certain physical phenomena present on the sun (sunspots, facules, filaments, plages, etc.) present a different aspect not only according to the element in whose light they are recorded or observed (for example Hydrogen alpha or ionized Calcium) but also if the observation is carried out at the center of the line of the mentioned elements or on the wings, for going from the wings towards the center of the line means going towards the upper part of the chromosphere and rising towards higher temperatures .

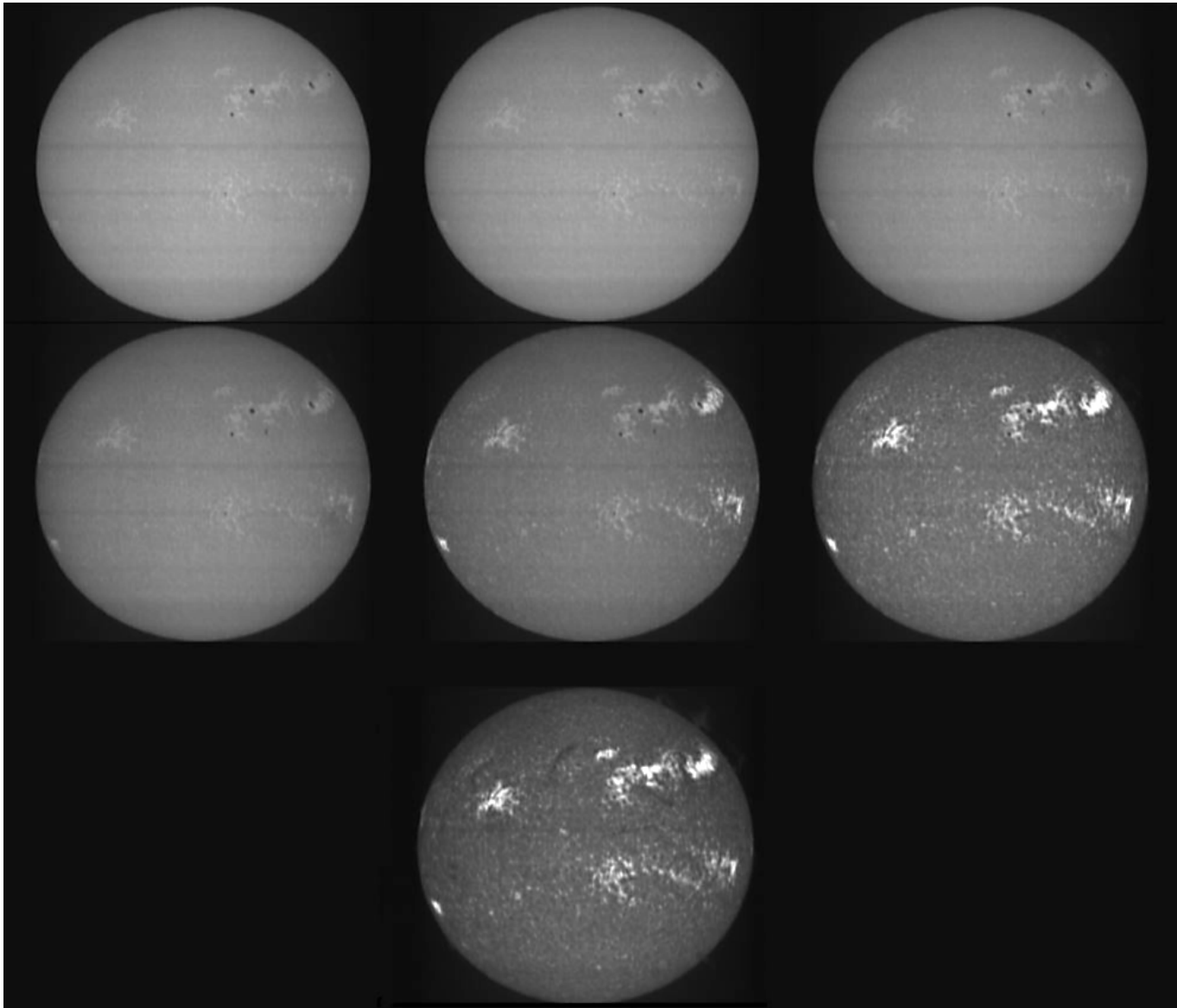
As can be seen in the diagram, the central part of the CaII K line (CaII K3) is placed in the highest part of the chromosphere, around 2000 Km on the photosphere, at the borders of the transition zone: not only, but going from the edge towards the center of this interesting line, a real tomography of the chromosphere is carried out, going from 500 to over 2000 Km above the photosphere and passing from about 5500 K to almost 10.000 K of temperature.



An evident demonstration of what has been previously pointed out is the sequence of images of the solar disk that goes from the end of the wing towards the blue of CaIIK line at the borders of the continuum, up to the center (CaII K3) of the same line. There is a dramatic intensify of the brilliance of the faculae and the visibility of the filaments on the disc as you proceed towards the center of the line and then towards the highest part of the chromosphere.

Sequence of images obtained by the author with its VHIRSS self-built digital spectroheliograph.





While the "core" of the H alpha line at  $6562.8 \text{ \AA}$  measures about  $1.0\text{-}1.2 \text{ \AA}$ , with wings it can extend up to  $10 \text{ \AA}$  from the center, the CaIIK at  $3933.68 \text{ \AA}$ , whose center, including the stationary points and the CaII K 3 covers about  $2.2 - 2.4 \text{ \AA}$ , with wings can reach  $20 \text{ \AA}$  of extension.

As can be seen, therefore, the spectrum is not a simple substitute for narrow-band filters that go by the greatest, but a scientific instrument that allows us to analyze each solar line, from the wings to the center, making a precise scan of the solar atmosphere Now, the solar lines are thousands, even 24000 those included in the atlas by Charlotte Moore and others, freely downloadable in the original text at the link:

<https://nvlpubs.nist.gov/nistpubs/Legacy/MONO/nbsmonograph61.pdf>

Some of them are duplicated and tripled, or too weak to be recorded by amateur means. However, in the writer's opinion, those potentially to be explored with very high resolution spectroheliographs could also be 7-8000: of these the most important, about fifty : Iron, Hydrogen, Calcium, Magnesium, Sodium, Helium, roughly those shown in the table below (source Columbia University, NY) lend themselves to be recorded without problems by amateur instruments at medium-high resolution.

Table 2. More Spectral Lines. (Note: 1 nm equals 10 Angstrom)

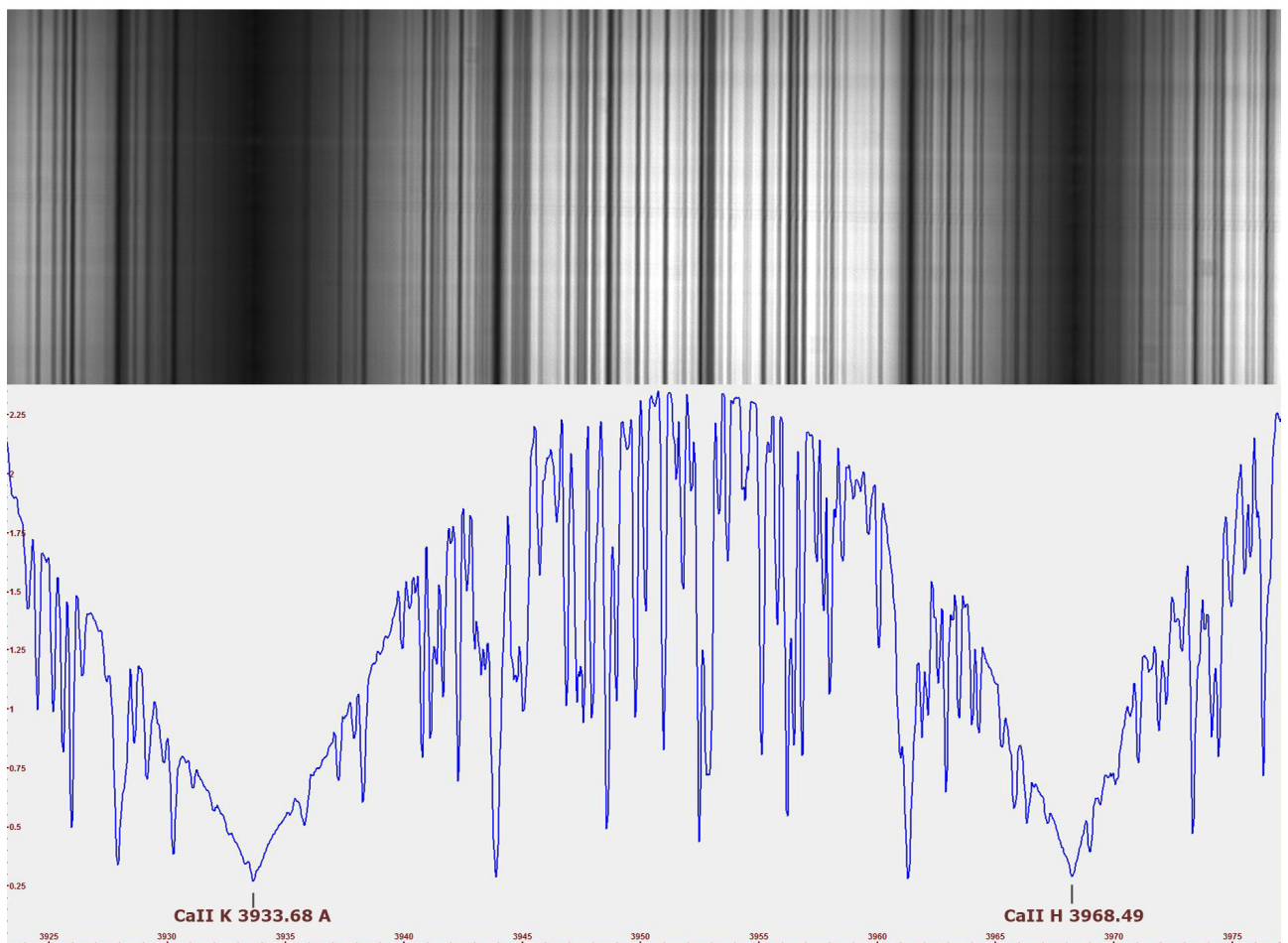
Wavelength (nm)	Line Width (nm)	Element		Wavelength (nm)	Line Width (nm)	Element
393.3682	2.0253	Ca II		440.4761	0.0898	Fe I
394.4016	0.0488	Al I		441.5135	0.0417	Fe I
396.1535	0.0621	Al I		452.8627	0.0275	Fe I
396.8492	1.5467	Ca II		455.4036	0.0159	Ba II
404.5825	0.1174	Fe I		470.3003	0.0326	Mg I
406.3605	0.0787	Fe I		486.1342	0.3680	<b>H</b>
407.1749	0.0723	Fe I		489.1502	0.0312	Fe I
407.7724	0.0428	Sr II		492.0514	0.0471	Fe I
410.1748	0.3133	<b>H</b>		495.7613	0.0696	Fe I
413.2067	0.0404	Fe I		516.7327	0.0935	Mg I
414.3878	0.0466	Fe I		517.2698	0.1259	Mg I
416.7277	0.0200	Mg I		518.3619	0.1584	Mg I
420.2040	0.0326	Fe I		525.0216	0.0062	Fe I
422.6740	0.1476	Ca I		526.9550	0.0478	Fe I
423.5949	0.0385	Fe I		532.8051	0.0375	Fe I
425.0130	0.0342	Fe I		552.8418	0.0293	Mg I
425.0797	0.0400	Fe I		588.9973	0.0752	Na I (D <sub>2</sub> )
425.4346	0.0393	Cr I		589.5940	0.0564	Na I (D <sub>1</sub> )
426.0486	0.0595	Fe I		610.2727	0.0135	Ca I
427.1774	0.0756	Fe I		612.2226	0.0222	Ca I
432.5775	0.0793	Fe I		616.2180	0.0222	Ca O
434.0475	0.2855	<b>H</b>		630.2499	0.0083	Fe I
438.3557	0.1008	Fe I		656.2808	0.1020	<b>H</b>

But already about fifty easy lines (perhaps a hundred including those a little more difficult), makes us understand the extreme usefulness and versatility of the spectroheliograph: admitted they were available, and they are not, how much they could cost the amateur 50-100 very narrow band solar interference filters? Surely an amount ranging between 200000 and 400000 € (\$ 231000 – 462000), not to mention that interference filters so narrow to select lines or parts of a line of 1 / 50th of Å probably do not exist. Here I will show how you can explore the secrets of our star with figures from a minimum of 500 to a maximum of 1000- 1500 € (\$ 580 to 1100 -1700).

Here are the high resolution spectral lines of the most important elements, with reference wavelengths (VHIRSS and POSS2 instruments).

### The lines of ionized Calcium CaII K and H

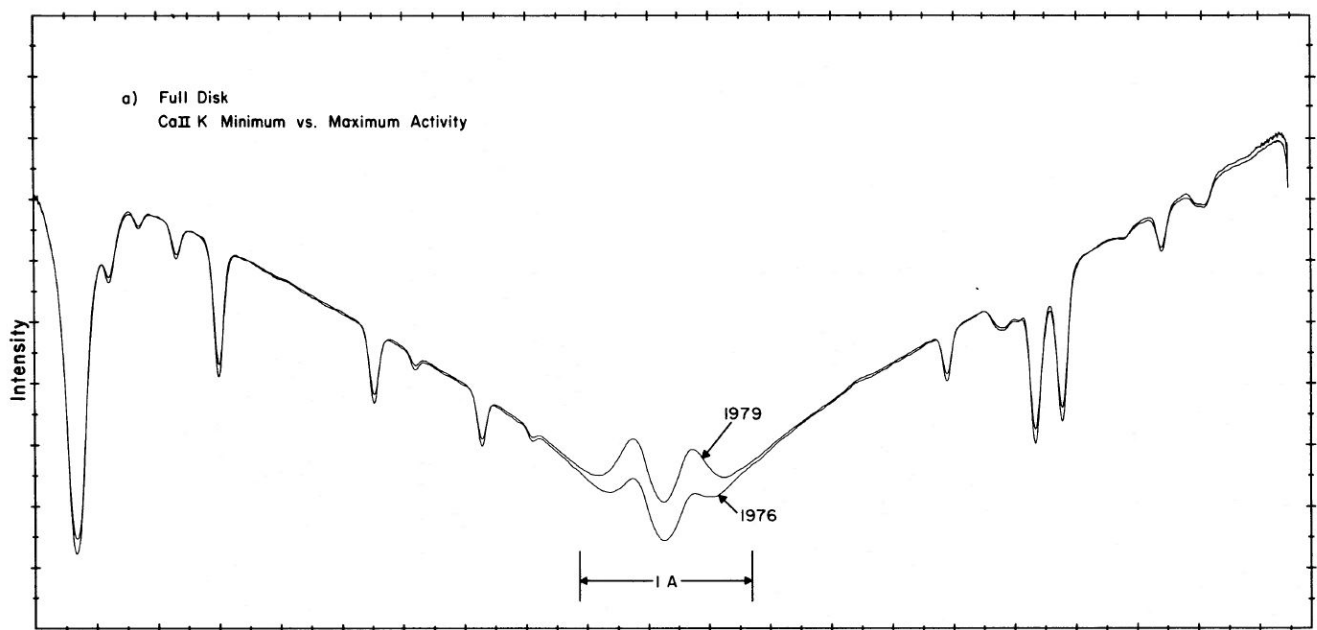
**POSS2 CaII K & CaIIH lines**



The lines Ca II K a 3933.68 Å and Ca II H at 3968.49 Å imaged by my self built "POSS2" Hires spectrograph – spectroheliograph.

The CaII K line is of great importance in the study of solar activity and of the chromosphere in particular. The National Solar Observatory (NSO) in Sacramento Peak, Arizona, USA, has carried out for a long period of time, from 1976 to 2015, a monitoring of the line in question, evaluating, among other things, the parameters of the emission index (EM) corresponding to the EW (Equivalent Width) of a range of  $1 \text{ \AA}$  centered on the line, and the core intensity values K3 ( $0.15 \text{ \AA}$ ) of the same line. Since October 2015, the Sacramento Peak monitoring program has been suspended, as data from the SOLIS project - ISS (Integrated Sunlight Spectrometer), now active at the NSO - Kitt Peak, are now being used. This is a spectrograph capable of resolution  $R = 300000$  and a wavelength range from 350 to 1100 nm. The monitoring also extends to the CaII line H.

An example of the variation of core intensity of  $1 \text{ \AA}$  of the CaIIK line through cycle 21, from minimum to maximum (source: "Solar luminosity Variations .Calcium K variations in cycle 21" -White and Livingstone-1981).



In addition to the ultraviolet, the line of ionized calcium also appears in the near infrared, at 8498, 8542 and 8668  $\text{\AA}$  (triplet of Calcium), the most used by professionals, that at 8542, would however be rather difficult to reach for an amateur, not so much for the spectroscope, which would require a grating optimized for IR, as for the lack of sensitivity of the amateur CCD or CMOS cameras at that wavelength.

## The lines of Hydrogen observable on the Sun

The spectrum of hydrogen is the simplest of the spectra since this element is made up of the nucleus containing a proton around which only one electron moves. The electrons move in orbits with quantized energy. The orbit 1s is the innermost one, a fundamental state, which corresponds to the minimum of energy. If the electron in a high-energy orbit passes to a low-energy orbit, it releases a certain amount of energy in the form of radiation having a given wavelength, giving rise to an emission line.

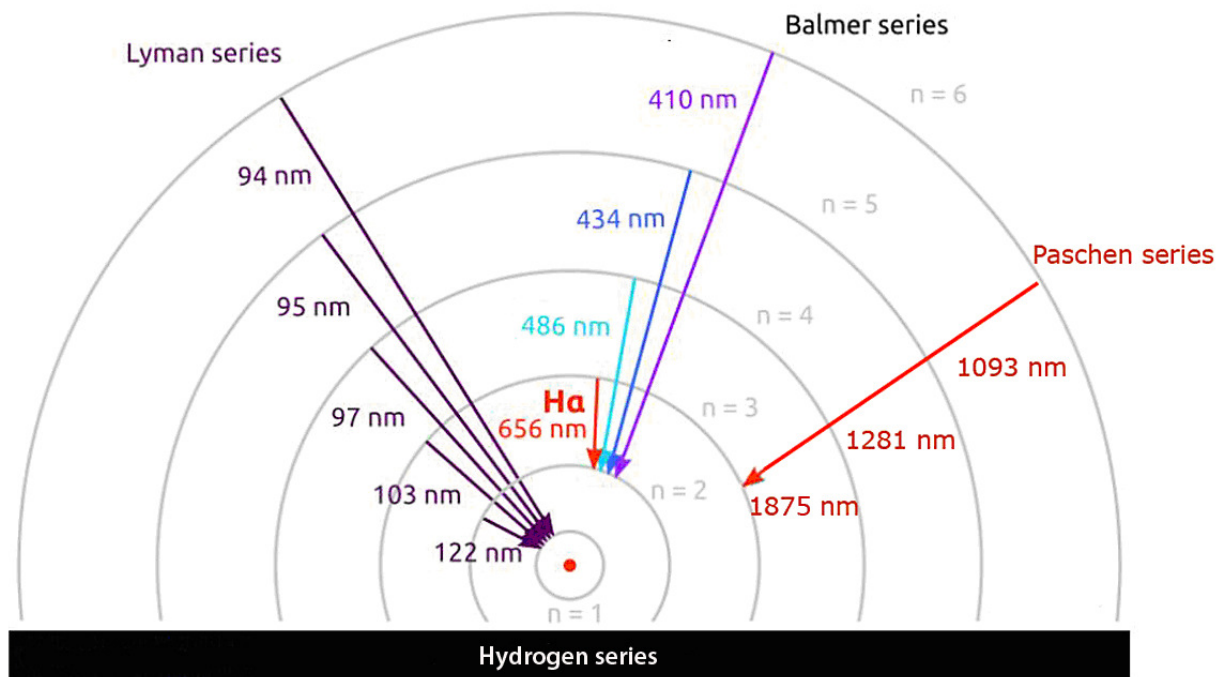
The transitions that the electrons perform from the peripheral orbits to the innermost ones can be ordered according to decreasing values of energy: the highest variations are recorded when an electron passes from a peripheral orbit to that corresponding to the fundamental state. The set of all the jumps ending in the orbit 1s gives rise to a series of spectral lines which take the name of Lyman series, the first lines of which are indicated with  $L\alpha$ ,  $L\beta$ ,  $L\gamma$  and correspond to the ultraviolet lines .

At immediately lower energy values are the jumps of the electron from the peripheral orbits to the second stationary orbit: we have energy of the visible spectrum and we obtain lines of the Balmer series. The first line originates from a jump from the orbit 3 to the orbit 2 and is indicated with  $H\alpha$ , the second from 4 to 2 and is indicated with  $H\beta$  while the third indicated with  $H\gamma$  corresponds to the jump from orbit 5 to 2 and so on. The same speech is repeated for the Paschen series whose lines correspond to the energy of the lines of the I.R.

### Hydrogen transition series

Lower Level	Main transition
$n = 1$ , <i>Lyman</i>	$L_{\alpha} = 1216\text{\AA}$
$n = 2$ , <i>Balmer</i>	$H_{\alpha} = 6563\text{\AA}$
$n = 3$ , <i>Paschen</i>	$P_{\alpha} = 18750\text{\AA}$





The Balmer series in the visible is undoubtedly the most interesting from our point of view, also because the ionized hydrogen H alpha at 6562.8 Å is the most abundant element in the solar atmosphere, giving it the red color we know.

The Balmer formula for the series that takes its name, in the visible, is as follows:

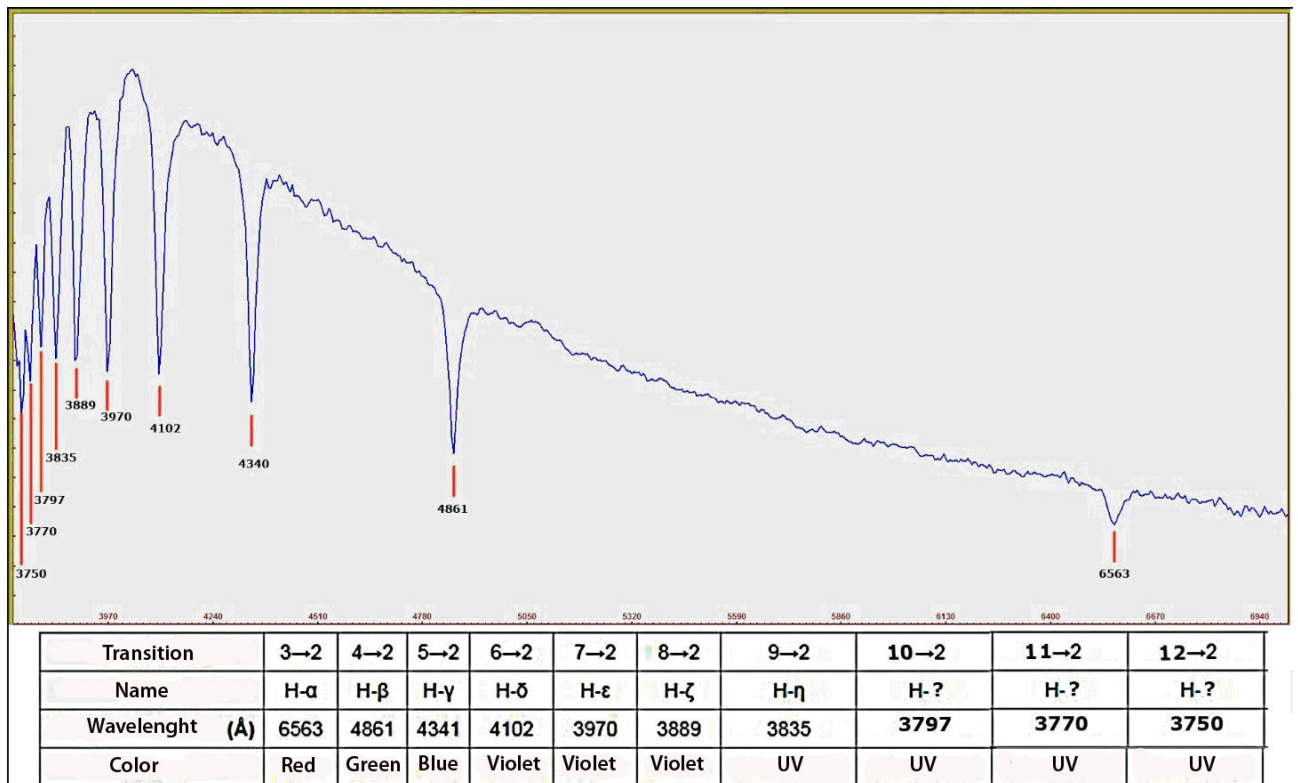
$$\lambda = B (m^2 / m^2 - 2^2)$$

where B is the Balmer limit at 3646 Å; m is any integer  $m > n$

Below, the absorption spectrum of the Hydrogen Balmer series I have calculated on the Vega star up to the 12> 2 transition:  
For example, for the transition 10> 2 is:

$$3646 \times (100/96) = 3797 \text{ Å}$$

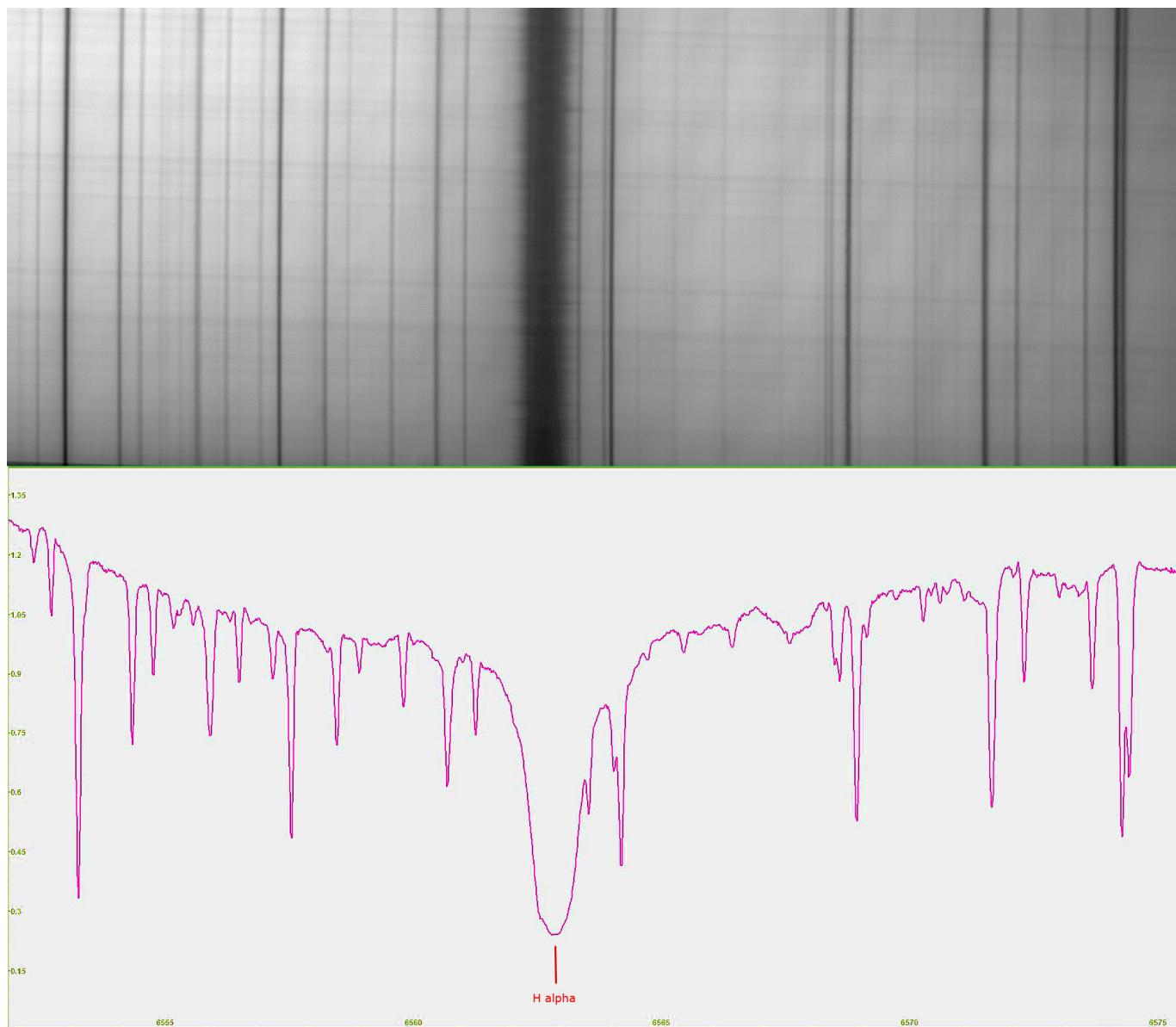


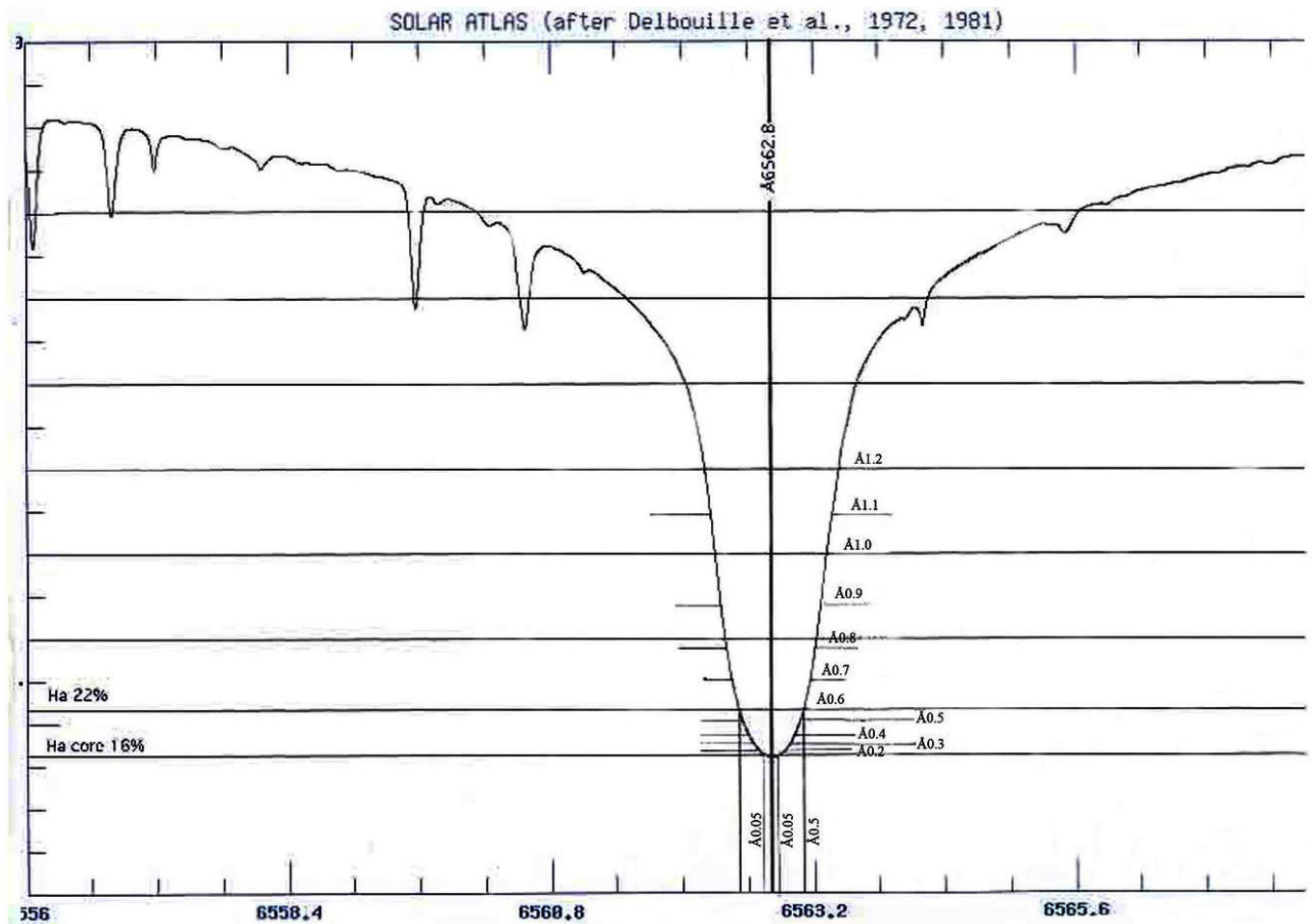


## The H $\alpha$ line

As mentioned above, the hydrogen transition  $3 \rightarrow 2$  at  $6562.8 \text{ \AA}$  (line H $\alpha$ ) is the element that characterizes the chromosphere and gives it its characteristic deep red color. While the wings of the line come from the lower chromosphere, almost at the border with the photosphere, the central part of the same refers to the high chromosphere, on average around 1500 km, as shown in the figure on page 45.

In high resolution (VHIRSS spectrograph-spectroheliograph) the line appears, in absorption, as follows: note the jagged profile due to vertical motions of elements of solar atmosphere.



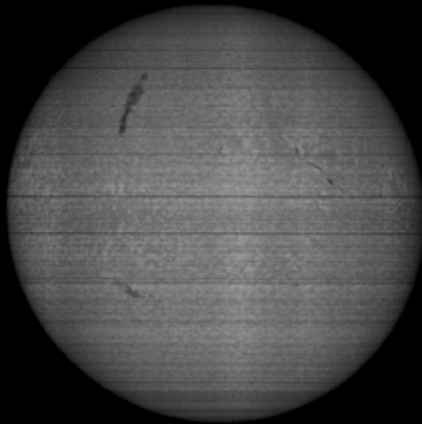


Profile of H $\alpha$  line in absorption with the extension in Angstrom of the core and the wings the FWHM is about 1-1.2 Å. Source : Debouille-Solar Atlas – BASS 2000.

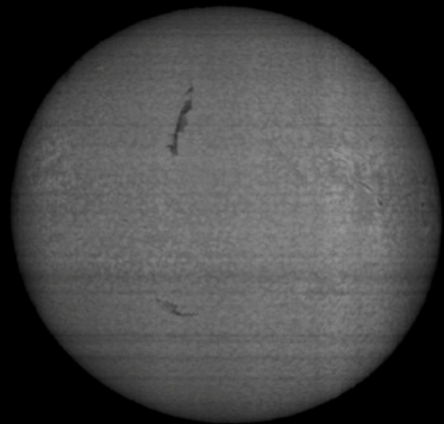
## The H $\beta$ line

The H $\beta$  line at 4861.34 Å would seem at first glance less important for the study of the solar atmosphere, both for the smaller extension with respect to the H $\alpha$  and for the attenuation of the same details, primarily plages and filaments. However, it is necessary to evaluate the good observability in the spectralograms in this line of solar flares. Who writes, participating in the survey "F-Croma" could verify this feature with a small flare observed on September 27, 2015: in the image that follows the sequence of the H $\beta$  light observations I made during the campaign with VHIRSS.

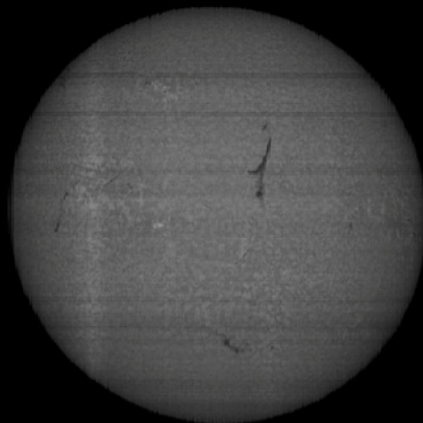
15-09-21



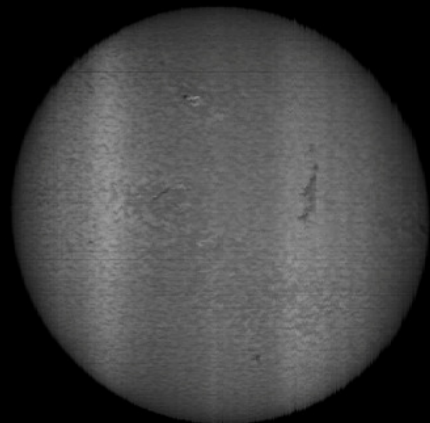
15-09-22



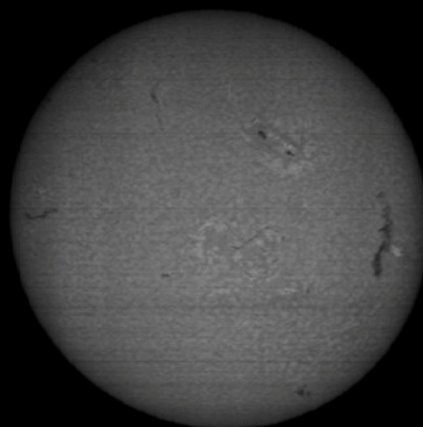
15-09-24



15-09-25

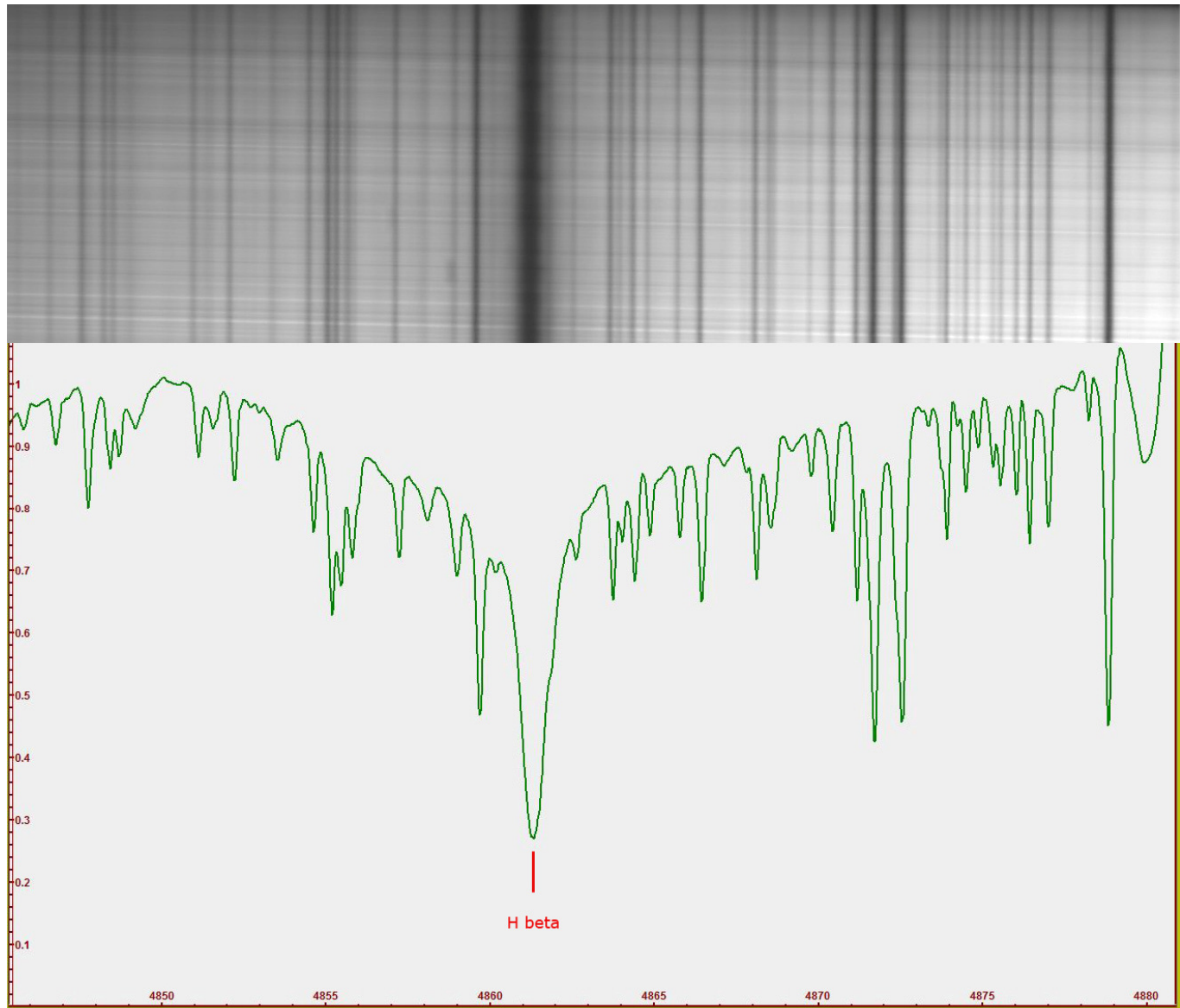


15-09-27



Sun in Hbeta light 486 Nm and AR 12 422 evolution September 21-27-2015 -  
VHIRSS digital spectrohelioscope Fulvio Mete, Rome , Italy

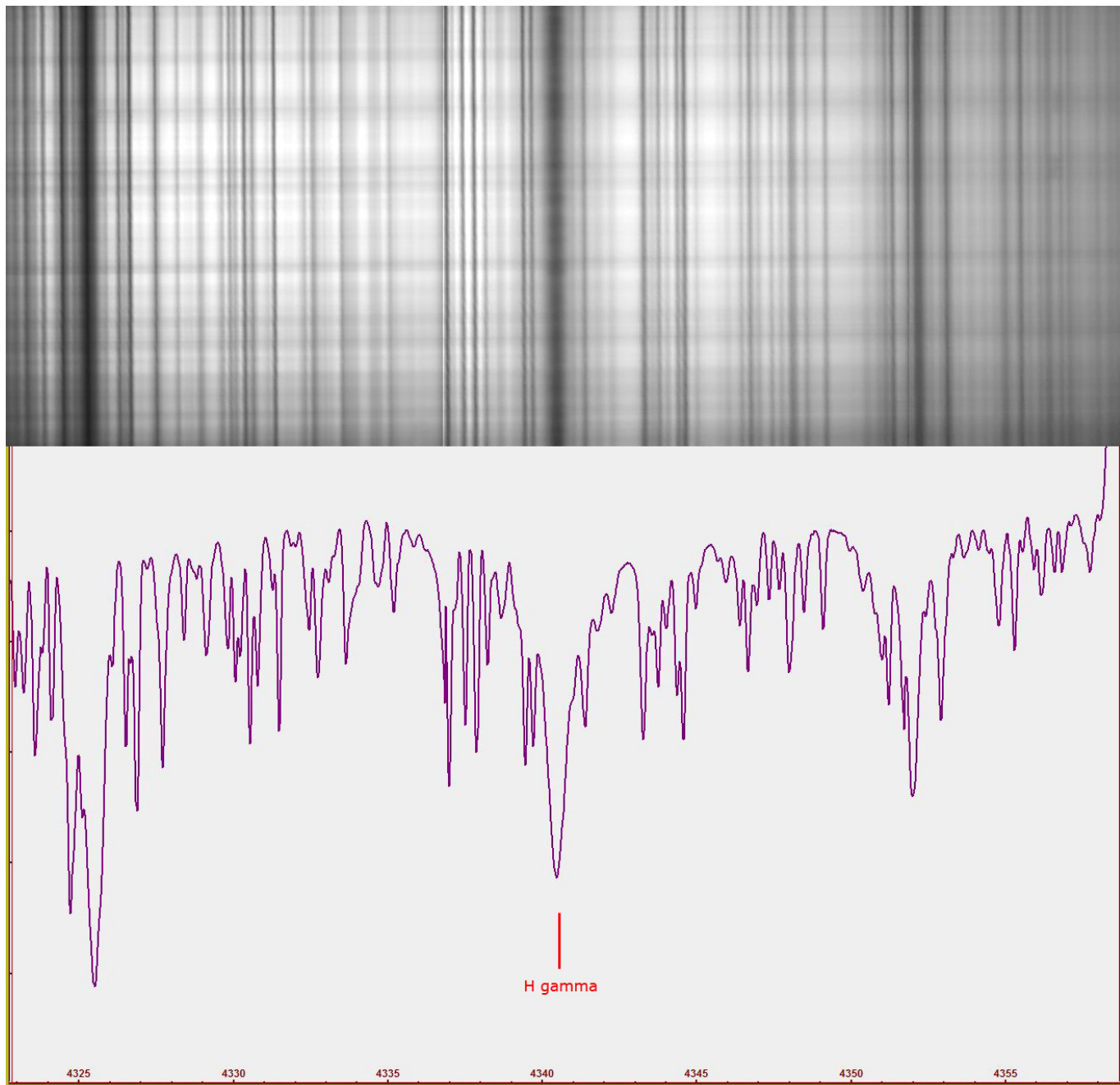
In the image that follows, the H $\beta$  line and its spectral profile imaged by VHIRSS in Hi res spectroscope mode.



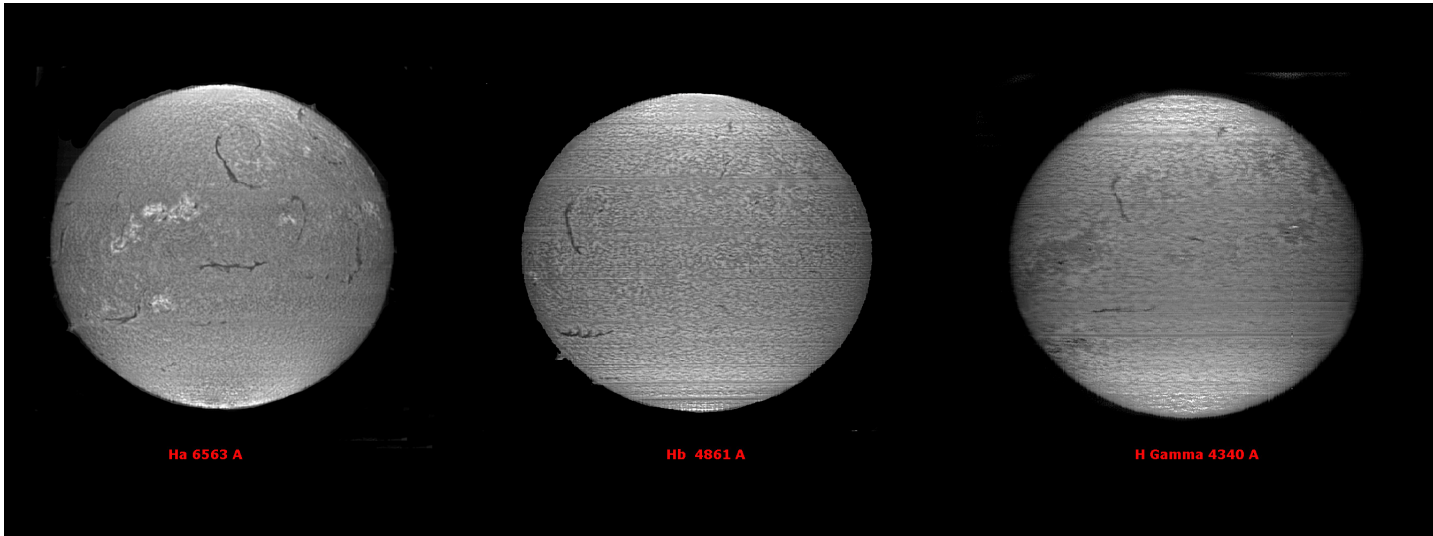
### The H $\gamma$ line

What I said for the line H $\beta$  is also valid for the line H $\gamma$  at 4340.47 Å in the sense that in the spectroeliograms obtained in this line the visible details are much less brilliant and evident than in the other two.





The following image shows the comparison between the spectroheliograms obtained with VHIRSS in the three previously mentioned Hydrogen lines: it is evident that, going from the Hydrogen alpha in the lower wavelengths, the plages lose their bright white color to pass to darker shades of gray, while the filaments lose contrast.

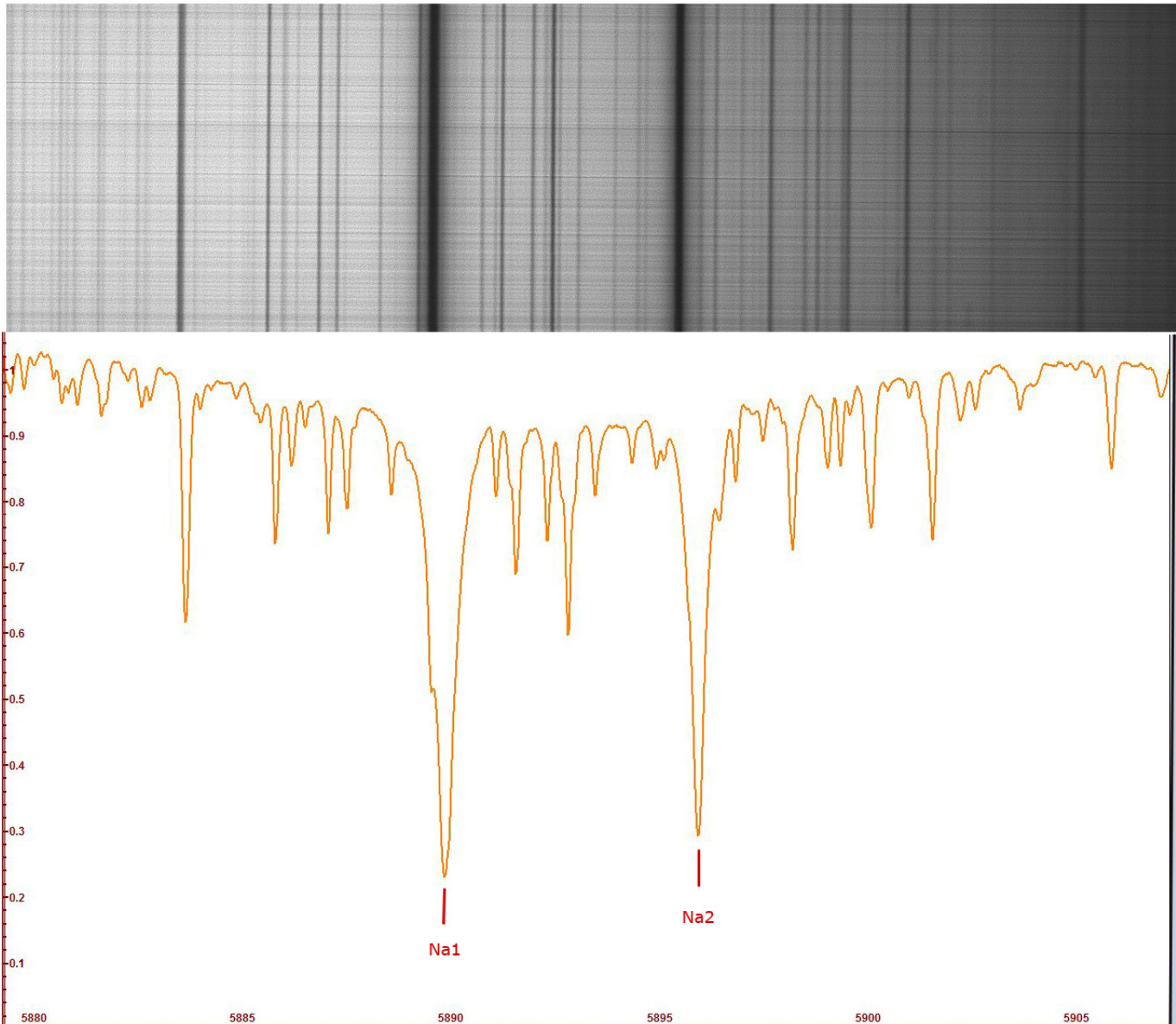


The lines Na 1 and 2 (sodium doublet).

These lines, respectively at  $5889.97$  and  $5895.94 \text{ \AA}$ , at low excitation, belong to the lower part of the chromosphere and are evident when the low chromosphere is heated, often showing the nucleus of the impulsive phase of the flares, or the faculae.

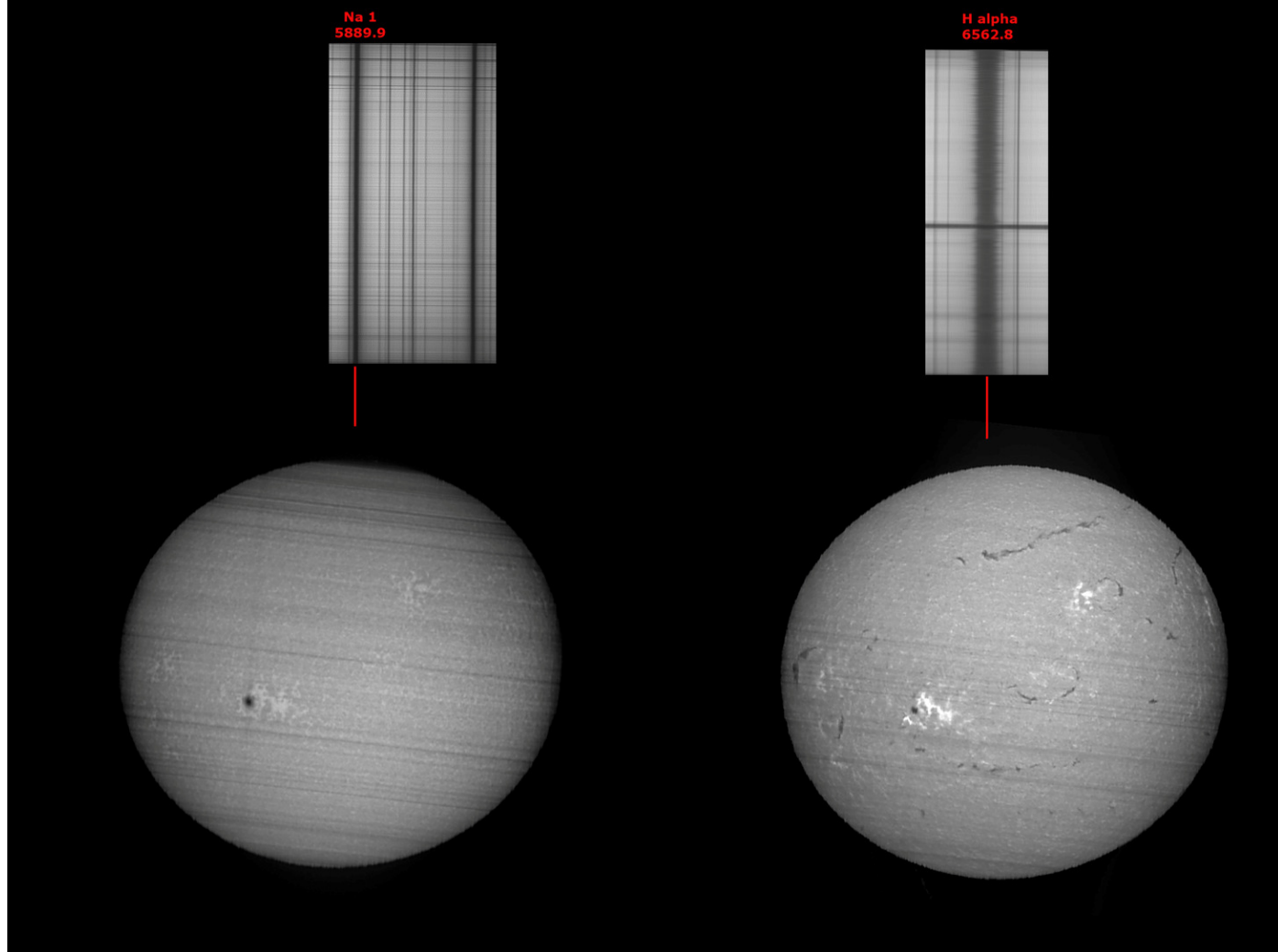
Incidentally, the lines in question were those used by the GOLF instrument (Global Oscillations at Low Frequencies) aboard the SOHO probe a few years ago, in order to measure the velocity of the photosphere along the line of sight for the whole disk in order to observing small oscillations, as well as, being these lines magnetically active, the variations of the global average of the magnetic field along the line of sight with the precision of 1 mGauss. GOLF, however, measured the sum of the contributions of the two lines, being unable to distinguish the two components .

In the image that follows the two sodium lines taken with the Solarscan instrument (many lines inside the doublet and in its immediate vicinity do not belong to the Sun, but to the Earth's atmosphere).



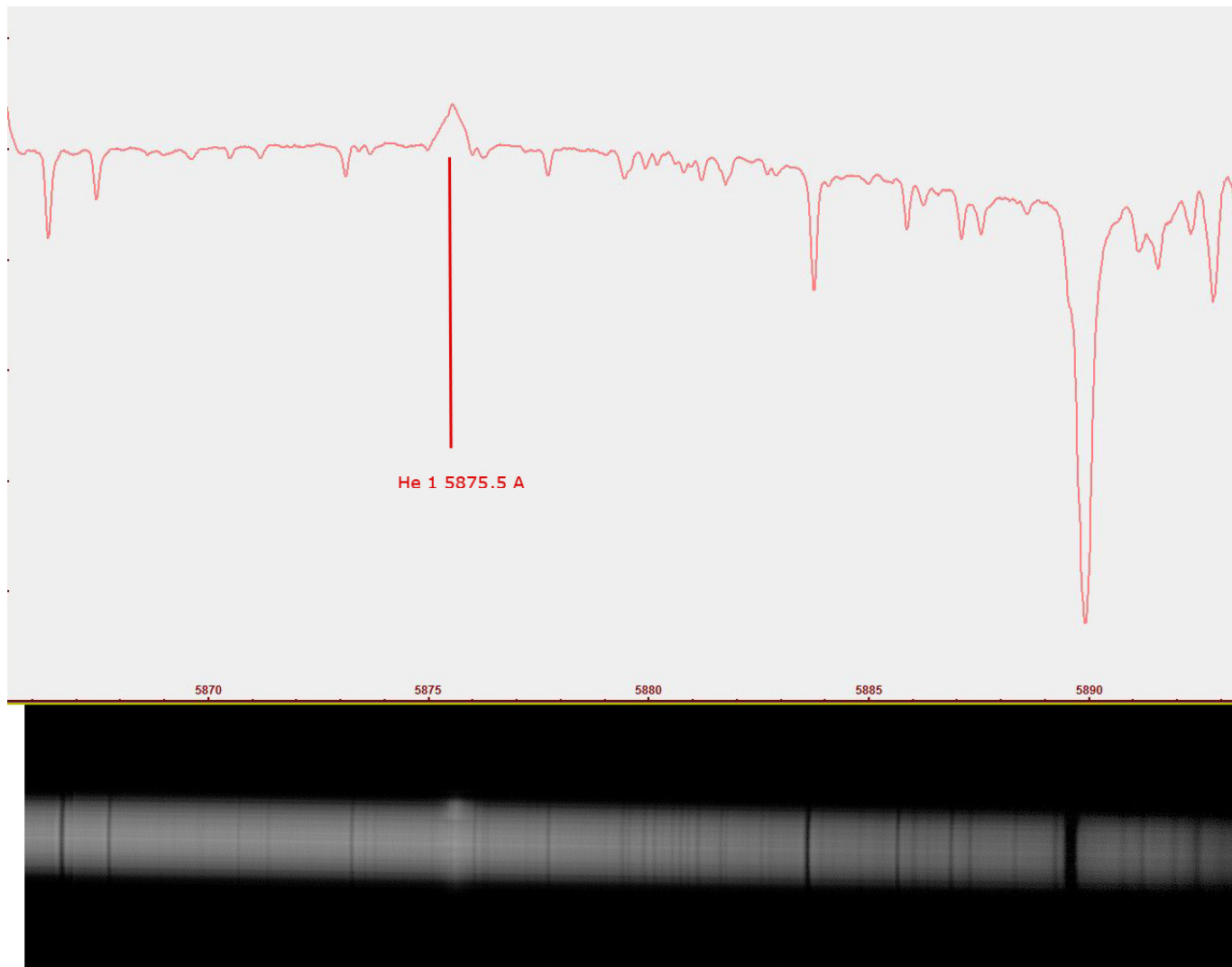
In the following image, a comparison between the sodium-Na and hydrogen Alpha spectroheliograms, then between low and high chromosphere and between two very different elements, an alkaline metal and a gas that is the first chemical element of the periodic table and the most widespread element in the observable Universe.

Appearance of sundisk in Na 1 line at 5889.9 Å and H alpha at 6562.8 Å: a tomography of cromosphere  
Solarscan in spectrohelioscope mode- May 22 2016 - Fulvio Mete Rome Italy



### The line of the Helium

The line of the Helium at 5875 Å in absorption is rather difficult to identify for its elusiveness: the line in emission is much easier, which can be observed by placing the slit of the spectrograph on the edge of the solar disk.

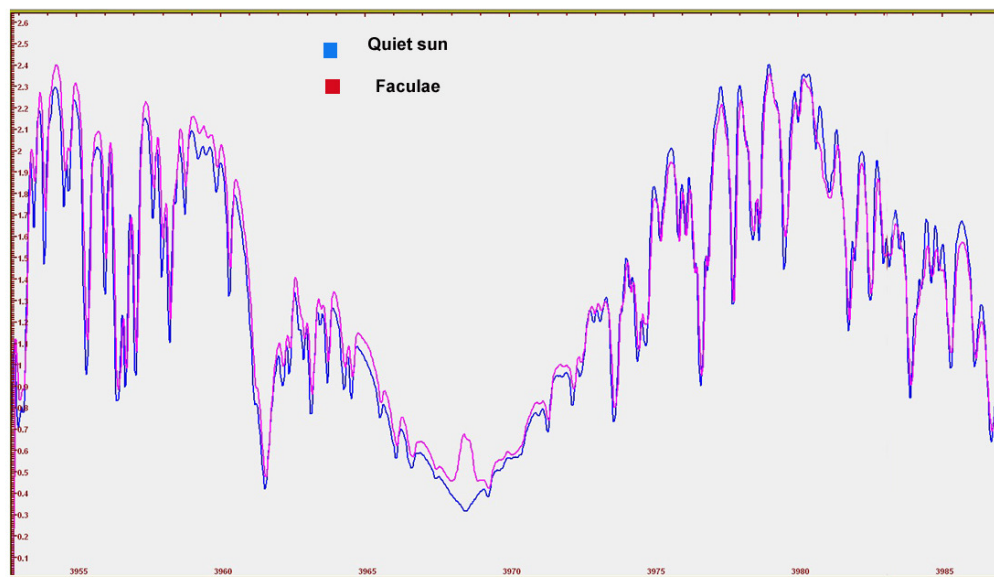
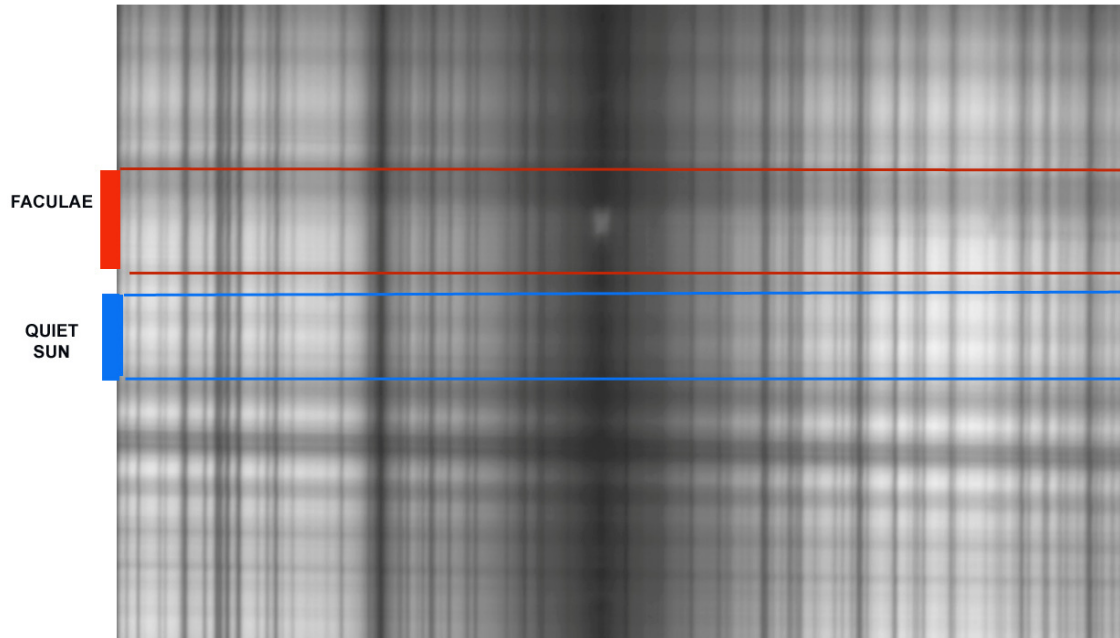


The lines CaII K and H

They are the famous lines of Ionized Calcium at 3933.68 Å, and 3968.49 Å whose characteristic is the particular sensitivity to the magnetic fields of the active regions and sunspots, in which they pass from absorption to emission, with the bright faculae that we observe on the disk. The example below shows the passage of the CaII H line from absorption to emission near an active region.



Appearance of Chromosphere in Ca2H light in quiet sun and faculae: note the spectral profile passing from absorption (blue) to emission (red).



## **Spectroheliography and Spectroheliography**

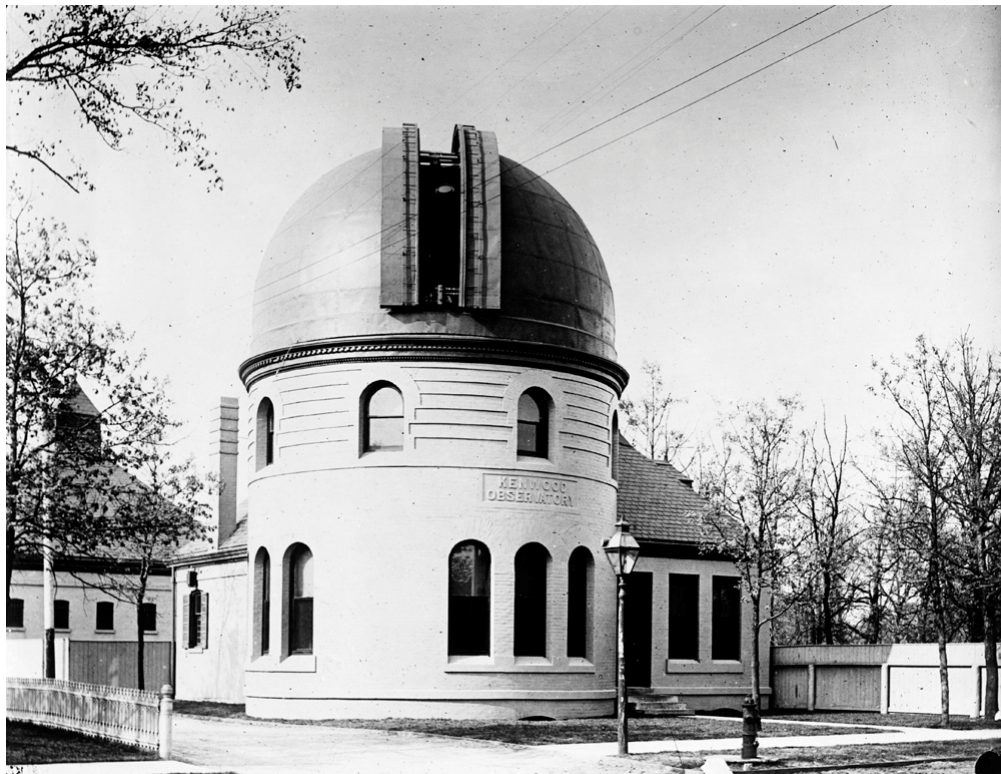
Spectroheliography can be defined as the capacity to make observations of the solar disk and its characteristics in the various wavelengths of the elements of its spectrum: in the case of photographic shooting it takes the name of spectroheliography.

The spectroheliograph (in photography spectroheliograph) was developed by George Ellery Hale in 1924, for the observation and shooting of the sun in various wavelengths. Hale was born in Chicago, USA, in 1868, he began his educational path when 17-year-old at MIT, and then at the Harvard College Observatory. In 1890 he became director of the Kenwood Astrophysical Observatory. He worked for the most important observatories of the time, such as those of Yerkes and Mount Wilson.



The spectroheliograph was, in fact, invented independently by Hale and the French Henri Alexandre Deslandres, but to Hale goes the merit of having perfected the invention creating a powerful means of investigation of solar physics. The development of the collodion plates, together with the invention and the diffusion of the first generation diffraction gratings of the physicist Henry Rowland, opened the way to the recording of the spectral images.

Hale's work on spectroheliographs dates back to 1889, when he developed his first ideas on the subject, which will then be developed many years later in the article "The spectrohelioscope and its work" published in the *Astrophysical Journal* of December 1929. The first prototype of the instrument was completed in 1892 and installed on the 12 "Brashear" refractor in its Kenwood Observatory. The spectroscope used two 1080 mm lenses each as a collimator and an imaging lens, while the grating was a 100 mm reflection and 568 g / mm: the entry and exit slits were 82 mm in length, in order to receive a 50 mm diameter solar disk image.



The Kenwood Observatory of G. Hale in Chicago (University of Chicago Photographic Archive, Special Collections Research Center, University of Chicago Library).

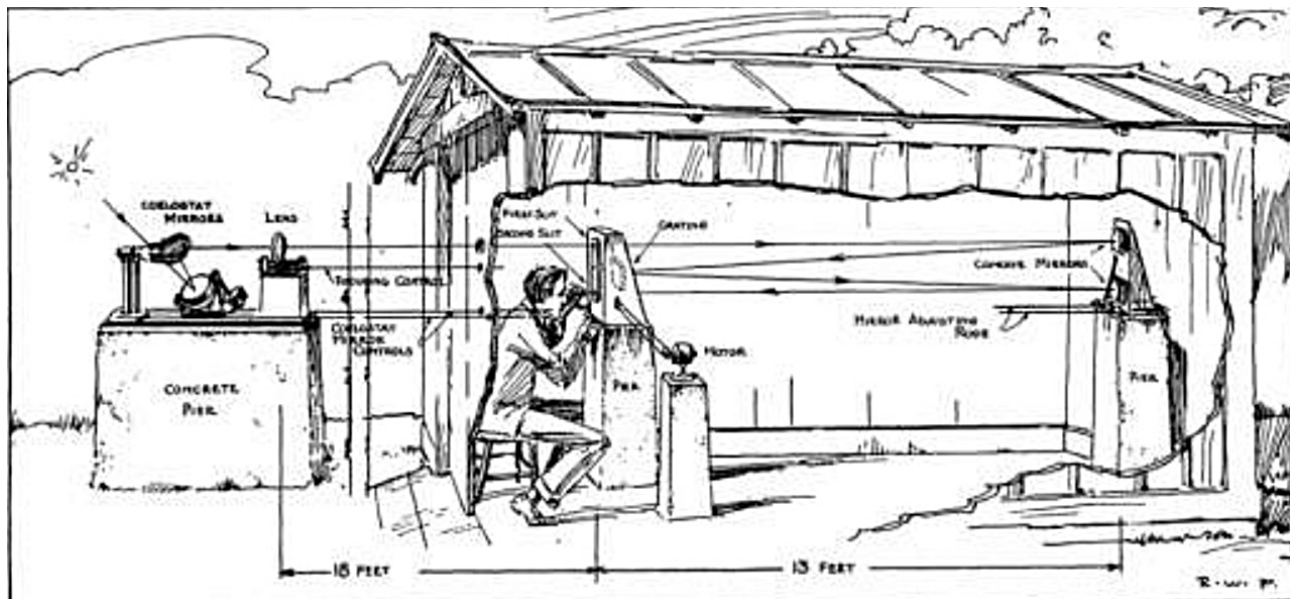
The Kenwood was Hale's Personal Observatory, built in 1890 by his father William Hale, where the 12 "Brashear" refractor was installed with the spectroheliograph



The spectroheliograph at the focus of Brashear refractor

Not many people know this, but Hale was also in Italy, in Florence, where he discussed solar astrophysics with Abetti and Tacchini, and in Catania, where he went to mount Etna in order to image the solar corona without eclipse with its spectroheliograph. The instrument was applied to the Bellini observatory telescope on the summit of Etna and the chosen wavelength was that of CaII K in the near UV, to reduce the glare of the atmosphere, but the experiment was not successful. He was one of the originators of the 60-foot solar tower of Mount Wilson's observatory in 1908, which was then a model for similar ones worldwide and contributed to the design of the gigantic Monte Palomar telescope that took its name from him. He was interested in the magnetic activity of the Sun, in particular that of sunspots and in the Zeeman effect. He discovered the inversion of the polarity of the magnetic fields of the sunspots at the change of the cycle. Hale died in 1938 after a life of intense scientific activity.

Around 1920, after the development of the spectroeliograph, Hale examined the possibility of using his spectroeliograph for visual observations, using it as a spectrohelioscope, and perfected this idea in 1924.



Hale spectroscopy (SHS) layout: the only difference with a spectroheliograph (SHG) is the replacement of the eyepiece in place of the camera, after the exit slit.

Terrestrial professional spectroeliographs still in service in Europe are: the Meudon Spectroliograph in Paris, that of Coimbra in Portugal, that of the Royal Observatory of Belgium. Their activity of spectroheliographic monitoring on the Sun is reported on the BASS 2000 website: [http: / /bass2000.obspm.fr/home.php](http://bass2000.obspm.fr/home.php)

Here are some photos of the Meudon Spectroheliograph in Paris (source: BASS 2000).

The spectroheliograph, with a lens of 240mm and 4000 mm of focal length, gives a solar image of 86 mm on the focal plane. Its purpose is to obtain images of the entire Sun disk in the various wavelengths of interest.



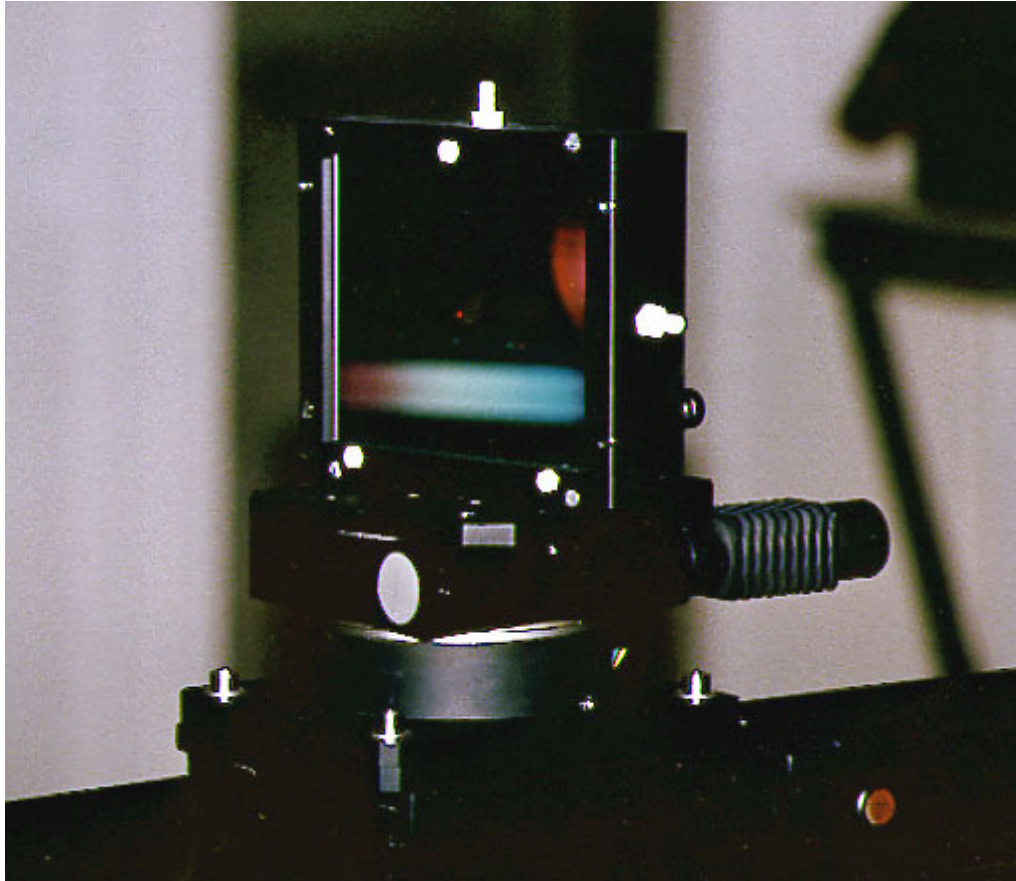


The celostate that powers the 240 mm objective and the objective itself





The spectrograph in the control room. This provides a dispersion of  $3.33 \text{ \AA/mm}$  in the 3rd order in H $\alpha$  light, equivalent to about  $0.03 \text{ \AA/pixel}$  with a camera sensor with pixels of  $10 \text{ }\mu\text{m}$  and  $0.016$  with a sensor with  $5 \text{ }\mu\text{m}$  pixels.



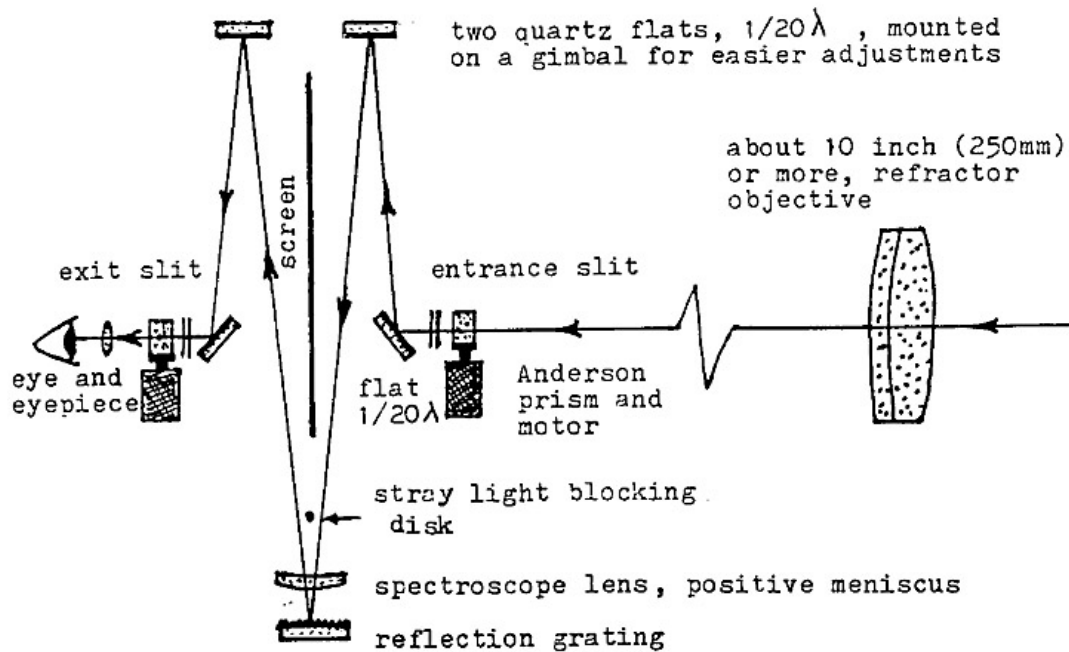
The diffraction grating, large in size but of only 300 grooves per mm. It's is used in the 3<sup>rd</sup> order for further increasing dispersion and resolution.

## **The amateur Spectroheliography**

### Classic" Amateur spectroheliographs

But what is a classic spectroheliograph (SHG)? In practice, it is a spectroscope, powered by a telescope that sends an image of the solar disk of adequate size on the input slit of the same, the diffracted sunlight is then selected in the line of interest by a second slit, said output slit. Immediately before and after the two slits, two image synthesizers are placed, (generally rotating prisms said Anderson prisms) controlled by a motorized system, the first feeds the input slit, and the second forms the output image. rotation of the prisms at a given speed allows, by a slow motion effect, to form an image of the solar disk in the wavelength corresponding to the examined line which is observed at the eyepiece or imaged with a CCD camera.

However, these are instruments that, although excellent, are very complex to self-build, especially for their electronic and mechanical parts, first of all synthesizers, of which there are various types, and for their size, since it is necessary to use at high focal lengths for obtaining an image on the input slit of the rather large spectroscop and then a final solar spectroheliographic image of adequate resolution. In the figure an example of a spectrohelioscope - spectroheliograph layout with a spectroscop in Czerny-Turner configuration and that uses two Anderson prisms as synthesizers.



In the following figure are shown the Anderson's prisms whose synchronized rotation, before the entry slit and after the exit slit, allows to obtain the sun image in the line under examination.



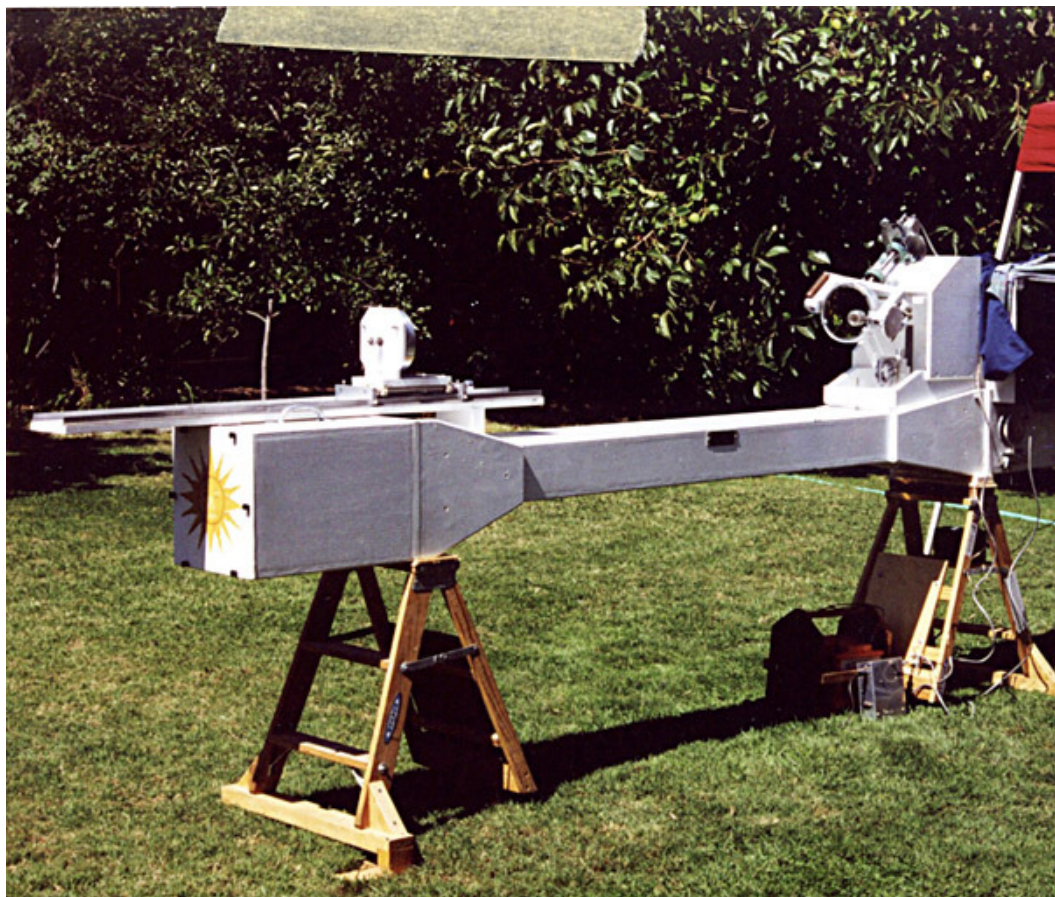
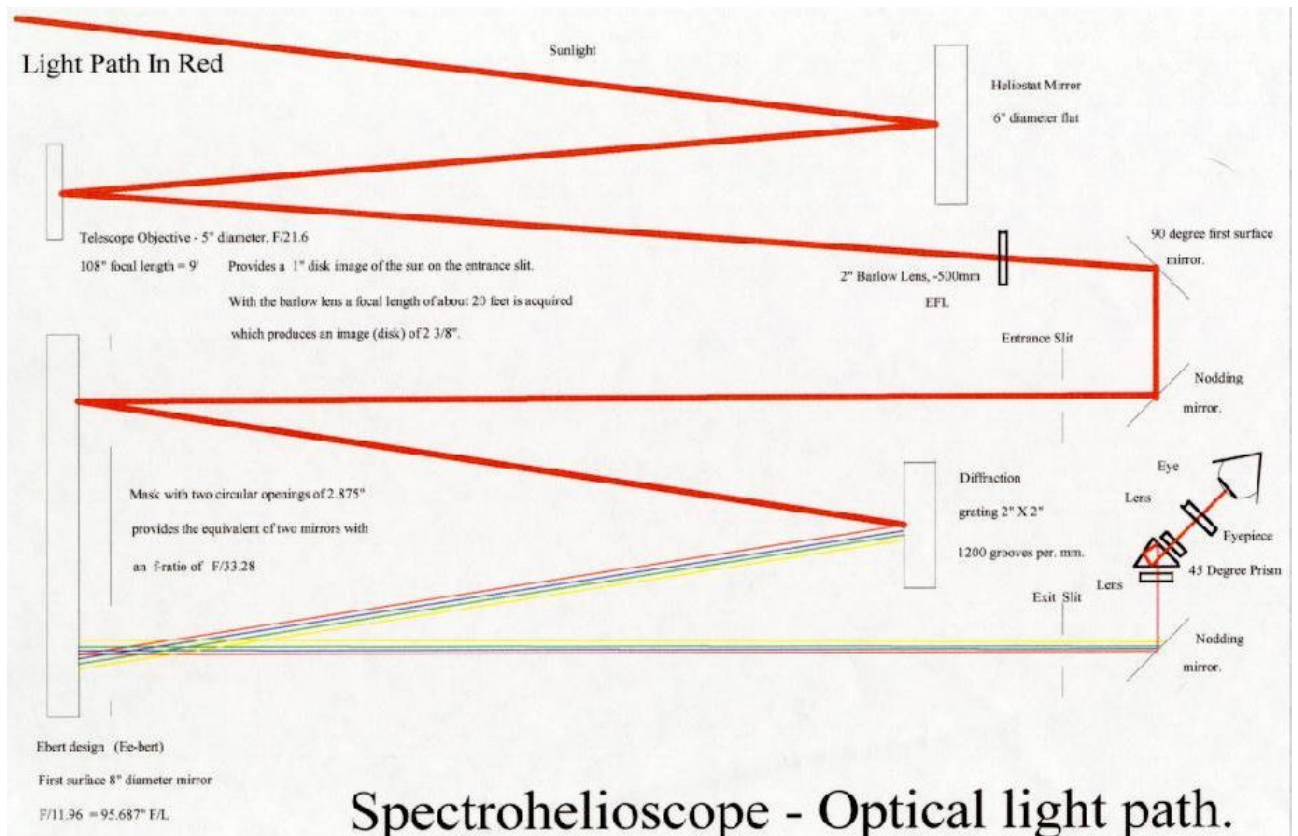


Below is the design (the last in a series of projects) of an amateur spectroheliometer of the well-known American self-builder Leonard Higgins built with the guidance and help of the equally well-known spectroheliometer expert Fredrick Veio (Source : Spectroheliometer .org).

Here too there is a long focal length refractor that powers an Ebert spectroheliometer: the main difference compared to the previous project is the use of oscillating mirrors (nodding mirrors) before the entrance and exit slits instead of Anderson's prisms.

Note the large size of the instrument, which is fed by a coelostat. (Source: Spectroheliometer.org)





As observed in the example, the two essential components of the spectrohelioscope / spectroheliograph are a telescope and a spectroscope. The telescope can be of various optical configurations, but for the solar observation are required configurations with lenses or all mirrors. The catadioptric, as we shall see, could not operate unless you have a solar filter, which would in every case limit the light grasp of the instrument (it may seem strange given the intensity of the sunlight, but in the spectroheliographic field, having to observe thin lines in absorption in high resolution and with slits closed at most, the light grasp is important because the photons collected are few even with noticeable apertures). All-lens or mixed configurations, as in the example above, are the most widespread among amateurs.

## **The revolution of Digital Spectroheliography**

The development of informatics in recent years has allowed, in the amateur spectroheliographs, to replace specific IT procedures to the task performed by the synthesizers: the digital spectroheliography was born and this field of application is now within reach of a much wider number of amateurs for the greater (relative) ease of construction. The digitalization of the spectral images has replaced the use of synthesizers - the realization and development of which is particularly complex - with simple computer programs.

At the beginning the final yield of the images of the digital spectroheliographs was qualitatively inferior to that of the traditional ones, but, with the progress of the development of the CCD sensors now the visible details are practically the same, while the gain in size and weight and therefore capacity of use and portability is simply enormous. In any case, compare the classic amateur instrument illustrated above and my VHIRSS, of 8.6 kg of weight and 110 cm of length, transportable anywhere with the greatest ease. Naturally, classical spectroheliographs have a greater resolution power given the diameter and long focal length of the optics, but my experience, as we will see, with short focal length optics, has shown that, at least in the full-disk images, the gap is very small or non-existent.

It is good to premise and highlight that specific instruments of this kind do not exist in the consumer market, and therefore the only way for the amateur to get one is self-construction, unless you want to use high-resolution spectroscopes for stellar use, such as Shelyak LHires III with a 2400l / mm grating, which, however, uses lenses with reduced focal length and therefore not having been designed specifically for this use, mounts 4 reflective slits.

Obviously those who already own such an instrument can use it, even if the reflective slits that could create diffused light, should in my opinion be replaced with a single fixed or adjustable, non-reflective one.

Ultimately, for instruments dedicated to this activity, the road to self-construction is currently the only one that can be used.

## Components of a digital spectroheliograph

The fundamental components of a digital spectroheliograph are:

- 1 - The telescope that projects the solar image onto the slit;
- 2 - The slit;
- 3 - The spectroscope, in the various possible configurations;
- 4 - A camera: a CCD or CMOS camera with a sensor of adequate size and resolution.

We will now see in detail the characteristics of these components.

### The telescope

The telescope performs the task of sending the solar image to the slit, or performs the same work of the solar telescope that sends the solar image on a narrow band H $\alpha$  or CaIIK interference filter, like those that have had and continue to have so much diffusion among the amateur astronomers. So, we can imagine that instead of a filter there is the slit and the spectroscope, with the big difference that while the filter selects a single line, H $\alpha$ , CaIIK or other, the spectroscope can theoretically select a very large number of lines, and therefore it is equivalent to an equally considerable quantity of filters, even though it is a single instrument.

The first choice to make is on the optical configuration, and precisely between mirror instruments, lens instruments and composite instruments (catadioptric).

The catadioptrics should be excluded for the obvious reason that, given the short focal length (f2-f3) of the primary mirror, the solar heat would be detrimental to the support of the secondary and its hood, as well as the lens hood of the primary itself, releasing furthermore, inside the closed tube a quantity of heat to make the observations impossible or inefficient due to turbulence. Naturally, this problem could be bypassed using a rejection filter of adequate size and bandwidth, ie an IR-UV cut in front of

The corrector plate, but both solutions would be very expensive (about 1500 € for 20 cm apertures) and unsatisfactory from the point of versatility as they would force to use only a few lines in the case of ERF, and excluding some in the case of IR-UV cut filters that normally have a spectral range of 4000-7000 Å. A Canadian astronomer has achieved good results with a 10 cm MTO Rubinar catadioptric, with an IR cut UV filter of this size and a wide band pass, which in any case allowed the CaIIK and H band to pass through (the normal UV-cut filters as those by Baader Planetarium normally exclude it). This solution could be rewarding only in the case you already own such a filter. Otherwise, ordering it ad hoc with specific characteristics would cost a significant amount of money, more than 2-300 € (230-240 \$) almost as much as the rest of the SHG, as we will see. For now, Hoya has a 77 mm UV-IR cut filter in the catalog costing about 150 €, on which I can not give any opinion never having tried it, but that would have a bandpass of 4000-7200 Å that would in fact exclude the lines of ionized calcium.

Therefore the two configurations of the only mirror instruments and refractors remain the only way to go.

### Mirror telescopes

#### Newton

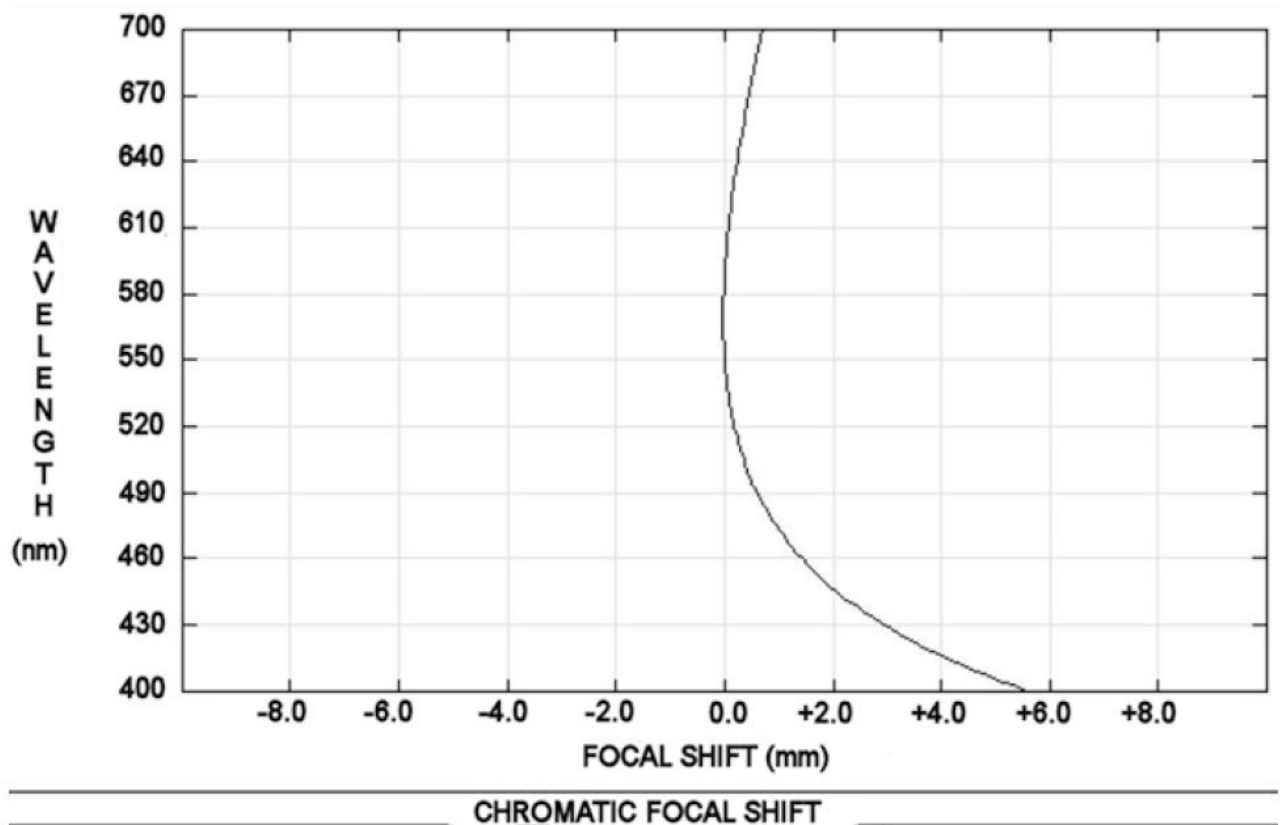
The newton would in principle be the ideal instrument from the optical point of view to feed a digital SHG, if only for its total acromaticity. However, the "bent" configuration of the optical beam, as well as the proximity of the focus point to the tube tend to complicate notably the design of the instrument, making necessary, among other things, a focus extractor element (a telecentric) to bring the focus itself on the slit. The French astronomer Phil Rousselle, of which I will speak later, has recently realized a spectroheliograph which used a Newton 114/900 optical tube as a telescope: but the assembly is complicated and not within everyone's reach. However, this interesting configuration will be discussed later.

### Telescopes with lenses: the refractors

#### a- Acromatic Refractors

The achromatic refractors are at first sight the ideal telescopes to carry out the task of a SHG telescope: low cost; possibility of using a wide range of focal lengths and diameters; furthermore, if well made, the chromatism would in any case be bypassed by the fact that they would work in monochromatic light. However, they present a major drawback for our purposes: the substantial variations of the point of fire at varying

wavelengths, which means that if, for example, I focused the SHG on the H $\alpha$  line and I want to go on the CaII K line I will have to refocus not only the telescope, but also the spectroscope, since the respective focuses intersect. Clear, it's not a tragedy, but it is nevertheless a nuisance.



In the image above, the focal shift of an acro 90/850 lens is indicated (source: Edmund Optics). As can be seen, the shift that is low up to 5200Å, from that wavelength becomes more and more consistent, until exceeding 6 mm below 4000 Å.

#### b- Apochromatic refractors

These are the telescopes that currently go by the greatest and which present a truly remarkable level of supply, with diversified and however acceptable prices. Focal length ranges from 300 to 1200 mm in a range of optics building typology that is limited to four basic types: air spaced triplets, oil spaced triplets, fluorite doublets, ED doublets.



Among these, the refractors with oil spaced triplets are in my opinion to be avoided for continuous use on the sun, being uncertain, but anyway not to be excluded, an effect of alteration in the layer of oil between the lenses due to UV radiation, and this apart from the very high cost, due to the fact that they were, and are generally produced by prestigious brands such as Zeiss, Astrophysics, TEC, Takahashi.

For the triplets spaced in the air and the fluorite doublets the most important thing is the price, given that these also have high purchase costs.

Ultimately, in my opinion the choice of doublets with ED low dispersion lenses type FPL 53 is the best and the one with the highest value for money.

Telescope constraints are the following:

- It must give a solar image of a diameter possibly less than that of the length of the slit, as we will see later, which is on average about 1/100 of the focal length.

- It must have sufficient resolving power to show the small solar structures in light H $\alpha$  and Ca II K. An instrumental resolving power between 1 and 2 arcsec is sufficient, even taking into account that it is limited by the diurnal seeing that hardly allows to overcome the 2 arcsec. A good instrumental diameter is around 100 mm, which provides a theoretical resolving power of 1.2 arcsec. Considering that the Sun subtends on average 1920 arcsecs, and that a focal length of 1000 mm would give a 9.3 mm solar image on the slit, on this one would have an image scale of 206 arcsec / mm, or 0.2" for  $\mu$ m.

An objective of 100 mm of aperture between f 8 and 10 would therefore be an interesting option, also considering the size and the bulk that would bring to the SHG.

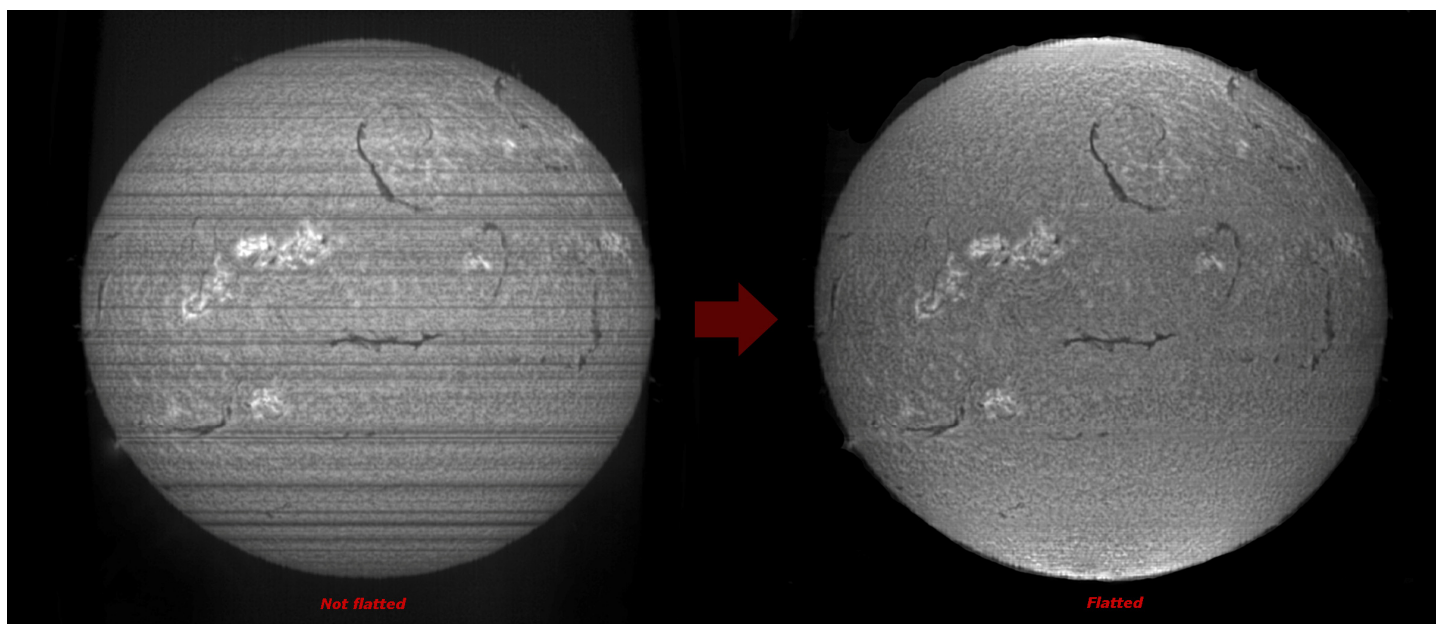
- It must not be an instrument with a group of rear lenses, potentially capable of deteriorating or breaking due to thermal stress.

### The slit

It might surprise that I consider apart a component like the slit that is normally thought to be an integral part of the spectroscope. The answer is simple; this component which, in its reflecting versions, is the heart of a stellar spectroscope, even more so it constitutes the fundamental element of a spectroeliograph, given its direct influence on the quality of the images.

As you know, closing the slit has a direct effect on the spectral resolution and therefore on the image quality of a SHG, but the possibility of closing the slit to the maximum possible (10-15 micron, for example) is a direct function of the quality of mechanical processing of the structure and of the

jaws of the same. To make understand what I mean, it is worth the comparison contained in the following figure, between a sundisk raw spectral image obtained with one of my SHG with a slit with very closed edges, but not machined at optical tolerances ( $1/4 \lambda$ ), and the same image after making a synthetic flat.



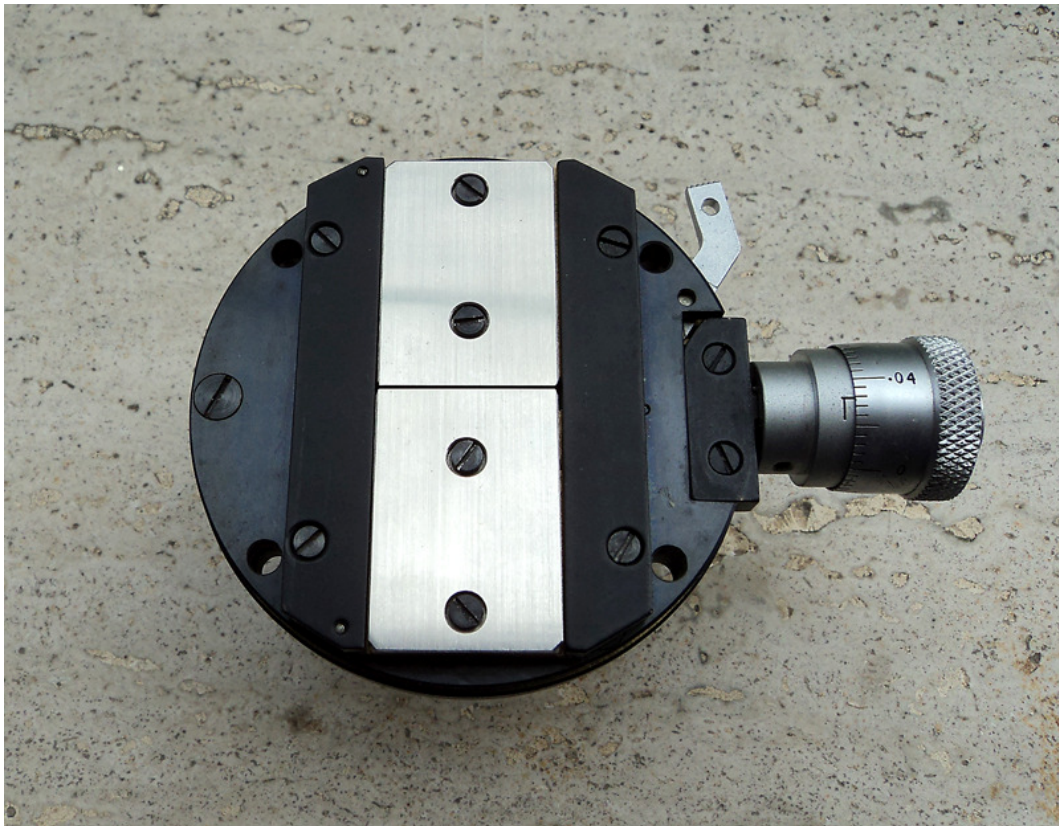
As you can see, the horizontal lines (transversalism) caused by small imperfections of the edges of the jaws are reflected in a merciless way on the quality of the final image. But then, just work the edges better, I already hear the reader answer the question, the right answer, but with a particular: the machining of optical tolerance plates, involving sophisticated and complex processes, would cost more than the same spectroscope, so it is necessary to use different systems that can be summarized as follows:

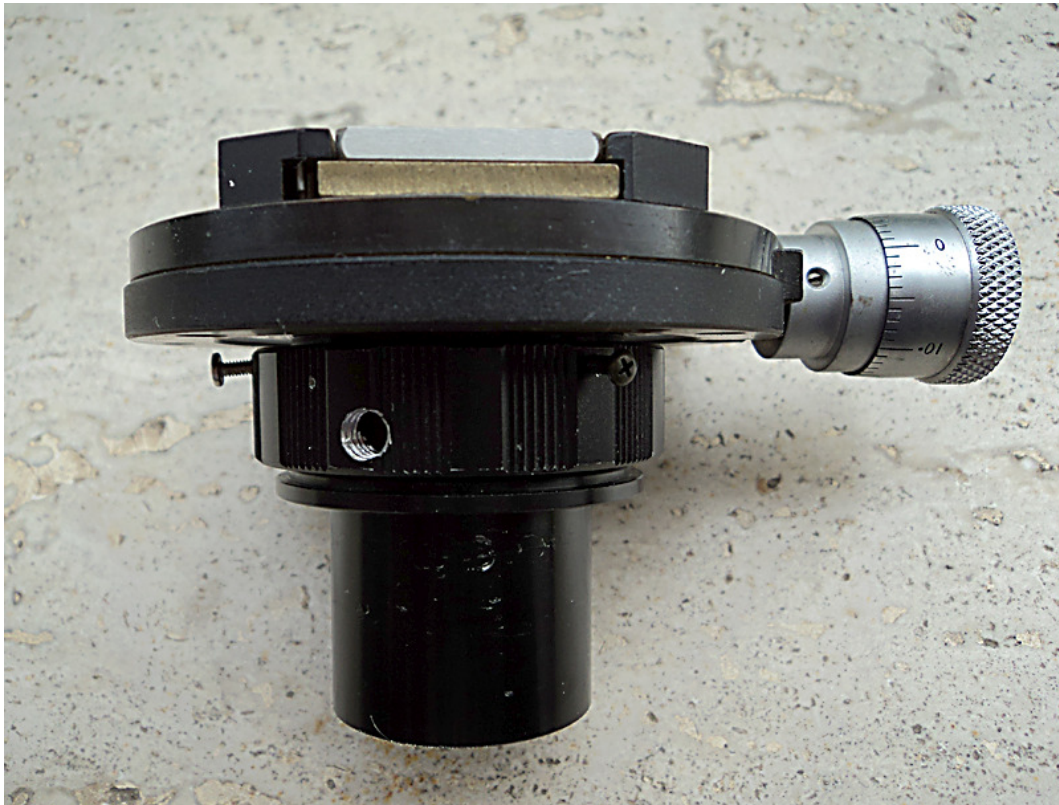
1- Proceed with the purchase of professional surplus slits on some online stores (prices ranging between € 50 and € 500 depending on the quality level).

An American retailer, BMI surplus, has a wide range of optical and mechanical components for spectroscopy, including slits: prices are varied and you need to know how to choose:

<https://www.bmisurplus.com/products/category/filters-iris-diaphragms-slits-apertures>

In the images that follow a professional slit adjustable with a micrometer purchased by myself for 100 € from the before mentioned retailer: the slit was then improved by disassembling and finishing the edges of the jaws and adding a 31.8 mm male support. The micrometric mechanical system of closure acts in a uniform way, so as not to move the parallelism of the blades to very tight closures.





On the new items market, so to speak, such slit would cost prices oscillating between 500 and 1000 € (\$ 570-1150), as a small apo refractor, and this should make us reflect on the importance of this component, of a level equal to that of the quality of the telescope optics with which we make our evening observations.

Another well-known surplus dealer, Surplushed, offers at very low prices adjustable slits made in India of 10 mm in length (about 8 mm free) which, although not the top from the mechanical point of view, are acceptable and susceptible of improvements.

<https://www.surplushed.com/pages/item/m1570D.html>





2- to improve the mechanical quality of surplus slits

To improve the quality of SurpluShed's low-cost slits I normally do the following:

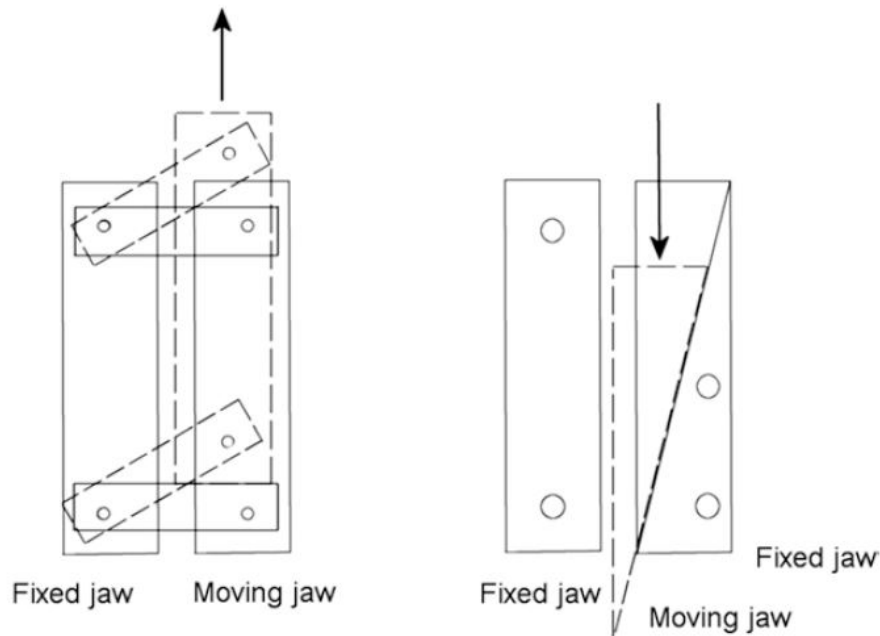
- a) I remove the brass plates;
- b) examine them under the microscope at about 500 x to observe their level of precision (or inaccuracy);
- c) I put the blades on a hard plastic surface (ideal polycarbonate) interposing between this and the blade a thin layer of abrasive paste for coachbuilder, much more readily available than cerium oxide, and rub the edge of the blade on the support with longitudinal movements with uniform pressure for a few minutes, then I repeat the observation under the microscope to verify the level of improvement.

This procedure seems to work and manages to improve the edges of the slit jaws sufficiently.

3- to proceed to the design and self-construction of the jaws.

This is a chance which I think it should be better avoided, as the complexity of the job does not guarantee better results than those already examined. However, if you want to make this experience, one of the simplest projects for closing the blades is shown in the following image.





Another question is whether to use fixed or adjustable slits; it can be summarized as follows:

The adjustable slit would be preferable as it has the possibility of varying its opening as the light intensity of the incoming optical beam varies, due to possible diaphragms or insertion of filters in front of the telescope, to the conditions of the sky, etc; however it presupposes a sophisticated mechanical system which in theory should guarantee the simultaneous closure of both blades maintaining their parallelism in the closing phase. Such mechanism is obviously expensive and for non-professional instruments maybe even not necessary. The adjustable slits of surplus, especially if modified in the above mentioned sense, can carry out their task adequately, also because they are easily more than 10 mm long, enough to accommodate the images of the whole solar disk even for very small telescope focal lengths; moreover, the blades, in brass or in steel, have the sufficient thickness to guarantee their resistance to thermal stress that, in the case of a 100 mm telescope without any rejection filter, can reach 7.85 W.

The fixed slits, often obtained by laser and not by mechanical processing, are those most easily found, even if at prices not exactly popular, within major retailers of optical material such as Edmund Optics and Thorlabs. They have however the drawback of having a standard length of 3 mm and a very thin support, which, if not adequately protected, could tend to the deformation under thermal stress. On the contrary, their edges, obtained by laser, have a high level of precision even with very narrow closures: these are available up to a minimum of 5 microns of aperture.

I mentioned the importance of the length of the slit, which is necessarily related to the focal length of the telescope that projects the solar image on it and the diameter of the image of the solar disk. A 3 mm slit in front of an image of the Sun of 6 mm in diameter would give us, the possibility of covering only half of the solar disk in the final spectroheliographic image.

The Sun covers on average about 32 arc minutes (1920 arcsec) to 1 AU, but, since its distance from the earth varies according to its orbit during the year, its apparent diameter will be 31.5' in January and 32.5' in July. The diameter of the disc projected on the slit will therefore be equal to:

$$D = FL \times 0.00948 \text{ in January}$$

$$D = FL \times 0.00917 \text{ in July}$$

Where D is the diameter of the disk, FL is the focal length of the telescope, with all the quantities expressed in mm.

For a focal length of 1000 mm D it will therefore be equal to 9.48 mm in January and 9.17 in July, an optimal diameter for a 10 mm-long slit. For a focal length of 500 mm it would be on average 4.7 mm., for a 5 mm slit.

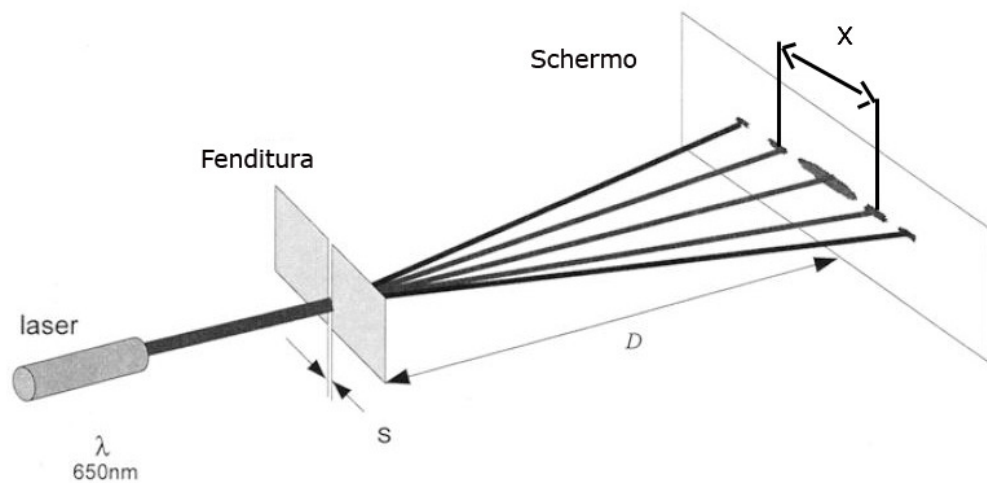
As for the opening of the slit, taking into account the above, a focal length of 1000 mm would provide an image scale of (1920 / 9.325), 205 arcsec x mm, or 0.2 arcsec x  $\mu\text{m}$ , which means that an opening of the 10 micron slit would provide a spatial resolution of 2", sufficient to record details on the Sun. However, we should also take into account the pixel dimensions of the camera: for pixels of about 10  $\mu\text{m}$  everything would be ok, but in case, let's say, pixels from 4.65 or 5  $\mu\text{m}$  sampling would be 2"x 2 pixels, roughly half that of optimal sampling.

A focal length of 500 mm would provide an image scale (1920 / 4.665) of 412 arcsec / mm, 0.412 arcsec / mm, or 0.4 arcsec x  $\mu\text{m}$  or a resolution of 4"x 10 micron. For the Nyquist principle it is necessary to sample 4" for 2 pixels, and, in the hypothesis of pixels of 4.65 or 5 microns, this principle would be satisfied.

So an aperture of 10  $\mu\text{m}$  would match well enough with a camera with pixels at 4.4-4.65  $\mu\text{m}$  like DMK 41 and 51, but also with cameras like ZWO ASI 174. Of course there is a downside, and closures of 10  $\mu\text{m}$  with an adjustable non-professional slit are possible, but often imperfect to the point to make it prefer 15 microns.

## The measurement of the aperture of the slit

In commercial slits not provided with micrometers or other measuring instruments, the problem of measuring the amplitude of a given aperture of the slit could be real. This can be obtained, with the classic experiment on diffraction, using a laser pointer and directing the beam through the slit on a screen at the distance  $D$ .



The formula for defining the opening  $S$  in microns is:

$$S = \lambda \times 3 \times D / 10000 \times X$$

Where is it:

- $\lambda$  is the wavelength of the laser in  $\text{\AA}$  (6500 the red ones and 5320 the green ones);
- $D$  is the distance in mm of the screen from the slit
- $X$  is the distance in mm between the centers of the two first-order images of the diffraction figure.

Ex. With  $D = 400 \text{ mm}$ ;  $\lambda = 6500$ ;  $X = 40 \text{ mm}$ , we have:

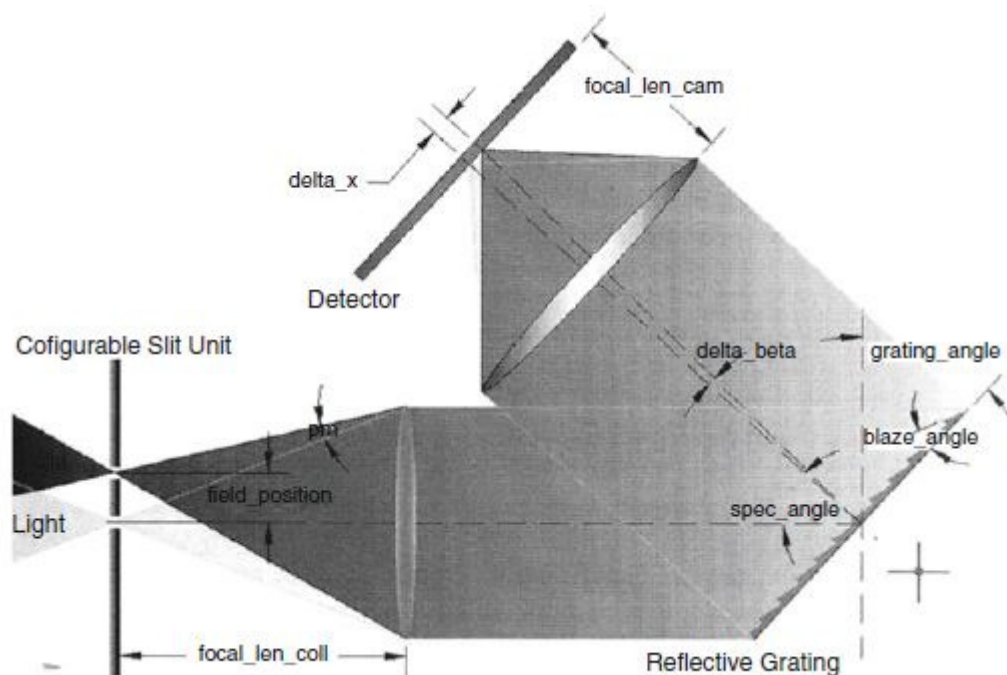
$$S = 6500 \times 3 \times 400 / 10000 \times 40 = 19.5 \text{ }\mu\text{m}$$

## Spectroscopes configurations for digital spectroheliography

I will refer hereinafter to the main configurations of spectroscopes for the spectroheliography most common among manufacturers.

### 1- The classic spectroscope

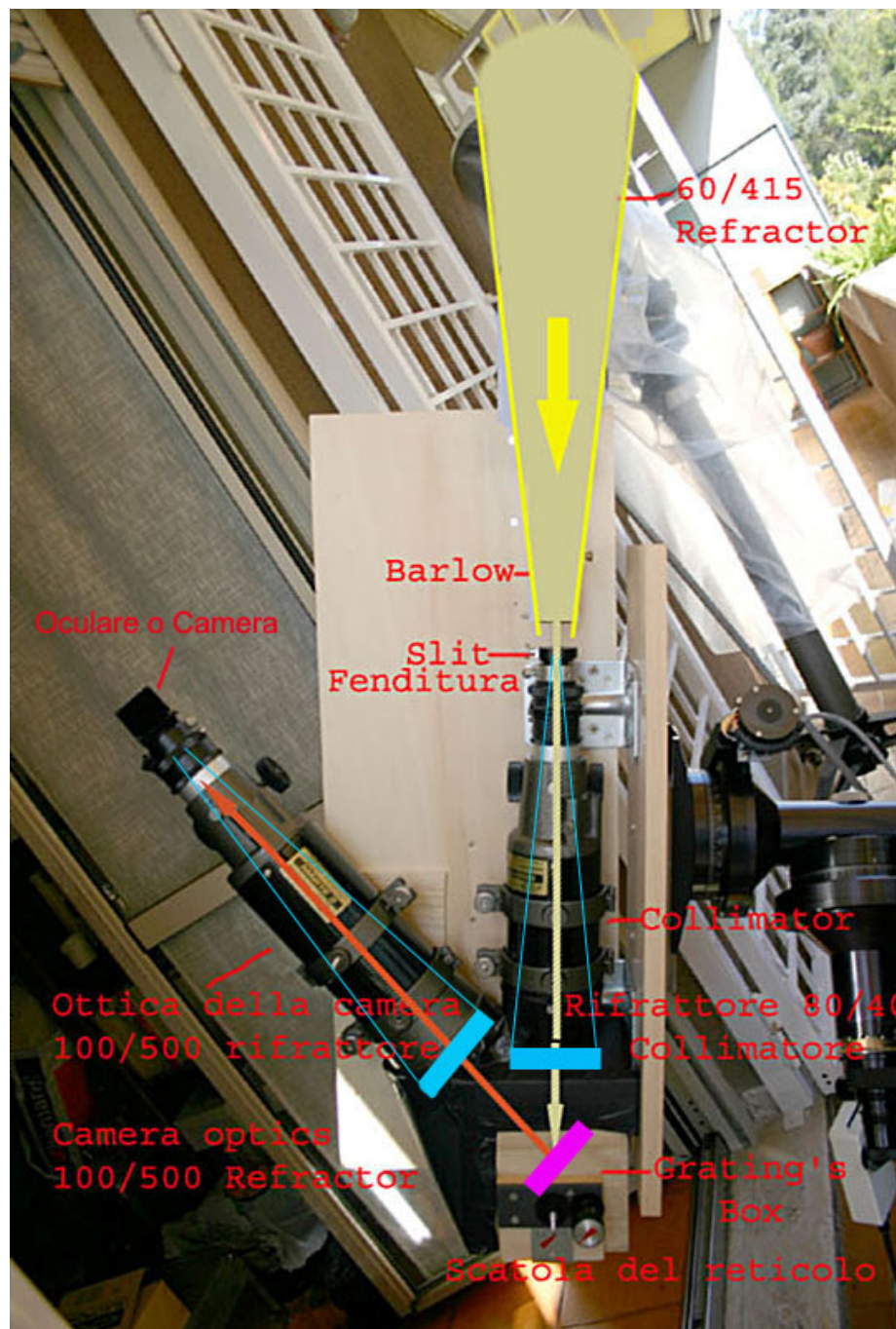
This configuration has been and is perhaps the most widespread in many self-construction projects. It is based on the use of two optics, generally of refraction type to contain the dimensions, but also of reflection: one that acts as a collimator, whose focus falls on the slit, and at the end of which, after the objective, is the grating, and a second one, placed at a certain angle with the first (about  $40^\circ$ ), which collects the diffracted optical beam coming out of the grating, the spectrum, to enlarge it and send it to the camera. The focal ratio of the collimator should be equal or very similar to that of the telescope that sends the solar image onto the slit.



An example of the layout of a simple classical refraction spectroscopy (source "Spectroscopic Instrumentation" by Eversberg and Vollman).

The mirror configurations, as used in the spectroheliography, give rise, as we will see, to heavy and cumbersome instruments, as well as to difficulties in their assembly and maintenance. The mirrors, in fact, to work at best require collimable cells and careful collimation with the others optical components, having, on the other hand, the merit of total acromaticity. As far as I am concerned, I have always preferred the use of refractive lenses because of their great ease of use and the consequent simplicity of the spectroheliograph design.

The mirror configuration that most closely resembles that of the classical refraction spectroscope referred to in the figure above is the Ebert-Fastie, which we will discuss in a moment.





In the photo above an example of a Hires spectroscope self-constructed by the author using short-focal length achromatic refractors. The cumbersome and excessive weight of this solution when adding a further refractor for the digital spectroheliograph led me to find others less challenging.



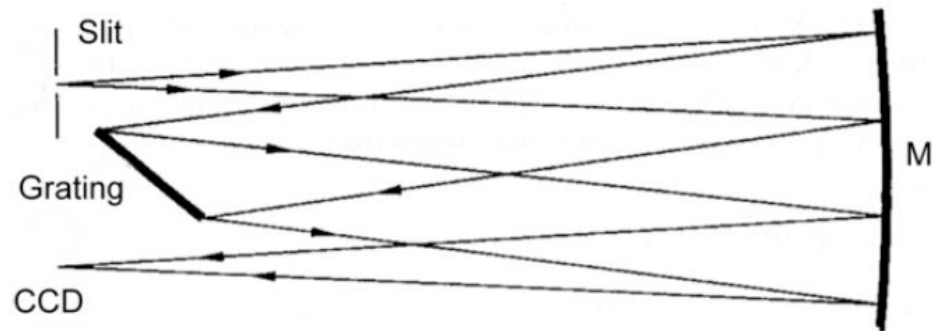
In the image above a spectroscope in the classical version that composes the model of the spectroheliograph used by the French amateur astronomer Daniel Deformeau, whose merit, together with Rondi, is to have introduced the principle of digital spectroheliography in the early 2000s, also creating a special computer program for the extraction of solar images from the spectrum.

The configuration in question, which generally uses refractive optics for obvious problems of mechanical construction and encumbrance, requires that the diameter and focal length of the collimator be adapted to the focal length of the telescope and to the dimensions of the grating; therefore the collimator will:

- have approximately the same  $F / D$  ratio of the telescope (this constraint is less binding than in the stellar spectroscopes)
- have a diameter equal to the diagonal of the grating, to cover with its optical beam all the grating itself.

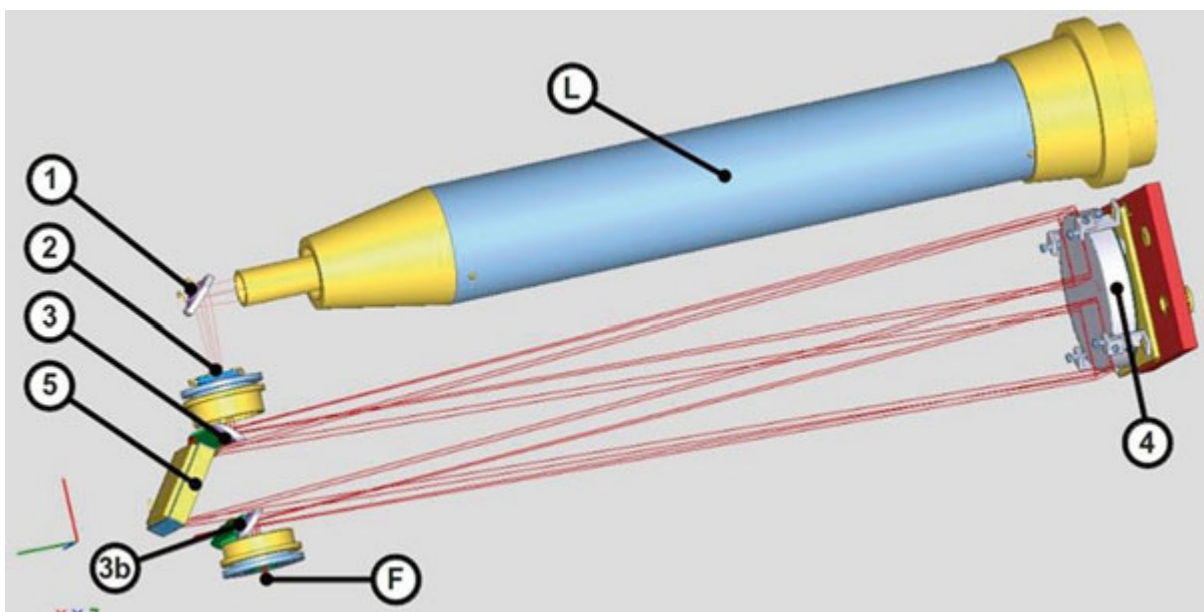
Let's take an example: let's say we want to use a telescope with  $F / D$  8, and a square grating of 50 mm of side: the ratio  $F / D$  of the collimator will also be 8, while its diameter of  $50 \times 1.4 = 70$  mm. it will therefore serve a 70 mm  $F$  8 achromatic lens, 560 mm focal length.

## 2-Configuration Ebert-Fastie



This is a fairly widespread optical configuration in spectroheliography, such as that quoted above by F. Veio: a spherical mirror of sufficient size and high focal length (with a high  $F/D$  ratio to control the coma) is used to intercept the optical beam coming from the slit, send it to the grating, and return it then diffracted to the camera; it is therefore a self-collimating system. There is a residual coma and the spectral lines are curves (smile). The dimensions of the mirror must be roughly 3 times those of the grating (diagonally) and the  $F/D$  ratio of the mirror must be at least 2 times faster than that of the telescope: if the latter is, for example, an  $F\ 10$ , you will need a mirror at  $F\ 5$ . It is still useful, in case of  $F/D$  ratios below 8, to evaluate the use of parabolic mirrors.

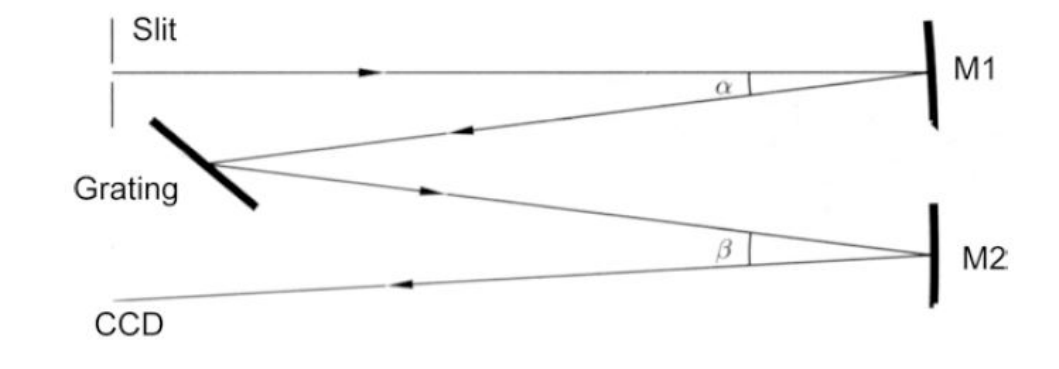
This configuration was the one used by the French amateur astronomer Andr   Rondi in his self made spectroheliograph.



L: 120/1000 acro refractor; 1: diverter mirror; 2: slit; 3-3B: deflecting mirrors; 4: 155 mm parabolic mirror of 954 mm focal length; 5: 1800 l / mm reticle. (Rondi)

Rondi's project, while proving excellent on a practical level, is of considerable optical-mechanical complexity, in my opinion essentially for the four mirrors, the main and the three deviators that are to be well collimated to ensure the quality of the spectra and of the final image. It is therefore a sophisticated project, suitable for those who have considerable skills and possibilities for working in the field of precision mechanics.

### Czerny-Turner Configuration

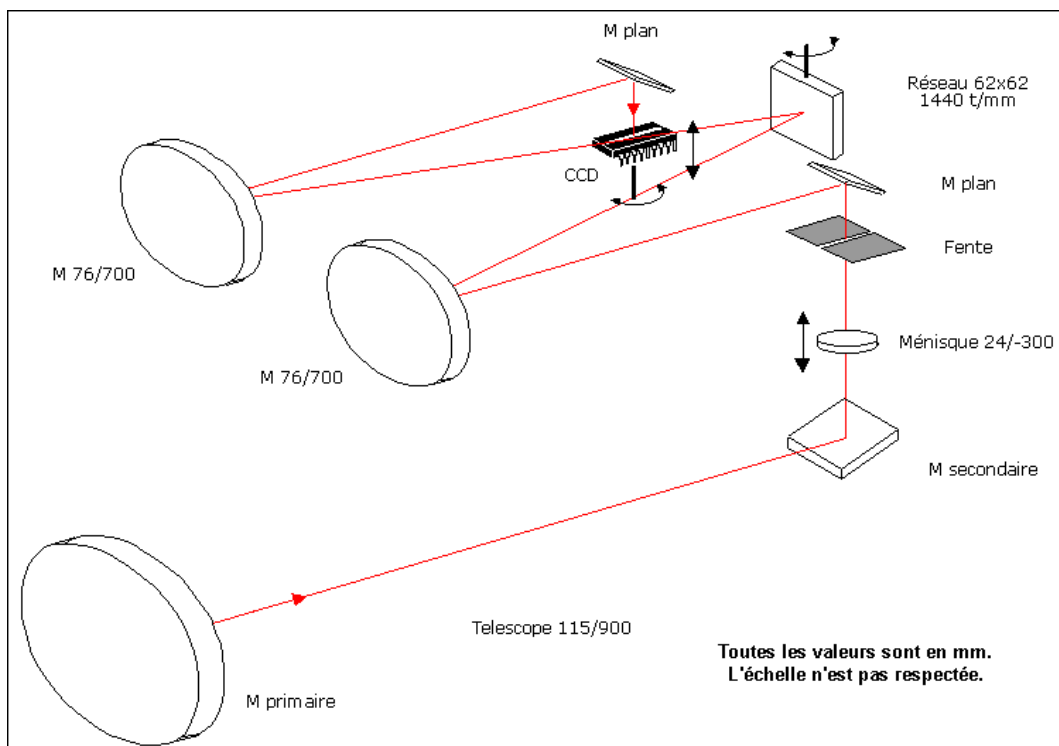


This is an optical configuration conceptually similar to the previous one, from which it differs for the use of two mirrors, one as a collimator, and one as an imaging optics, in order to reduce aberrations as astigmatism and coma. The mirror used as a collimator ( M1) must meet the following requirements:

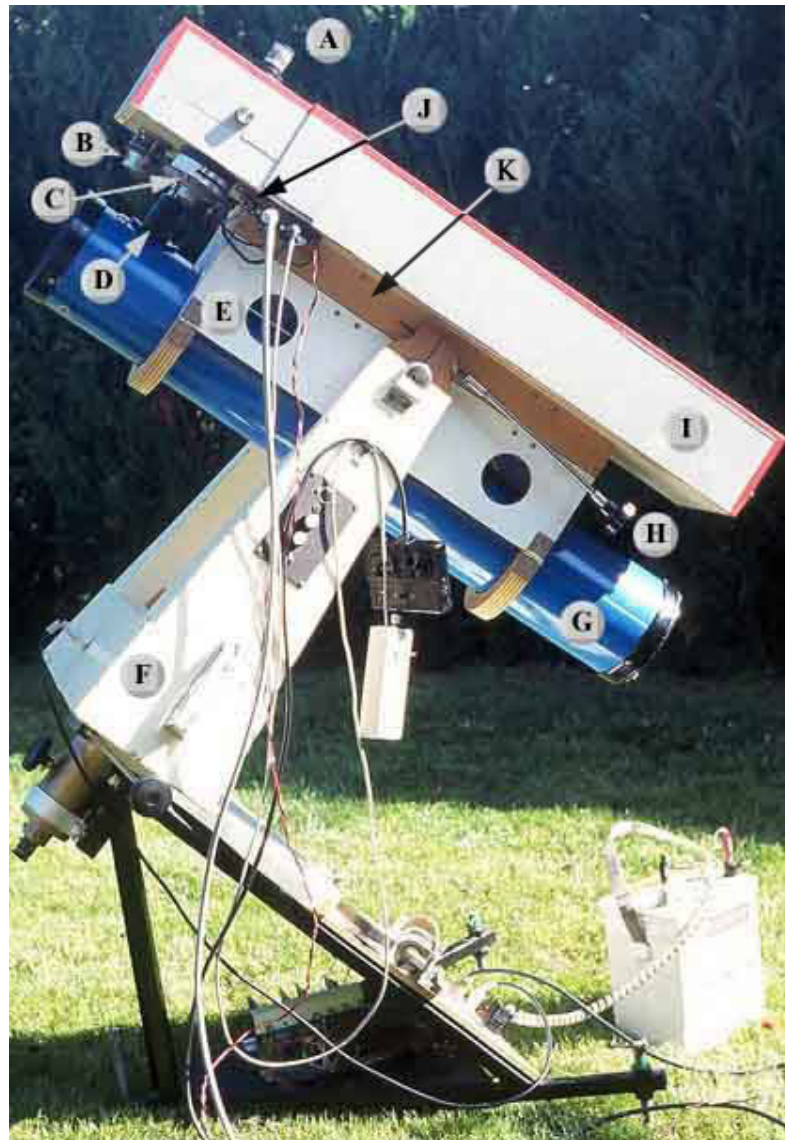
- Be larger than the grating and equal or larger than the Imaging mirror M2
- Having an F / D ratio similar to that of the telescope

The imaging mirror, on the other hand, must have a diameter such as to intercept the diffracted optical beam of the grating, and therefore equal to or greater than the diagonal of the grating itself.

This type of configuration includes the spectroheliograph realized by the well-known French amateur astronomer Phil Rousselle, who also used a commercial 114/900 Newton reflector as a telescope: in the image that follows the layout of the instrument.



It is an "all-mirrored" instrument of a certain constructive complexity, which nevertheless produced good results, even if it was subsequently replaced by a lens system. In the figure we observe the complexity of the structure and the fork mount also self built by the author.



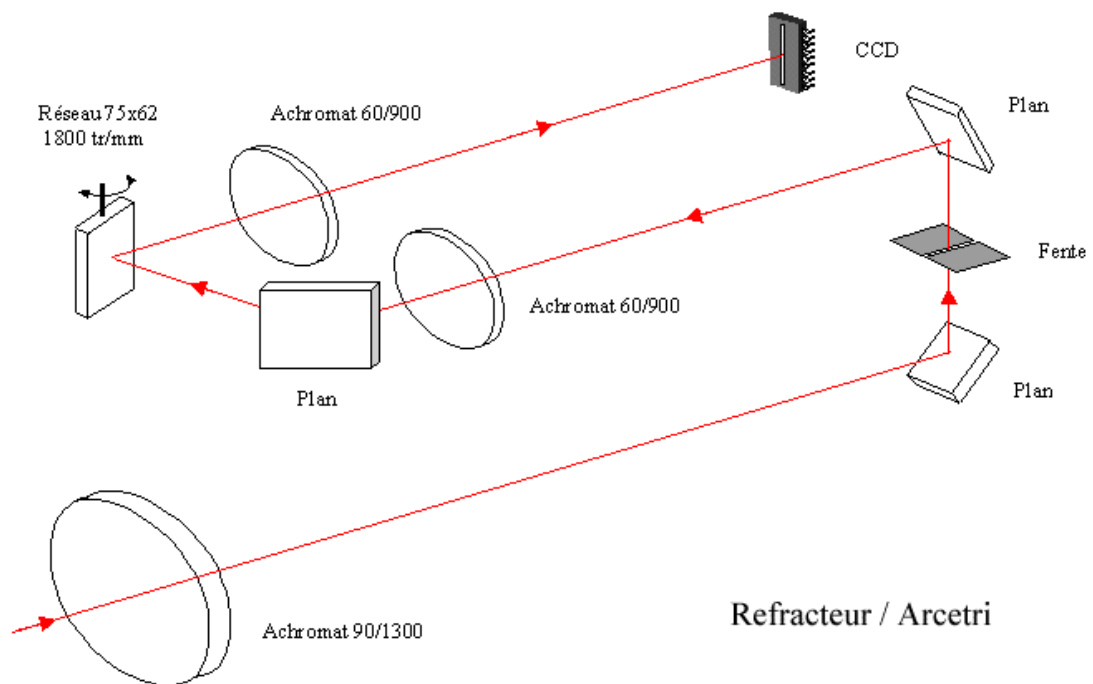
### "Arcetri" configuration

.

In some ways conceptually similar to the previous one is the configuration "Arcetri", used by Phil Rousselle in his last realization, the big difference is that this time it is a lens instrument. It is also a construction of a certain optical-mechanical complexity, which has asked the author considerable sacrifices for the construction and development, sacrifices well rewarded by the excellent quality of the images obtained.



The layout of the instrument.



In the following image the instrument as it appears in operational conditions on its fork mount, also self built by the author.



## Auto collimating Littrow configuration

### 1-Littrow configuration: why?

When I started the adventure of solar spectroheliography, I posed, for the spectroscope, the problem:

- a-what optical configuration to choose for high resolution;
- b-if to use lenses or mirrors;
- c-how to minimize the size, weight and number of optical components of the nascent instrument.

The configurations previously illustrated, although excellent in terms of the quality of the images obtainable, proved to be unsatisfying, as far as I was concerned, from the point of view of size, weight and transportability. Certainly, it is not said that such an instrument should be necessarily transportable from one place to another, but this feature, in my idea, would have added an extra gear to the project. The more sophisticated configurations, moreover, with a certain number of optical elements, presuppose a careful collimation, often difficult to obtain in a complete way, and nevertheless laborious.

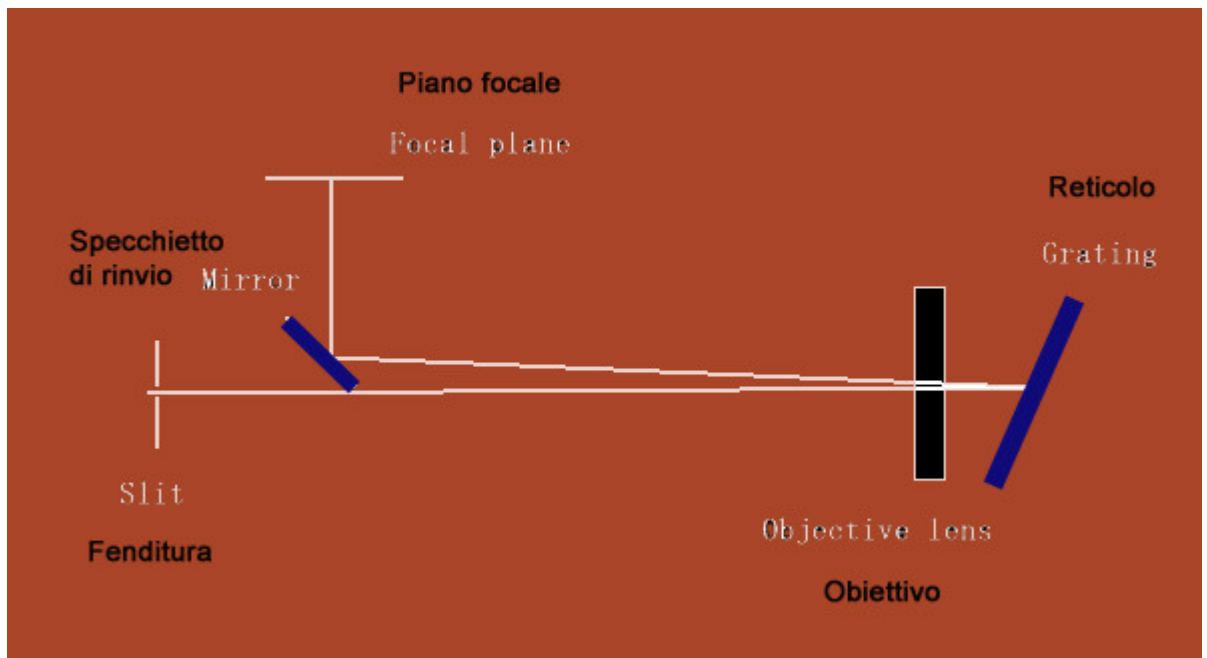
In the belief, therefore, that what does not exist does not create problems, my ideal configuration should have had the minimum possible number of optical components: this last requirement is present in only one of the spectroscopic configurations, the Littrow.

This project was conceived and developed by the Viennese astronomer Otto Von Littrow in 1862 and conceived, in an absolutely brilliant way, to use a single lens as collimator and camera, making the light perform a double passage: at the entrance, from the slit as a beam of light directed to the optical element and to the grating and back, after striking the latter, in the form of a diffracted beam (spectrum) directed to the imaging element or to the eyepiece by means of a prism or a small deflecting mirror.

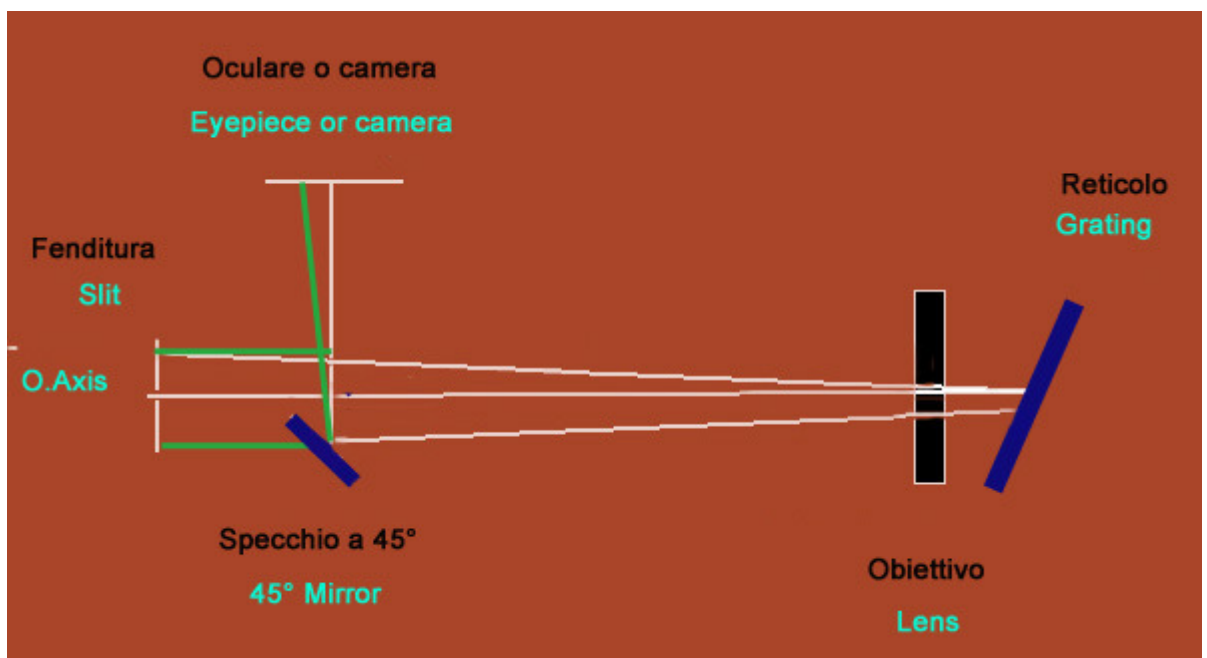
This configuration, minimizing the angular deviation, has two enormous advantages:

- 1- High dispersion and resolution;
- 2- Extreme instrumental compactness (compatibly with the focal length used).

Among the disadvantages, there is the diffused light deriving from the double reflection on the optical surfaces and a slight curvature of the spectrum (smile).



"Classical" Littrow layout with lens objective, and 45°deviation mirror near the camera



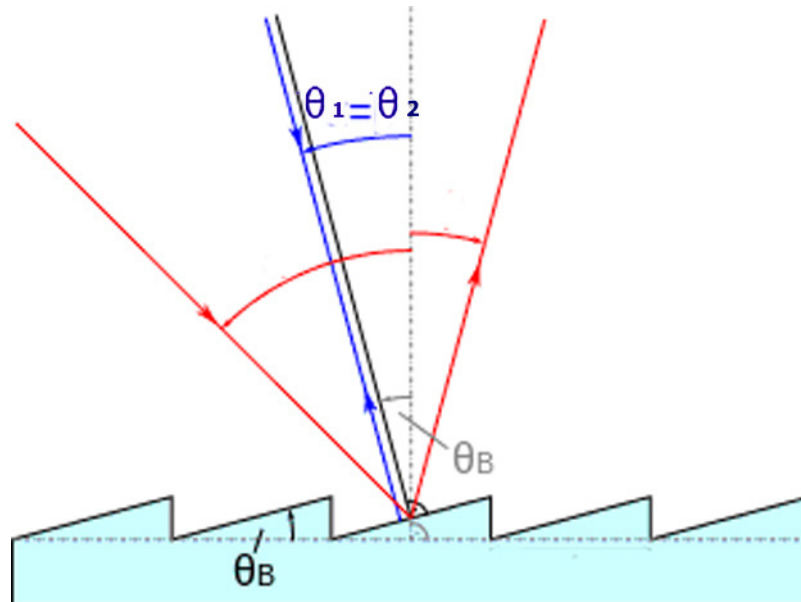
Littrow layout with lens objective, and 45°deviation mirror far from the camera , used in my VHIRSS spectroheliograph.

### The Littrow configuration on a technical level

In the Littrow autocollimating configuration, as we said, there is only one optic that acts simultaneously both as collimation optics and camera optics. In it the incident and diffracted light beam have the same angle, as the light makes a double passage before reaching the sensor, and this angle is the "blaze" angle of the grating (ie the angle of the grating incisions).

In it therefore it is  $\theta_1 = \theta_2 = \theta_b$ , where  $\theta_b$  is the blaze angle

Furthermore, in the Littrow configuration the anamorphic factor, ie the ratio between the angle of the diffused and the incoming beam  $\theta_2 / \theta_1$  is 1.



The general formula of the grating

$$m \times \lambda \times r = \sin \theta_1 + \sin \theta_2$$

where  $m$  is the order;  $\lambda$  the wavelength and  $r$  the number of lines per mm of the grating

in this case it becomes:

$$m \times \lambda \times r = 2 \sin \theta_b \quad (1)$$

from which:

$$\sin \theta_b = m \times \lambda \times r / 2 \quad (2)$$

$$\theta_b = \arcsin (m \times \lambda \times r / 2) \quad (3)$$

The Littrow condition is also important because all the commercial ruled gratings only report the blaze angle, assuming a Littrow configuration, indeed it can be said that the profiles of the incisions and the blaze angle are calculated precisely for the Littrow configuration. For example : in the Edmund catalog a 1200 l / mm diffraction grating blazed for 5000 Å is reported with an angle of 17 °; applying to the present case the formula (3) we have, in the 1st order:

$$\theta_b = \arcsin (1 \times 6000 \times 10^{-7} \times r / 2) = \arcsin [(5000 \times 1200) / (10000000 \times 2)] = \arcsin 0.3 = 17.5^\circ$$

It also follows that all the fundamental relationships will be referred to the blaze angle of the spectroscopy grating only.

In the above example, the angular dispersion A in Å per degree, defined by the relation:

$$A = [(\cos \theta_b / r \times m \times 10^{-7}) \times \pi / 180] \quad (4)$$

where r is the number of l / mm, m the order,  $\pi / 180$  the conversion factor from radians to degrees, will therefore be:

$$A = (\cos 17.5 / 1200 \times 10^{-7} \times 1) \times \pi / 180 = 139 \text{ Å} / ^\circ$$

As for the non blazed holographic gratings, since they convey the maximum of the luminous energy towards the 0 order ( $m = 0$ ), we can consider a blaze angle  $\theta_b$  equal to 0, ( $\cos \theta_b = 1$ ).

### A Littrow for the spectroheliograph

Let's assume that we want to design a Littrow spectroscopy for a spectroheliograph.

As specified above, the winning points of this configuration are the resolving power and optics of an adequate diameter, but with reduced dimensions and weight: it is therefore necessary to find a solution that would satisfy both requirements.



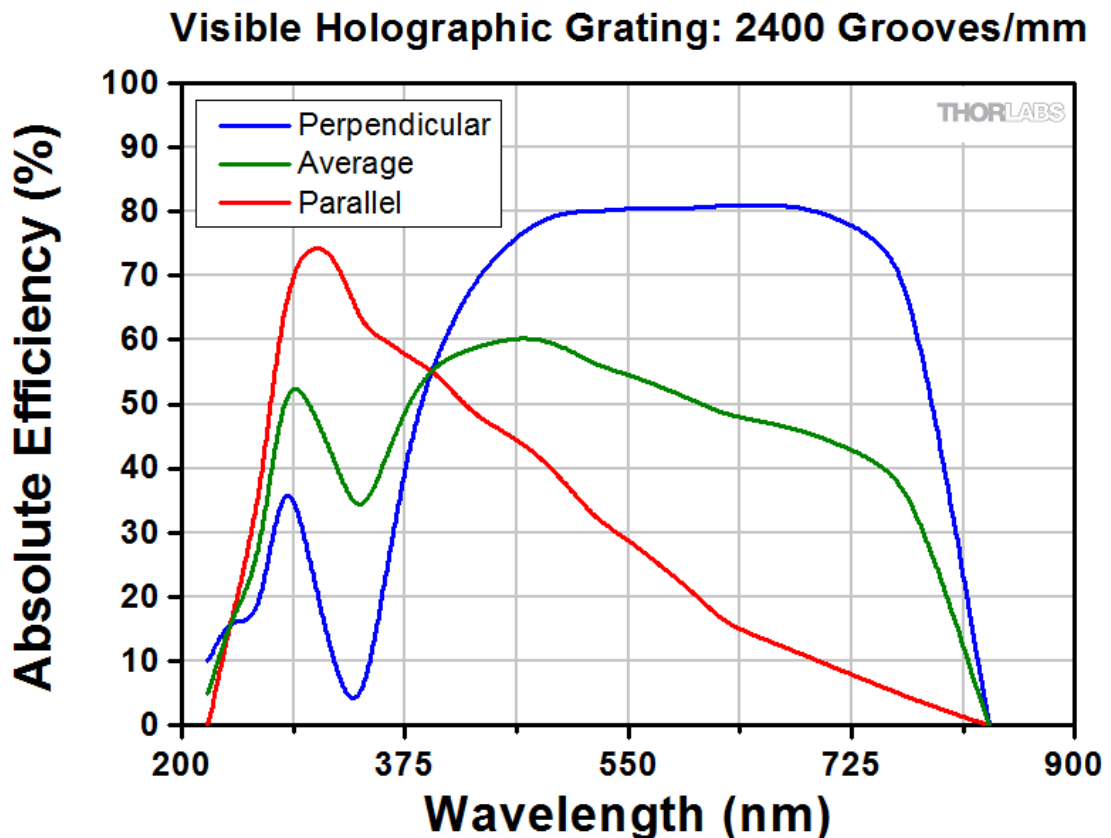
Spectral resolving power depends on the following factors:

- The number of lines per mm of the grating (increases with their increase)
- The physical dimensions of the grating in the hypothesis that its surface is completely covered by the incoming optical beam. (increase with these)
- The aperture of the slit (increases with decreasing of these)
- The pixel dimensions of the camera (increases with decreasing them).

For the first two points, it will be necessary to choose the grating with the maximum possible number of lines per mm, bigger, and at the same time with an acceptable cost, in a word an excellent quality / price ratio. Correspond to these requisites the "Ruled" gratings blazed for the visible at 1800 l/mm (the maximum possible) at the cost of about 175 € (in European market) in the 50 X 50 format (Thorlabs); for them I recommend a blaze angle of 500 nm. The blazed square holographic gratings of 50 x 50 mm side by 2400 l/mm in the catalog to the main sellers, Edmund Optics and Thorlabs are sold at fairly accessible prices (about 285-299 €) There are also blazed holographic gratings but they stop at 1200 l/mm (Edmund).

While the ruled blazed gratings offer a very high efficiency at the blaze wavelength they often suffer from problems like ghost images and diffuse light, instead the blazed holographic gratings do not have such drawbacks.

In the figure that follows a graph of the efficiency of holographic gratings of 2400 l/mm (source Thorlabs). It should also be said that at the highest number of lines 1800/2400 the holographic gratings have an efficiency almost equal to that of the ruled ones.



It will then be necessary to choose the size of the slit, and in this regard we could make two hypothesis: that of a slit closed at 30  $\mu\text{m}$  and at 10  $\mu\text{m}$  (two acceptable hypothesis in an adjustable slit of good quality).

For the camera we will assume a sensor with small pixels but not too much, in order not to reduce the sensitivity of the camera; we say 4.4-4.65  $\mu\text{m}$ .

So far the data related to the spectral resolving power, but we must also consider:

#### Diameter and focal length of the spectroscopy optics

In the hypothesis of wanting to use an F 8 telescope to project the image of the solar disk on the slit, it will be necessary to have a spectroscopic optic of this focal ratio, while its diameter it must cover the diagonal of a square grating of 50 mm (50 x 1.4) and therefore be at least 70 mm in diameter. A target of 80 mm will be even better, and will have to be at least 7-7.5. In this regard, on the consumer market there are excellent ED lenses of this diameter with FPL 53 glass that perfectly fit our needs and are easily found used at prices around 300 € (about 340 \$). Personally I used for most of my instruments such 80 mm to F 7.5 ED lenses (600 mm focal length). I currently own three, which are part of the instruments VHIRSS, POSS2 and Solarscan, costing me an average of € 250 each on the used market: an almost ridiculous amount in relation to their excellent performance.

## Spectroscope parameters

It will then be necessary to measure the parameters of a autocollimating spectroscopy equipped with a 2400 l/mm 50 mm side square holographic grating ,a 600 mm focal length lens, a 30 micron aperture slit and a camera with pixel of 4.65  $\mu\text{m}$  (Imaging Source DMK 41). The holographic gratings of this power are not blazed, placing, as we said, a zero blaze angle (cosine equal to 1) would be:

### 1- Angular dispersion:

The angular dispersion defined by the relation (4) is equal to:

$$A = [\cos 0 / (2400 \times 10^{-7} \times 1)] \times \pi / 180 = (1 \times 100000/24) \times 3.14 / 180 = 72.68 \text{ }^\circ / \text{\AA}$$

### 2-Linear dispersion:

The linear DL dispersion in  $\text{\AA} / \text{mm}$  is defined by the relation:

$$DL = \cos \theta_2 / (r \times m \times F_{\text{cam}}) \text{ (5); where } F_{\text{cam}} \text{ is the focal point of optics}$$

It will therefore be:

$$DL = \cos 0 / [(2400 \times 10^{-7} \times 1) \times 600] = 6.94 \text{ }^\circ / \text{mm} = 0.0069 \text{ }^\circ / \mu\text{m}$$

$$\text{and, for pixels from 4.65:}$$

$$DL = 0.0069 \times 4.65 = 0.032 \text{ }^\circ / \text{pixel}$$

### 3 – The theoretical resolving power at 5000 and 6563 $\text{\AA}$

The relationship of the resolute power is:

$$R = \lambda / d\lambda = m \times n \text{ (6)}$$

Being:

$$d(\lambda) = dL_f \times DL \text{ (7)}$$

where  $dL_f$  is the width of the slit projected on the sensor plane

For a 30 micron slit opening

$$d\lambda = 0.030 \times 6.94 = 0.21$$

at 5000  $\text{\AA}$ :

$$R = \lambda / 0.21 = 5000 / 0.21 = 23809$$

and, at 6563  $\text{\AA}$  (line H alpha):

$$R = 6563 / 0.21 = 31252$$

For a 15 micron slit opening will be:

$$d \lambda = 0.015 \times 6.94 = 0.10$$

$$R = \lambda / 0.10 = 5000 / 0.10 = 50000$$

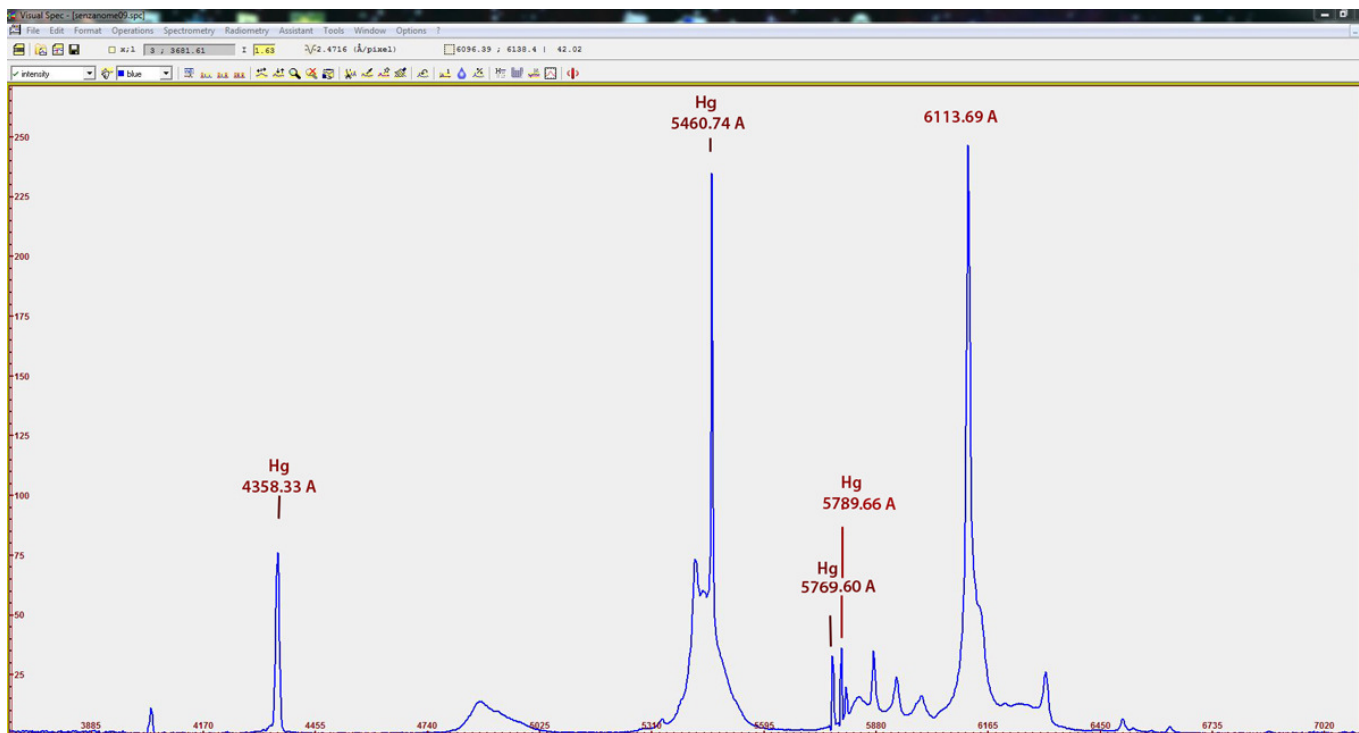
and, at 6563 Å (row H alpha):

$$R = 6563 / 0.10 = 65630$$

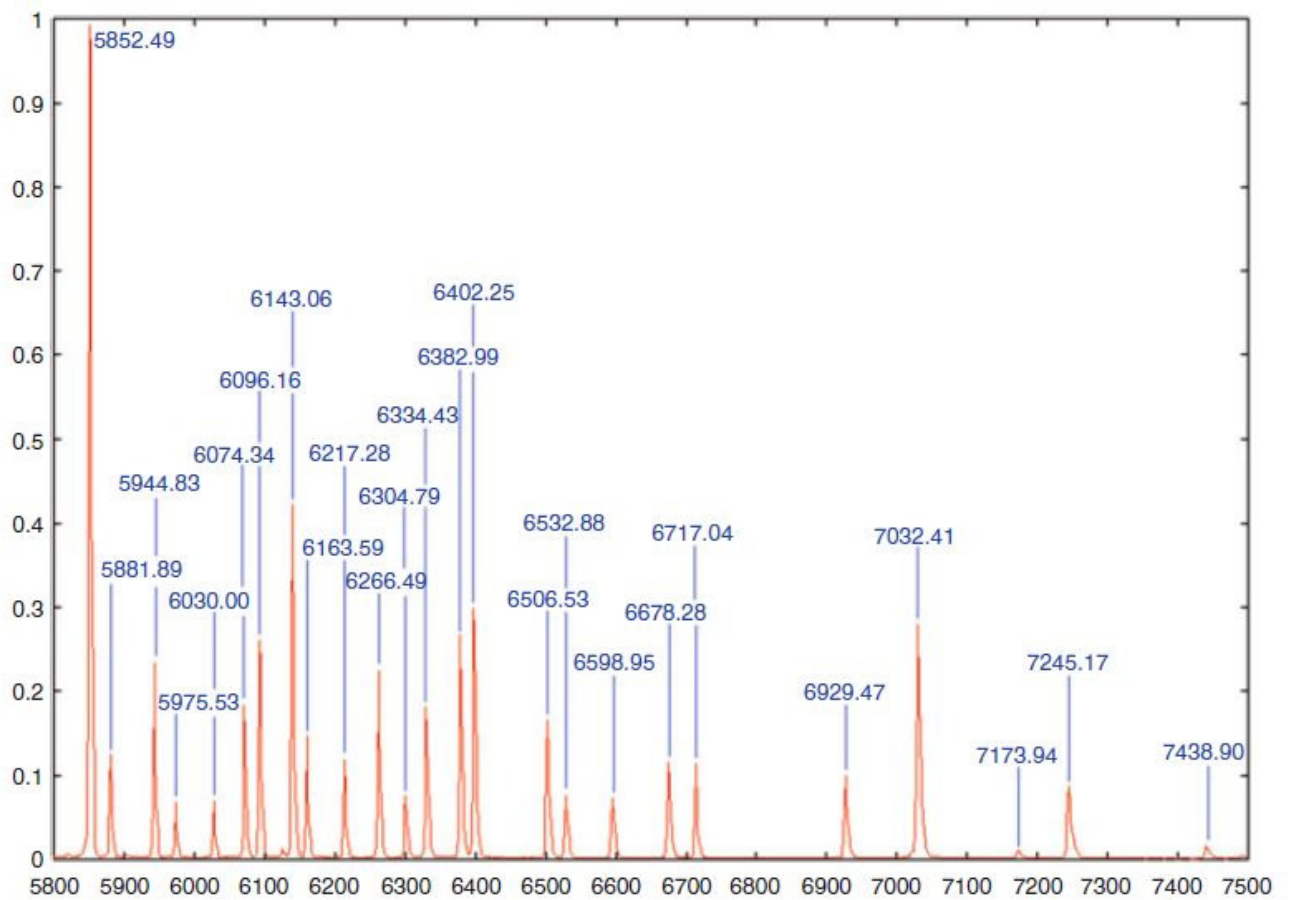
The theoretical values of linear dispersion and resolution previously calculated agree in principle with those I have obtained in the field with the VHIRSS and Solarscan spectrographs (both having 2400 l/mm gratings). It is also to say that the actual values on the field of the linear dispersion and of the resolution are slightly better than the theoretical ones, averaging on the 0.022 Å / pixel with 4.65 µm pixels (values from 0.019 to 0.025) and about 35-43000 as resolution R. A possible explanation is given, for VHIRSS, from the displacement of the slit closed at 30 µm with respect to the optical axis, while, for Solarscan, it may affect the closure of the slit at lower values (20-15 µm).

As far as the spectral resolving power is concerned, the calculated theoretical values also vary considerably in the practice of observations on the basis of diurnal seeing. If you want to measure the actual PR of the instrument, you can do it indoors, pointing it (with the slit closed to the working position) towards a light source such as a low consumption lamp or a neon lamp, obtaining the calibrated spectrum and measuring the FWHM of the thinnest line. Some authors also suggest to do it in the field, flanking the image of the sun absorption line that of the emission lines of a neon or low-consumption lamp placed at the opening of the telescope during the filming. While this solution would provide a safer data of the generic resolute power of the instrument at the time of shooting, in my opinion would not provide equally reliable data on the effective resolution of the spectroheliographic image, provided by the absorption lines. Nothing, however, forbids that resolutions can be measured in both ways, capturing any differences.

Below is the spectrum of a low consumption lamp obtained with my Spec 600 stellar spectroscope and one of a neon lamp (source C.Buil).



Low cons lamp spectrum



Neon lamp spectrum



### Parameters of the telescope to be used with the Littrow

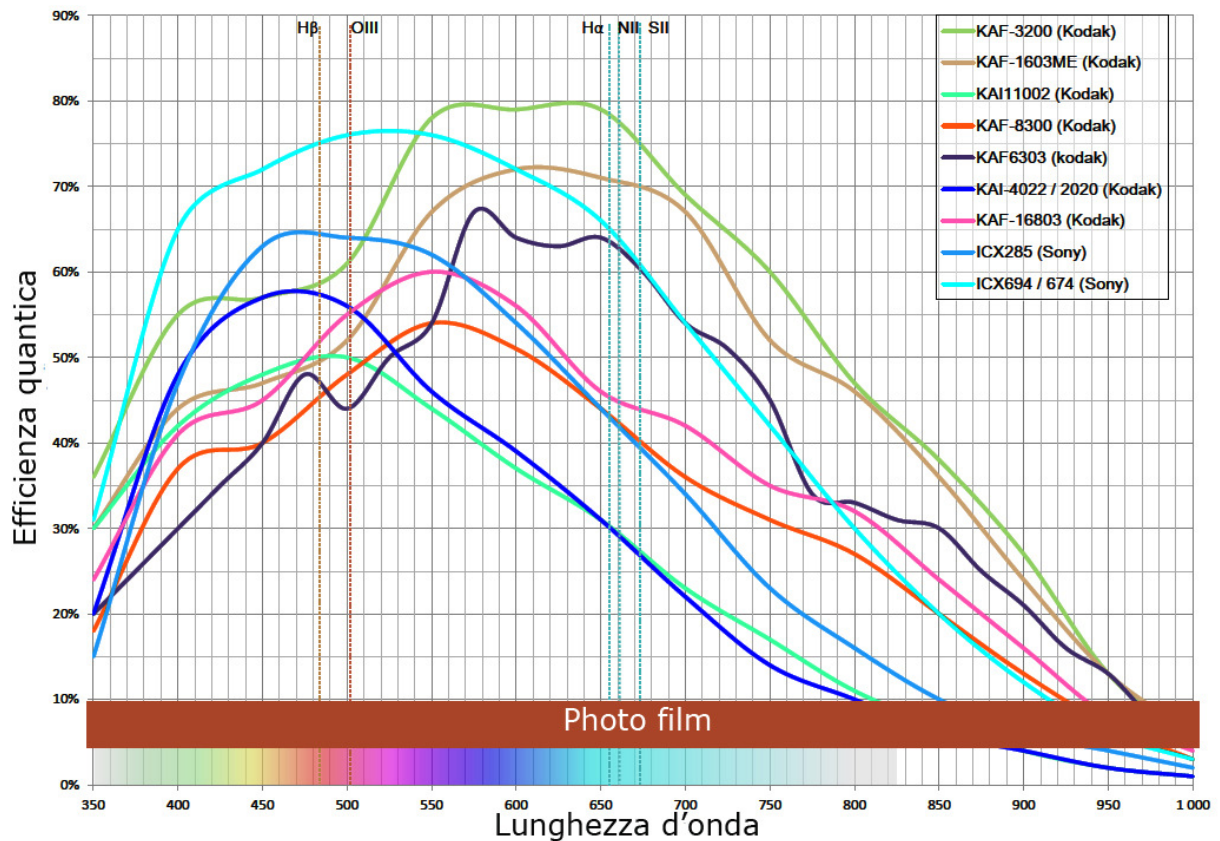
We hypothesize in this regard to want to use a telescope at 7.5-8 that at the same time gives an image of the solar disk on the slit not exceeding 8 mm (better than 7 mm), if you want to use low-cost slits from SurplusShed ,appropriately modified as mentioned previously. The focal length should be kept low both to contain the overall dimensions of the instrument and to adapt to the dimensions of the camera sensor in order to produce full images of the solar disk without having to make mosaics. A focal length of about 500 mm, with a 4.7 mm focal plane image disk might be fine for our purpose if coupled, as we shall see, with a CCD sensor of appropriate size. This focal length is common to a certain amount of lens instruments on the market, both achromatic, ED and apocromats. Personally, for my VHIRSS spectroheliograph I have used an excellent doublet of military origin of 60 mm and 480 mm focal length that in numerous tests has letterally outperformed for definition and contrast different refractors ED of the same diameter. With some sensors, as we will see, the focal length can also go up to 560 mm, always assuming we want to get full disk images in a system not too long and bulky , but it can also be reduced to a range of 350-450 mm without appreciable decrease in overall system resolution: with Solarscan I used a 355 mm focal length Takahashi FS 60 C.

### The CCD or CMOS camera

#### The type of sensor

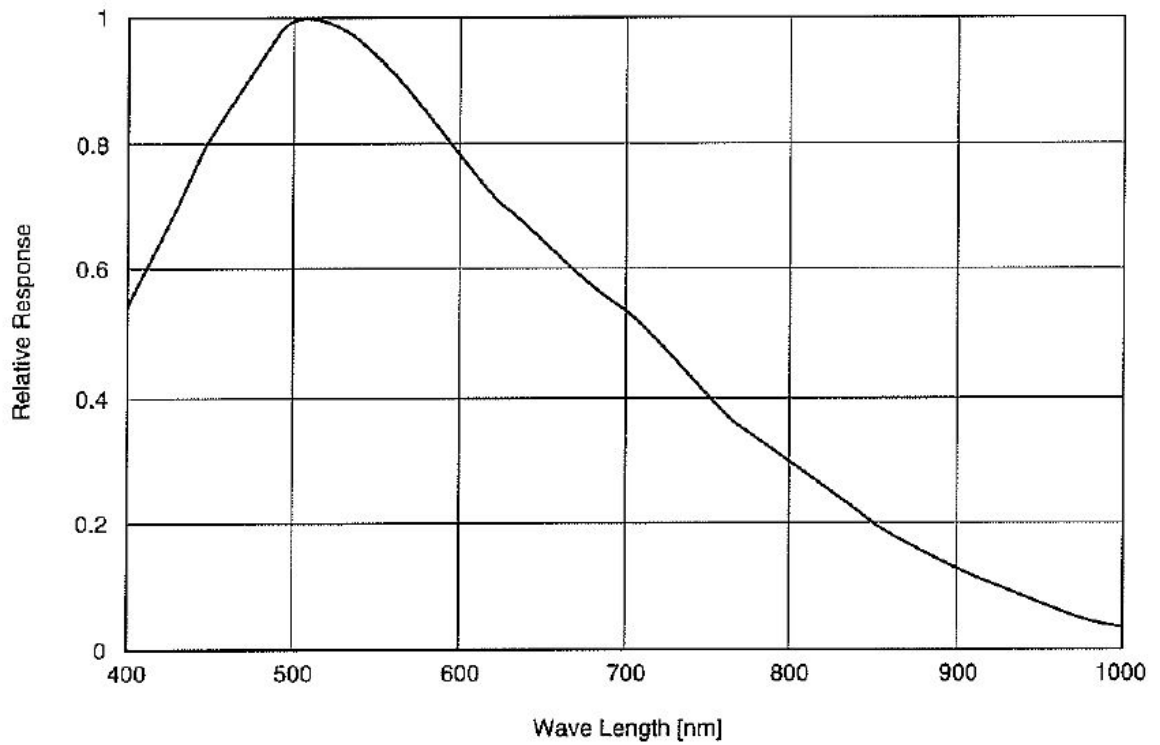
It is the last of the components for our digital spectroheliograph, but perhaps the most important. The key to the success of the digital spectroheliography was precisely the advent and the affirmation of CCD and CMOS sensors, whose quantum efficiency (EQ) exceeded enormously that of the old photographic plates with which they were made, at the end of the 1800s , the first experiments of spectroscopy and that of the most modern photographic film of recent years. Given that quantum efficiency reports the response of the sensors, ie the ability to convert photons into electrons across the spectrum, the EQ of photographic film stood in a range between 4 and 10% (for hyper-sensitized films), moreover this was higher in the blue part of the spectrum than the red one, so much that the professional astronomical films were hypersensitized for red (famous was the Kodak 103 AO film) .

The comparison below shows the range of E.Q. (relative response) of photographic emulsions (about 4-10%) and that of modern cooled CCD sensors for astronomy.

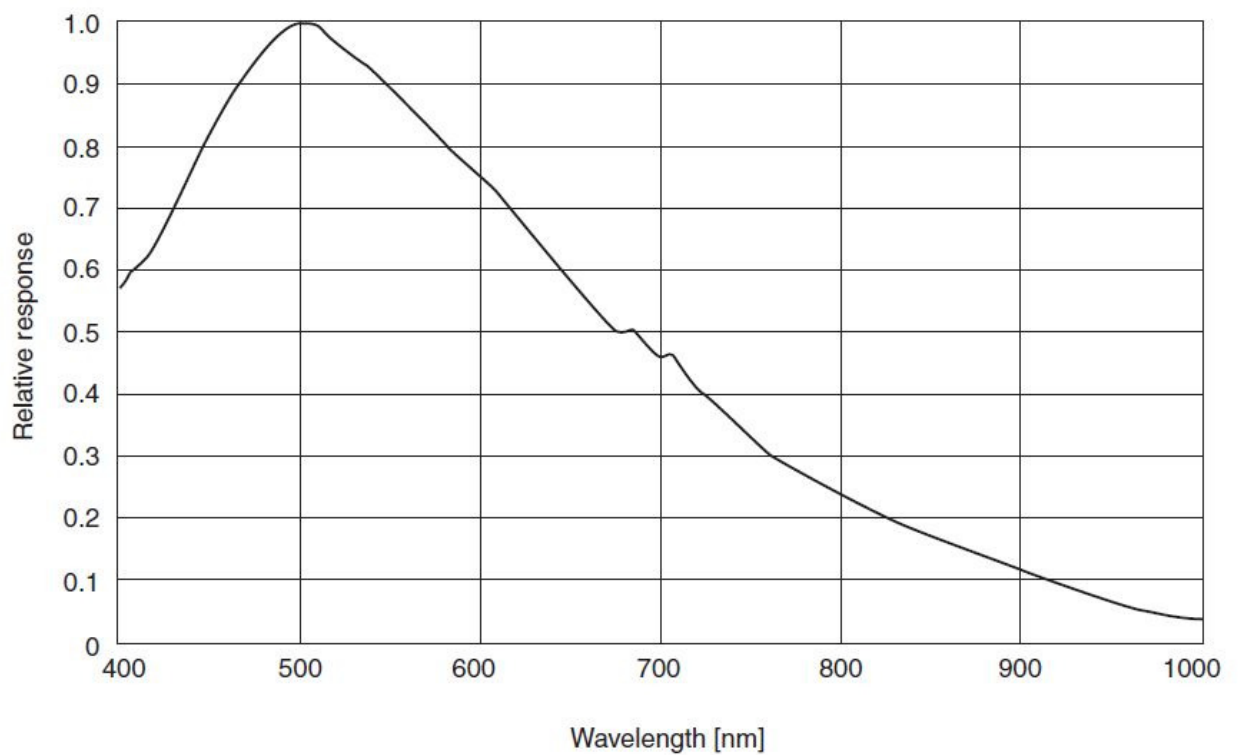


Here, however, we are not talking about CCD or CMOS cameras that give single images, but cameras able to record movies, or the video of the passage of the solar disk on the slit, as we will see. These range from simple and inexpensive webcams to sophisticated and therefore expensive astronomical cameras such as the Imaging Source DMK in the various versions with CCD sensor (in particular DMK 41 and 51) and the ZWO ASI with CMOS sensor (very fulfilling for our purposes is the 174 mm).

The two DMKs, 41 and 51, have very similar relative quantum responses, and their characteristic is a high sensitivity in near UV (about 50% to 3900 Å) which makes them ideal in the spectrum of ionized calcium lines; the sensor dynamic is 8 bit, while the ZWO ASI 174 is 12 bit.



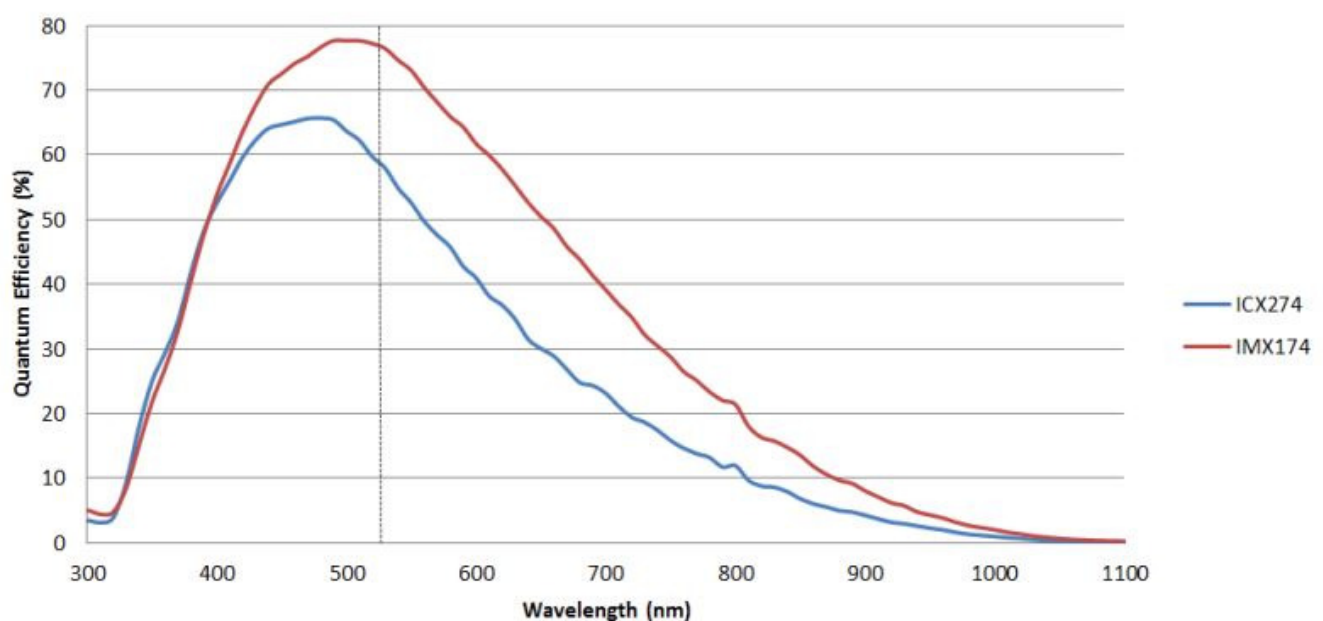
The relative response of Sony ICX 205 AL CCD sensor of I.S. DMK 41  
( source Sony)



The relative response of Sony ICX 274 AL CCD sensor of I.S. DMK 51  
( source Sony)

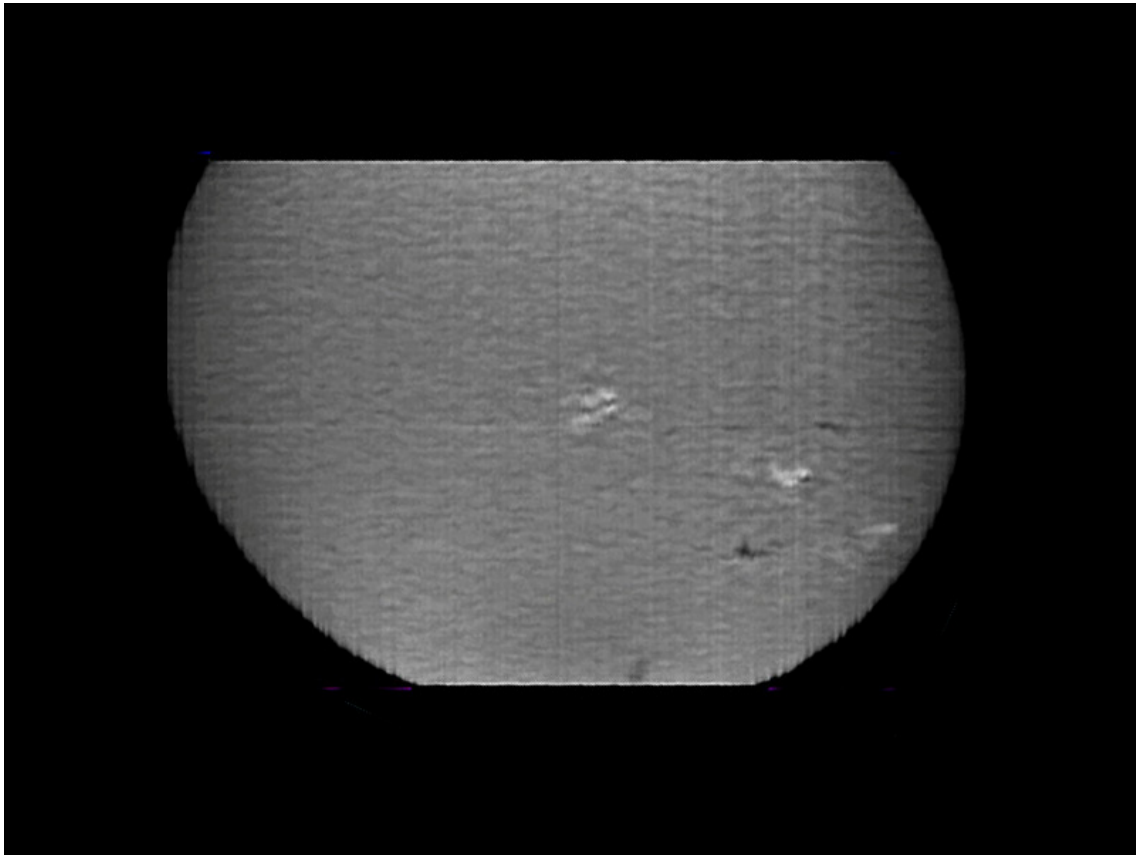
As can be seen, the EQ of the two cameras fully meets the needs of the digital spectroheliography, being about 52-53% in the spectral region of the calcium lines and 60% in that of the H $\alpha$  line, with a peak at 5000 Å, in the H $\beta$  zone. Obviously the DMK 51 has a larger sensor, which allows us, assuming other things being equal, to use a longer focal length of the telescope than the DMK 41.

An even more exiting behavior is the CMOS exmor IMX 174 LLJ sensor from Sony (ZWO ASI 174), whose EQ is in the following image compared to that of the ICX 274 of the DMK 51 (source FLIR -white paper series):



### The dimensions of sensor

The physical dimensions of the sensor are important because they will determine (remaining the slit length) the part of the solar disk recorded by the CCD. If, for example, I use a webcam with Sony ICX 098 BQ 3.6 x 2.7 mm sensor and a 500 mm telescope that projects a 4.7 mm sun disk image on the slit the recorded AVI file will have a coverage of  $3.6 / 4.7 = 0.76$ , ie it will cover about  $\frac{3}{4}$  of the disk, obtaining a partial image, like the one that follows, which was my first solar image recorded with a Philips Toucam webcam.



If, however, we will use a DMK 51 with a sensor of 8.50 x 6.80 mm, then the coverage will be:  $8.5 / 4.7 = 1.8$ , then more than enough to image the entire solar disk.

This argument holds in the hypothesis of Littrow spectroscopes with a single optic, for which it is not possible to change the ratio collimator focal length / imaging lens focal length. Instead, in the case of spectroscopes using both optical elements, it will be possible to act on the focal length of the imaging lens to reduce the image of the solar disk to the dimensions of the camera sensor. Let's have a 500 mm telescope projecting a 4.7 mm sun image, a webcam, a classic spectroscope with a 200 mm focal length collimator and a 200 mm imaging lens: let's imagine now to change the focal length of the imaging lens from 200 to 100 mm: this will result in a reduction of the magnification factor of  $100/200 = 0.5$ , and then the solar disk will now have an apparent diameter of  $4.7 \times 0.5 = 2.35$  mm and will enter the chip of the webcam.

The pixel dimensions

The diurnal seeing, as we know, is characterized, even in winter, by ascents of air caused by the heating of the ground, up to about 100 meters in height. These are precisely, apart from the masses of air at high



Altitude, to cause a worsening of the day-time observing conditions compared to the nocturnal ones: things get even worse in the presence of roads and buildings of all kinds. The ideal conditions for daytime observation would be those located outdoors in a large grassy area: but not all have such a possibility. This premise is necessary to state how in daytime solar observation, even more than in the long-term nocturnal observation, is the seeing and not the diameter of the optics to determine the attainable resolution: and this also with times of integration closer to those of planetary imaging than to those of the deep sky. By assuming an average seeing of 4 ", the necessary sampling, according to the Nyquist criterion, will be then 2 "per pixel, and the focal length of the resulting spectroscope will be:

With 4.4  $\mu\text{m}$  pixels (DMK 51).

$$F = (0.0044 * 206265) / 2 = 453 \text{ mm}$$

With 4.65  $\mu\text{m}$  pixels (DMK 41)

$$F = (0.00465 * 206265) / 2 = 480 \text{ mm}$$

For 5.86  $\mu\text{m}$  pixels (ZWO ASI 174) would be

$$F = (0.00586 * 206265) / 2 = 604 \text{ mm}$$

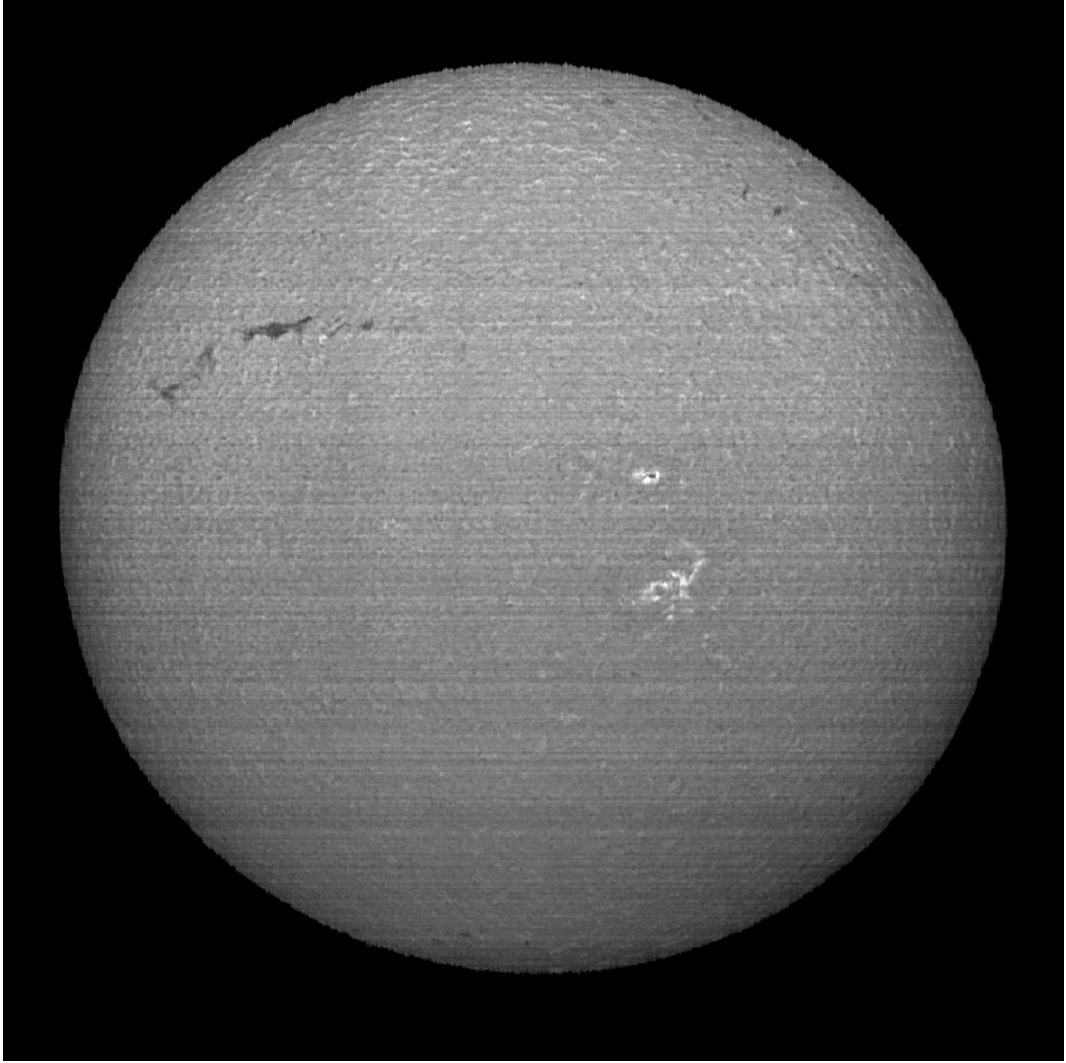
All this in harmony with an opening of the slit of 10-15 microns as previously mentioned.

The frame rate

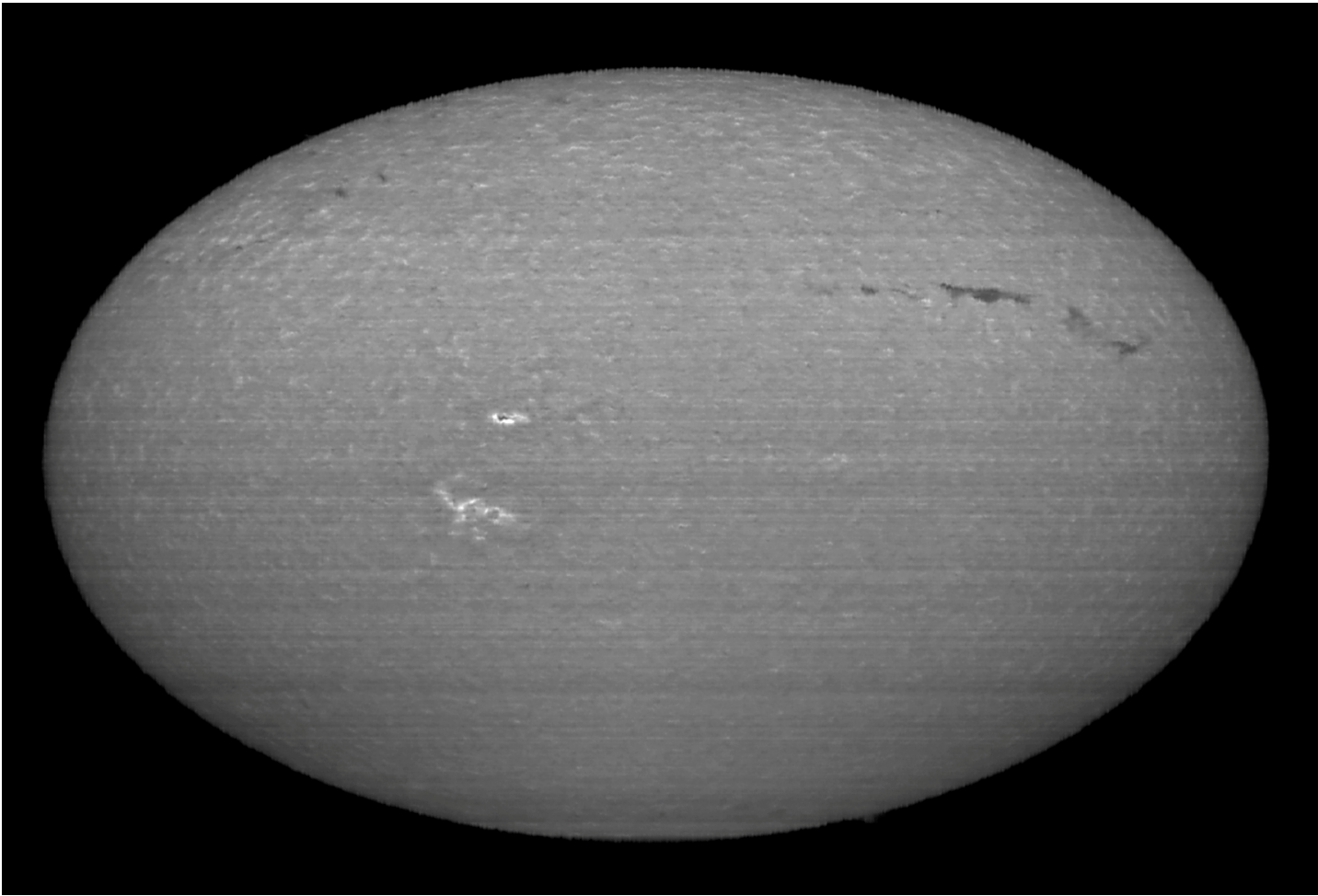
The frame rate is important because it depends on the resolution in pixels of the image along the x axis. In my solar scans I always let the solar disk run along the slit with the motors of the equatorial mount off, and then, the average duration of the sun's passage on the same slit would be  $1920 \text{ arcsec} / 15 \text{ arcsec for sec} = 128 \text{ sec}$ . Naturally, to have also a dark outline of the solar disk in the final image it is necessary to prolong for a few more seconds the duration of the scan, which thus reaches 150-160 sec, about 2.5 minutes.

With a DMK 51 (oriented with the longer side of the chip along the AR axis) and a frame rate of 7.5 fps I get a solar image that extends along the X axis for  $128 * 7.5 = 960$  pixels the only disk and  $160 * 7.5 = 1200$  pixels the full image, including edges. Along the Y axis the format is the native one of the 1200 pixel camera.

The appearance is about this:



With a frame rate of 12 fps I would get 1536 pixels for the disk only and 1920 pixels for the full image, with an appearance similar to the following:



As you can see, the frame rate increases the resolution along the X axis, and then you need to rescale the image to make it look normal. From the tests done by me, however, the difference in resolution and detail is much less important than one might think, probably because the increase in the frame rate negatively affects the quality of individual frames.

In any case, the distortion induced between X and Y axis can easily be corrected in post-production with any photo editing program.

The high frame rate with full-frame images could give problems of downloading on PCs not very performant with IS DMK, which have a USB bus 2.0. This problem can however be easily controlled by selecting the spectral line of interest by software with a ROI ( Region Of Interest). For ZWO ASI, which use a 3.0 bus, this problem does not exist on the latest generation PCs.

### Final note: the exit slit

As we have seen, the traditional spectroheliograph projects have two slits, one at the input and one at the output, for reasons linked to the synthesis of the images. In digital spectroheliographs this is not necessary, since synthesizing is done via software but, especially in the case of the Littrow configuration, it is easy to create diffused light along the optical path. The use of internal diaphragms is rather complicated because, if not performed perfectly, it risks creating obstructions to the optical beams of entry and return.

An extremely easy solution is to use at the output of the instrument an interferential filter centered on the wavelength of the line in which we want to obtain the image: this is worth, during the filming phase, to eliminate a good part of the diffused light and increase the contrast. This filter can be inserted into the 31.8 mm nose of the camera.

A second solution, at least with H $\alpha$  imaging, may be to use a rejection deep red filter (normally used in solar H $\alpha$  imaging) placed in front of the telescope lens, ie along its optical path. Also the common 2 "35-12 nm filters placed at about 30 cm from the focal point may be useful for this purpose. However, in this last case it is necessary to consider that in the long run the UV radiation can be harmful for the coating of the filters themselves, and that's why we recommend the use of UV-IR cut filters in front of these.

### In conclusion:

We have analyzed in detail the components of a SHG, arriving to some interesting ideas that agree quite well with the practical experience I have carried out with my own instruments, namely:

- 1- To reconcile portability, compactness, lightness and high resolution, both spatial and spectral, the Littrow configuration presents itself as the best in terms of overall efficiency, ie the performance / size ratio, weight and ease of construction.
- 2- Within this configuration the telescope, which sends the solar image to the slit should have a focal length around 500 mm and a focal ratio of F 7-8.
- 3- The slit, to accommodate the solar image of the aforementioned telescope should have a length of at least 6-7 mm, and opened at 10-15  $\mu\text{m}$ .
- 4- The spectroscope optics should have a diameter of 70-80 mm at f 7: ED refractors from 80 mm to f 7-7.5 are the ideal candidates.
- 5- The grating should be an holographic one, 2400 l / mm and 50 x 50 mm side.
- 6- The camera should have a quite large sensor and medium-small pixels between 4 and 5  $\mu\text{m}$ .

Of course, these considerations are indicative and are not the tables of the law. For example, in my three main instruments (VHIRSS, POSS2 and Solarscan) in conjunction with identical spectroscope optics (3 ED 80 mm f 7.5 refractors) I have used different telescopes, although of excellent quality (a 60 mm f 8, a 70 mm f5, a 60 mm f 6) and yet I did not notice any particular differences in the performance of the three instruments in terms of resolution. Nothing prohibits, for example (adapting the size of the camera chip for the full disk image) and slightly sacrificing size and weight, to adopt two 80 mm f 6.5 as a telescope and optics of the spectroscope.

But let's now look more closely at the 5 Littrow projects I have made, similar in layout, but different in size and weight, and each with different specific functions which I will discuss in detail in the following pages. Is it necessary to build 5 similar instruments, if in the end, their functions could have been performed by only one of them? The answer to this question is very simple:

a) The construction of the 5 instruments, in principle quite similar (even if Solarscan is a separate case) allowed me to verify the repeatability of the project in the field.

b) From my house in Rome I have an observation window of about 1.15 h, (after which the sun is covered by the ceiling of my balcony) which means that I can shoot only during such period of time. In this context, using an instrument (eg) already developed on the Alpha and another on the Ca II K, greatly facilitates the operation and allows me a greater efficiency by dedicating the little time available to the output instead of focusing and to centering on the line. Obviously these problems do not occur with Solarscan whose PC-controlled setup procedures are very fast and accurate.

Of course mine is a special case, but perhaps not too much, and anyway the pleasure of dedicating myself to such a self-constructive activity has overcome any inconvenience. After that, let's talk about the individual instruments.

1 VHIRSS (Very High Resolution Solar Spectroscope): it was the simplest project, but also the most outstanding among those assembled in a homely way without having the need, if not to a minimum, of a mechanical workshop. This is dedicated to H $\alpha$ -Na-H $\beta$  spectral area;

2 POSS2 (POrtable Solar Spectroscope2): Littrow now dedicated exclusively to shooting in the Ca I K and H ionized calcium band;

3 SOLARSCAN is the main and better instrument from the constructive point of view, as it was realized on my project in an excellent way by



Avalon Instruments of Pomezia (Rome). It was initially used as a spectroheliograph, and subsequently modified by me for the imaging of Zeeman effect of Iron lines on sunspots and the measurement of magnetic fields of the same sunspots;

4 HIRSS2 (High Resolution Solar Spectroscope<sup>2</sup>) is now used by me only for experiments of various kinds, among which some in the field of quantum mechanics.

5 UPS (Ultra Portable Spectroheliograph) due to its very small size and weight (an Eq2 mount brings it without problems) is exclusively used for field demonstrations at events of various kinds both as spectroscope and spectroheliograph

### **Self made digital spectroeliographs in Littrow configuration**

But let's now examine in detail some digital spectroscopes built by the writer: They all are, as we said, in autocollimating configuration or Littrow. They are continuously updated in optics and mechanical systems to maintain the overall performance at high levels.

Making a digital spectroheliograph is certainly much less complex than a traditional one, but still requires a good dose of manual skills, mechanical skills and, good experience in the field of spectroscopy.

Anyone who wants to try out his skills should be fully aware that not only the theoretical preparation and manual attitudes count, but also and mainly a certain experience in spectroscopy and its practical applications. This does not mean that even a spectroscopy newby cannot try to build such an instrument: simply he will encounter more difficulties and will take more time in the development of the project and in its realization. The layout and schemes are, in principle, quite simple, but the problems of aligning the optics and the spectra increase more than proportionally compared to the focal length of the lenses or mirrors used. I would like to start from the instrument that gave me and still gives me the most satisfaction: VHIRSS, acronym that stands for Very High Resolution Solar Spectroscope. The architecture of the instrument is in principle very simple, and it is precisely this simplicity of construction, combined with the weight and small size (8kg x 110 cm in length) which makes it the instrument I use the most. I have dedicated it to the imaging in H $\alpha$ , H $\beta$ , Na 1 and 2 lines, but obviously it can be used in any wavelength and element.

## 1- VHIRSS



Photo in actual scheme of VHIRSS

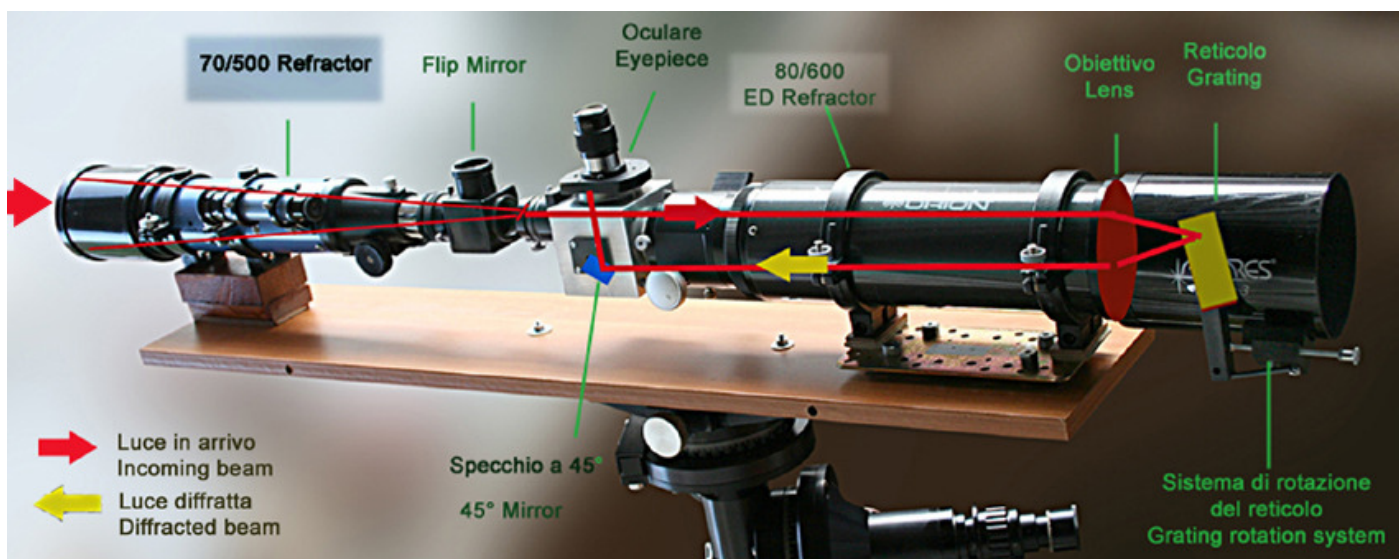
### The initial project

The philosophy of the project was to create a sophisticated instrument with almost professional performance, easy to assemble, disassemble and transport, as well as weight and not excessive bulk. I have therefore decided its composition in 5 elements, each easy to disassemble, decreasing therefore the overall dimensions and increasing the ease of transport.

The elements are:

- The case containing the grating and its movement system, obtained from a simple hood of a 102/500 refractor, already used for another instrument (HIRSS2). I did not consider using the same hood of the ED 80 as I had to pierce it to pass the grating axis, and I preferred to intervene on a piece that was no longer useful.

- The Orion ED 80 refractor tube
- The 80 x 80 square aluminum case containing the 20 mm square deflection mirror and the adjustable slit.
- the Skywatcher 70/500 refractor tube used to send the solar image to the slit
- the 20 x 100 laminated multilayer plywood strip used as a support for the rings of the two refractors, so that the optical cone of 70/500 was in register with the entry of the slit, and in focus on it.



The project was carried out in July 2009 and for the first attempts at spectroscopy a Philips Toucam webcam was used. Now, after 9 years, observing the images obtained, I can see the huge gap in the qualitative output of the instrument during this period of time, thanks to improvements made later.

The first critical element was the multilayer plywood strip initially used as a base, which, although apparently robust, with the course of time and use started to deform, risking to jeopardize the alignment of the telescope and spectroscope. I preferred then to use a square steel plate of 30 mm side x 3 mm thick x 1 m long available at any good hardware store: Of course such a component is much more difficult to drill than the wood, but in return ensures a rocky, stable and definitive tightness.

The second was the telescope that sends the image on the slit, initially a 70 mm diameter SW and 500 mm focal length, the lens was good for the cost, but not excellent: I then looked around to see if I could replace it with something better. I found, among my innumerable optical devices, a 60 mm and 500 focal length lens of probable military derivation.

At first glance it looked very good, so I tested it comparing it not only with SW 70/500, but even at two 66/400 EDs, and this objective outperformed all three as to definition and contrast, then I unscrewed the original lens from the tube and replaced it with my new purchase (so to speak).

That said, let's move on to the details of the constructive notes:

### 1-The grating

The chosen grating was a holographic one , not blazed, of 2400 g/mm purchased by the company Edmund Optics at the price (at the time) of €250. It is the grating with the greatest number of grooves per mm in the visible, and thus allows to obtain the maximum resolution possible, provided, of course, that its surface is entirely covered by the diameter of the collimation optics. This grating has proved to be of excellent quality, adequate to the cost not very negligible. Moreover, the diffraction grating constitutes the heart of a spectroscope, and wanting to save on it is like wanting to buy a sport car with a 50 cc engine. Obviously the grating itself must be handled with the utmost care, taking it from the sides since any marks of fingers or rifling on its surface are permanent and not eliminable.

### 2-The grating cell

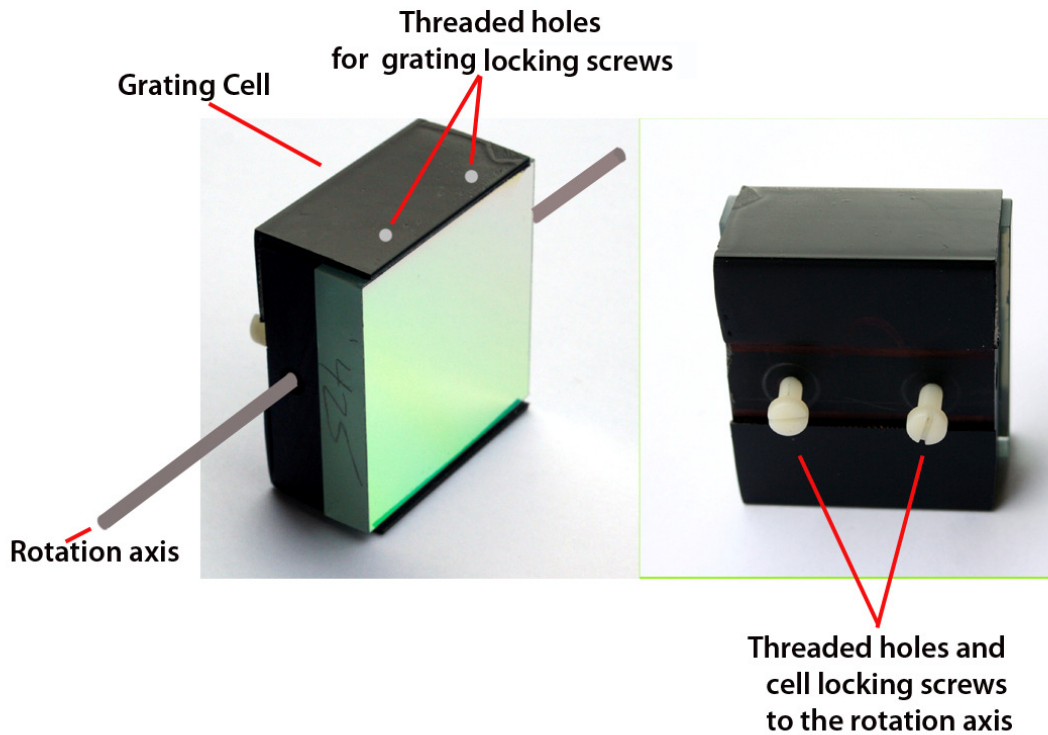
This is a non-secondary element, as it must contain the grating in a perfect way without forcing it into its seat.

I then had to mill a block of PVC Black 50 x 60 mm in my possession about 20 mm thick for a depth equal to the thickness of the grating (9 mm) so as to accommodate it perfectly in its seat, in the rear of which had been applied a piece of good quality double-sided adhesive. Once pressed (keeping it from the sides) on the double-sided adhesive, the grating is no longer moving.

It can, in principle, block it even better, threading an M3 hole in the upper and lower parts of the cell, so as to accommodate two brucoli or screws: this fixing must be carried out with the utmost care, since excessive pressure could affect the performance of the grating (plastic screws or brucoli would be recommended).

The cell was then drilled longitudinally with a 6 mm hole to accommodate the rotating rod, and in its rear part, along the longitudinal hole, drilled with two M4 threaded holes intended to accommodate as many lock screws of the cell itself on the axis of rotation, in order to make it suitable to this.



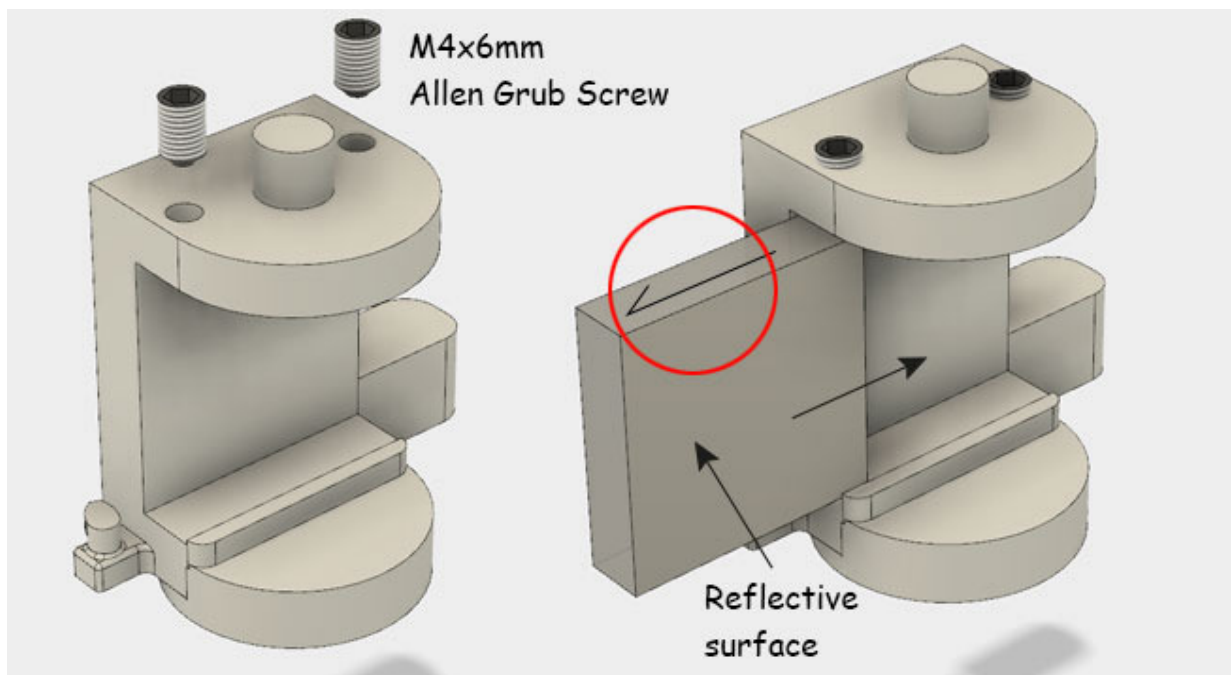


It should be noted, that with the increasing diffusion of 3d printers, the grating cell (as well as other minor components) could now be conveniently printed on PLA or PVC with a printer of good resolution, as from the project "Low Spec" by the Dutch amateur astronomer Paul Gerlach, at the link:

<https://www.thingiverse.com/thing:2455390>

3d printers of considerable resolution and the technical requirements useful for our purposes are in fact available today at prices around € 1000 (\$ 1130), and greatly facilitate the production in plastic material of secondary important components of SHG that do not have to be subjected to excessive loads by their nature, as the case of the cell described before.





The layout of 3D plastic cell for the grating of Low Spec spectroscopy

It is good to specify that the grating cell should be orientated so that the indicating arrow on the side of the grating points towards the optics of the auto collimating spectroscopy for maximum efficiency.

The axis of rotation can be chosen as desired diameter, however, given the very low weight of the cell and the grating, a threaded M6 bar is more than sufficient. The assembly of the grating in its cell (and therefore the holes in the box that accommodates the rotating axis of the cell itself) must be carried out at the minimum distance from the spectroscopy optics compatible with the complete rotation of the grating.

### 3-The Collimation optics

As mentioned, the optics used for VHIRSS was that of an Orion 80 ED (practically equal to SW 80 ED) from 80 mm in diameter and 600 of focal length purchased at € 250, with excellent performance for definition and contrast. Due to its versatility for this use, a similar optics were also adopted for my other two spectroheliographs, Solarscan and POSS2.

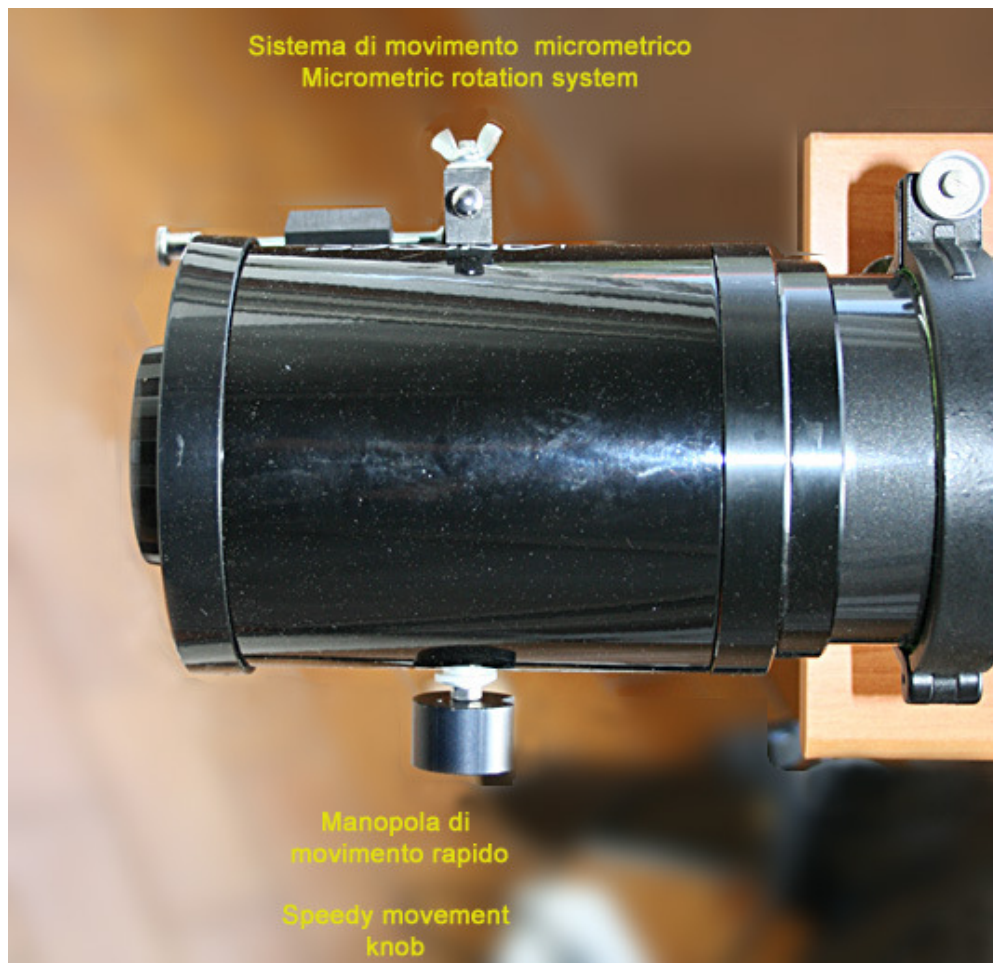
### 4-The Box

The box in which to insert the grating with its cell can comfortably be constituted by the same lens hood of the spectroscopy.

In my case, not wanting to pierce the original lens hood of the Orion 80 ED that constituted the optics of the spectroscope, I used the lens hood of a 100/500 Antares acro refractor already in my possession. About the drilling of the Box (in my case the lens hood), it is better to specify that the holes in which the axis should be housed must be absolutely homologous, better then if obtained with a long bit and a drill column. In the image that follows we observe the hood drilled with the rotating rod. About the mode of rotation of the grating in its cell, which, as you know, is used to select the wavelength and the line of interest, I tried to combine the simplicity of construction with the maximum efficiency of the tilt, basic for the proper use of the instrument.

In stellar spectroscopes, given the low resolution, the modest length of the spectrum and the reduced rotational range, it is convenient to use a micrometer to select the wavelength: in the solar ones with focal length over 5-600 mm, the length of the Spectrum is remarkable, and going from one extreme to the other of the same with a micrometer becomes exhausting and annoying. I thought then to equip the rotation rod of two movements: a rapid, obtained by manually moving a knob engaged on one of the ends of the axis, and a micrometric one on the opposite side, with a tangent arm which is operated, always manually, through a clutch screw that goes to engage on the axis. Obviously the simplest thing would have been to equip the rod with a rotational movement controlled by an electric motor, but, apart from the complication, experience has taught me that entrusting exclusively to an electric motor and batteries a task basic for the operation of a device can be a source of problems. I would recommend therefore, that an eventual motor drive should be applied to the manual micrometric motion, leaving the fast one hand-operated. Of course, for those who have the necessary knowledge of electricity and electronics would not be a problem the use of stepper motors for the fine adjustment not only of the tilting of the grating, but also of the system of focusing of the telescope and the Spectroscope, as it is done in Solarscan.

In the picture below the detail of the two systems of adjustment of the grating cell movement, micrometric one.



In the following figure is observed the detail of the micrometric movement, extremely simple to carry out with household means. The PVC arm inserted in the axis (but it can be of any material, better aluminium), once it is joined to the axis itself by tightening the clutch screw, is controlled by a screw with a spring of recovery of the clearance. It's quite a zero cost system, but very effective and easy to build, and faster than an usual micrometer: it can be modified or improved according to one's ideas.



## 5-The Relay box

This is also an important component of the instrument. In some cases it may be convenient to adapt an off-axis guide that can also be found on the used market at affordable prices.

Obviously, the connection on the eyepiece holder of the spectroscope must be that of the internal diameter of this, of 50.8 mm, which is however restricted to approximately 38 mm by the male adapter 42 x 0.75/50.8 mm. For a box I used a piece of aluminium square 80 x 80 x 3 mm thick closed on two sides with closure caps also of aluminum and blocked with screws M3. The box was then drilled on three sides and threaded 42 x 0.75 to allow, as is observed in the figure, the attachment of the 31.8 eyepiece holder of the slit, that of the eyepiece and the camera and then the connection to the optical tube of the spectroscope normally aligned with the first. In the figure it is also noted that, in the case of VHIRSS, the eyepiece holder of the slit is placed out of axis with respect to the axis of the optical tube, but we will talk later about this interesting point.

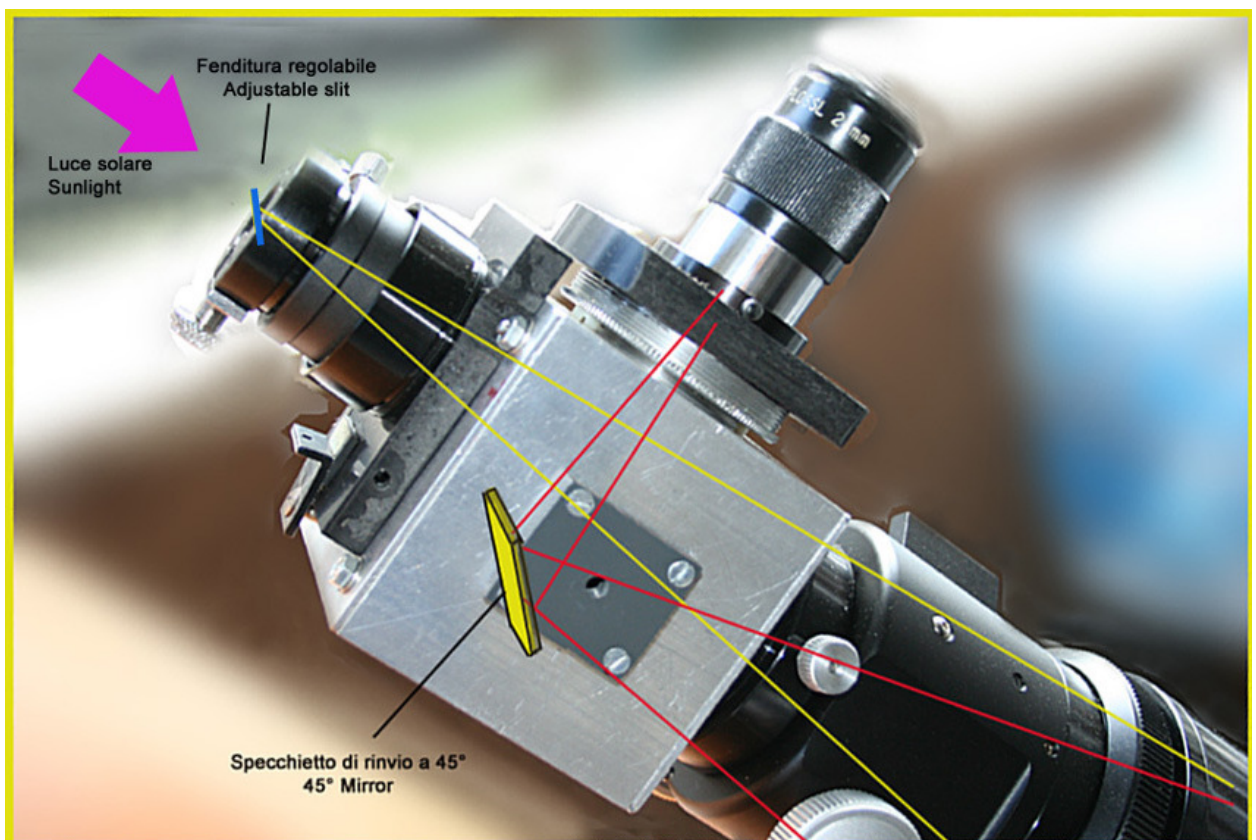


The reference mirror that redirects to the camera the return light beam coming from the grating and the lens (spectrum) should have a dimensions equal to the full light cone of the 80/600 lens necessary to cover at the point of focus the sensor of the camera diagonally, at a distance of about 70 mm before the focus itself, or 530 mm. Given that the largest of the mentioned sensors measures 13 mm (Sony Exmor 174 of Zwo ASI), a mirror size of 15 x 20 mm would be enough.

It is obviously necessary, positioning this mirror into its cell, to be careful that it has a length such that, when placed at 45°, does not interfere with the light beam coming from the telescope through the slit.

Of course in place of an aluminized mirror can also be used a prism of suitable size, but the assembly could be a little more complicated.

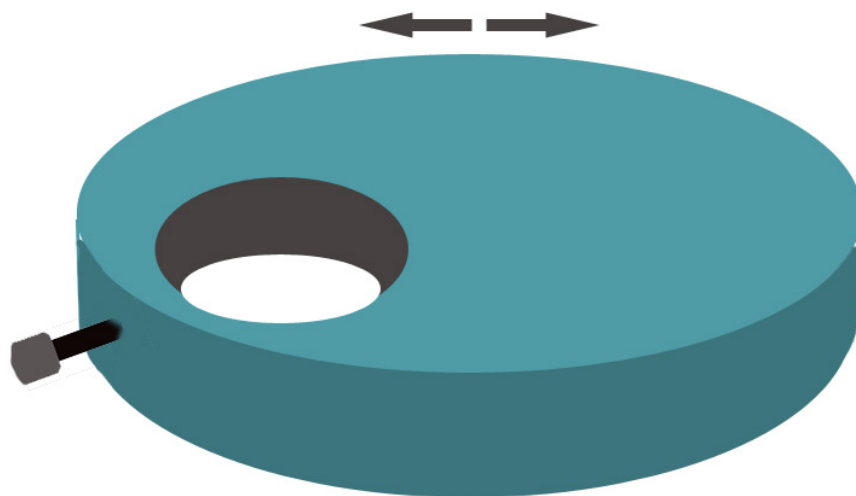
With regard to the assembly, the mirror cell or prism should be strictly assembled in such a way as to allow the optical beam to be adjusted on three points at 120 °, similar to the Newton diagonals cells: however in practice I have noticed that this adjustment, which does slightly complicate the assembly, is not absolutely necessary and can be partially replaced by three regulating screws at 120 ° in the base of the camera-eyepiece holder.





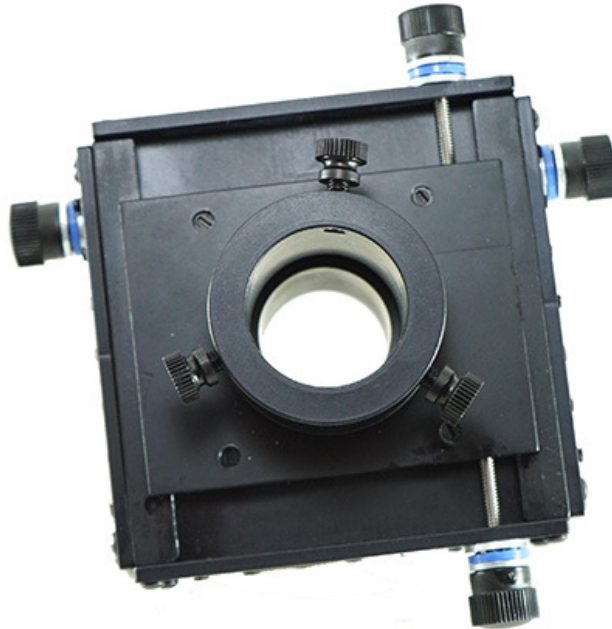
One of the features of VHIRSS compared to other built by my self Hires spectroscopes is the positioning of the slit off optical axis. This variation was dictated by the intuition that a larger angle could allow for a linear dispersion and a better resolution. Now, the displacement of the center of the slit with respect to the optical axis was about 7 mm, equal to 1 degree on the plane of the grating: if in the formula of the linear dispersion (5) to Pag 99, it replaces that angle to that  $= 0$  of the Littrow configuration with non-blazed holographic gratings we obtain, with the slit closed at 30 microns, a dispersion of  $3.75 \text{ \AA} / \text{mm}$ , equal, with a camera with pixels of  $4.65 \text{ \mu m}$ , to  $0.017 \text{ \AA} / \text{pixel}$  and a resolution  $R$  of 59660 in H Alpha. These values are close to those I obtained in the field with VHIRSS and the DMK 41 in the H Alpha zone for the dispersion ( $0.019 \text{ \AA} / \text{pixel}$ ) and resolution  $R$  (43700) and much higher than theoretical calculated for this opening of the slit at Pag 99. It seems therefore be confirmed that this displacement could make an improvement in linear dispersion and resolution.

Another particular feature of the instrument is the 31.8 off-axis eyepiece holder, which allows the line of interest to be centered even if the spectrum, as expected, moves slightly along its axis as the wavelength varies. An alternative to this system could be to make a grating cell adjustable with 3 screws at  $120^\circ$  and therefore slightly decentrable, however this system does not excites me due to the suspicion that a grating placed obliquely respect to the optics of collimator can produce optical aberrations as coma and astigmatism.



Scheme of rotating off axis eyepiece holder of VHIRSS

A commercial accessory useful to achieve the same effect is the X-Y Finder, which however has the defect to cost about € 175, while the device that precedes, if made in black PVC by a turner, should cost around € 20-30 approximately.



It is good to specify that, in case you do not opt for the solution of the slit off axis, the box with the slit and the eyepiece holder for the camera can be advantageously replaced with a good off axis guider, however, mounting so that the prism is facing the grating, rather than be placed towards the telescope.

I have owned and used several off-axis guiders for such use, but the best of all was that of the image that follows, marketed by some Italian and German sellers, and fortunately purchased by me on the second hand market at € 80. This OAG, in addition to being absolutely robust, has the merit of being able to extract the large prism as you will, so you can position it at the best point, and, after extracting it completely, turn it to the opposite side, toward the grating, as necessary in our case. It needs, however, connecting rings and, of course, a male adapter of 50.8 mm to be able to enter the eyepiece port of the spectroscopy optics focuser (in my case of the Orion 80 ED).

Of course it can be used in principle any off axis guide, as long as it has a prism of size appropriate to the optical beam that is intercepted.

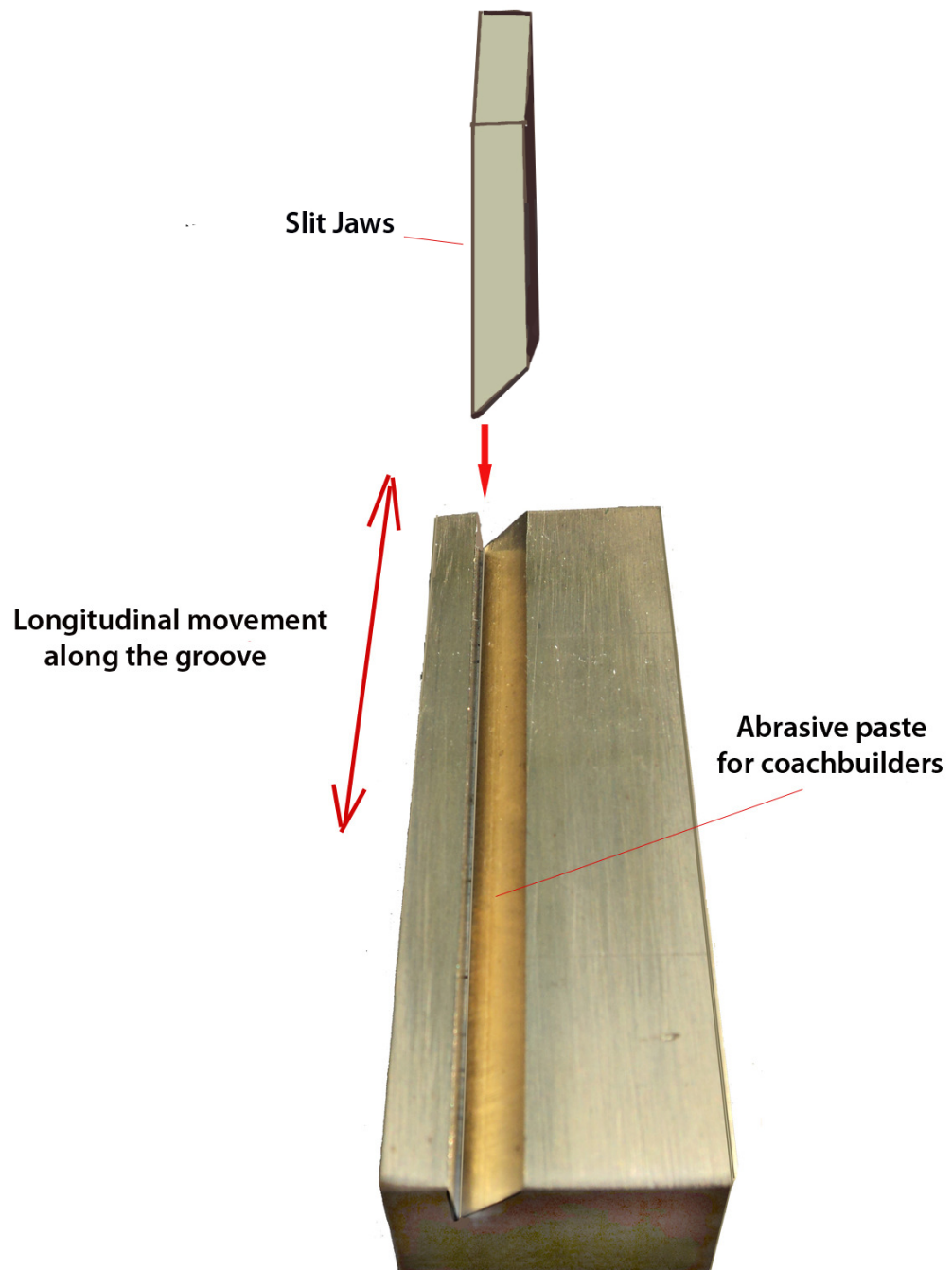


## 6-The slit

Last I left the slit talk because this component, together with the grating, is the determining factor for the resolution of the system and it is also the most problematic one, as we have seen, from the point of view of jaws machining and general mechanics. We have also seen how a slit worthy of that name can cost considerable sums and not be adaptable to the needs of a delicate instrument such as a spectroheliograph. Many recommend the machining of the jaws in their own, but this is not easy without owning and being able to use a mechanical workshop with milling and emery machines.

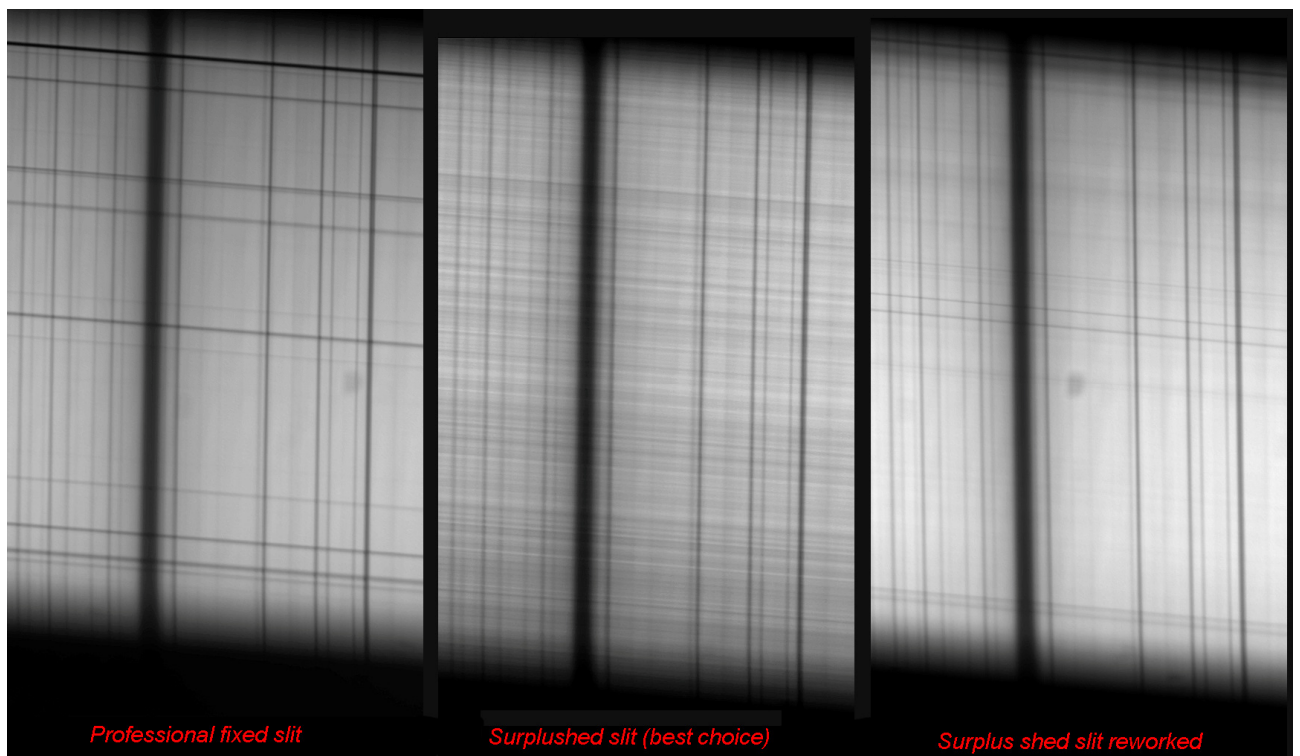
For VHIRSS I adopted a hybrid solution, that is to buy a low-cost commercial slit and to improve the finishing of the blades by myself.

The slit is that of Indian production and marketed by Surplushed <https://www.surplushed.com/pages/item/m1570D.html> the one we talked about previously. It was disassembled and the blades controlled under a 400 X microscope, after which the edges of the same were worked making them pass on of a specially made brass tool, interposing abrasive paste for coachbuilders. After a few passes at medium strength, the improvement was also evident under the microscope, and they were reassembled.



Obviously, the finishing work of the slit jaws can be carried out even without the apparatus shown (which in practice acts as a guide), inclining the blades appropriately on a perfectly smooth surface of hard plastic or, better, of glass, interposing the abrasive paste for coachbuilders, if you do not have cerium oxide.

Below is a comparison of this modified slit (the last on the right) with one of the best of SShed (in the center) and with a fixed professional (last on the left) on a spectrum of the H $\alpha$  line, which confirmed the usefulness of the work carried out: the horizontal lines of the transversalium are in fact almost completely gone and the spectrum is more clear. All this obviously with the same opening of the jaws.



## 7- Final checks on the correct assembly of the instrument

Once the various components have been assembled, before proceeding to a field test, it is advisable to carry out some checks.

- Check that the slit is placed exactly at the point of focus of the collimator;
- Check that the grating-optics of the refractor distance is the minimum possible;
- Check the alignment of all components (telescope-slit, reticle, deviation mirror or prism) with a laser collimator inserted, where possible, into the lens hood of the telescope with a special adapter (it is easy to make it with a round of PVC of outer diameter equal to the inner one of the lens hood



and, at its center, a hole of 31.8 to accommodate by pressure or with a blocking screw the laser collimator).

Verify the instrument's functionality in the field by observing the solar spectrum lines and focusing both the telescope and the spectroscope optics. Finally check, indoors, with a neon lamp or with low consumption (better) the dispersion and resolution provided by the instrument itself.

VHIRSS is currently operative for spectroheliography in Hydrogen Alpha light at 6562.8 Å, and for this purpose it has been equipped at the output of the telescope focuser with a 10 nm H $\alpha$  filter that selects the incoming wavelength and contains diffused light, increasing the contrast .Be careful, anyway, to place the filter non too close to the focus point, or (better) after an IR-UV cut filter that cuts the UV radiation harmful for the coating of the filter itself, keeping in mind that such IR-UV cut is to be removed in case of CaIIK line observations.

## **A bit of accounts**

At the end of this discussion on the constructive details of instruments like VHIRSS, someone could observe "yes, that's fine, very interesting, but how much would it cost? Probably not all fans of self-construction can afford it " the question would be legitimate, and the doubt that it does the same, so I will try to make the point, even if approximate, about the costs, distinguishing two cases: the purchase of a part of components on the second-hand market, as in my case, and the purchase of each of them new, from traders in the sector. My VHIRRS costed about 600 € (about 680\$), but basically buying only grating (new) and the Orion refractor (used) and using components already in my possession, and not all amateur have this possibility.

### **1- Mixed purchase, new and used**

The components of the spectroheliograph available on the used market are certainly: Refractor optics, as in my case; the slit, the deviation box or, in its place, an off-axis guide.

The ones to buy new are definitely the grating and the iron or steel bar supporting the structure.

In detail, applying the costs of the new and the average costs of the used (in dollars):

- Refractor 66/400 Ed or similar to be used as a telescope (used) ..... 250
- Refractor SW 80 ED or similar as optics of the spectroscope (used) . .300
- Off-axis guider(used) .....100
- Edmund holographic grating 2400 g/mm (new) ..... .300
- Steel bar from 1 meter 30x30 or similar (new) ..... 10
- Small metal parts and small accessories ..... 40

Total .....\$ 1000

## 2- Purchase of the new only

- Refractor 66/400 Ed or similar to use as a telescope .....400
- Refractor SW 80 ED or similar as optics of the spectroscope .....500
- Off-axis guide  
.....200
- Edmund holographic grid 2400 l / mm (new) .....300
- Steel bar from 1 meter 30x30 or similar (new) .....10
- Small metal parts and small accessories ..... 40

Total .....\$ 1450

This in the hypothesis that we want to use ED refractors (which I still recommend); in the case of purchase of commercial achromatic optics, the prices indicated may decrease by between 10 and 30%, depending on the type and quality of the optics. The cost of any accessory filters was not considered, assuming that almost all amateur astronomers who deal with CCD shooting have some.

Let's now have a simple consideration: with an overall cost oscillating around 1000-1500 \$ or the cost of a low-end H alpha filter you would get an instrument that would be able to image the sun not only in H alpha light, but in all the wavelengths of the elements of a certain interest (H $\beta$ , H $\gamma$ , Na1 and 2, Mg, Fe 1, CaII K and H, etc.), without considering the other uses of the instrument (Solar spectroscopy, measurement of solar magnetic fields, differential spectroscopy , etc).

## 2-POSS2

POSS2 (POrtable Solar Spectroscope 2) is in practice a clone of VHIRSS, as it was built with the same exact criteria, even if a telescope was used first of the 80 mm D and 400 mm focal lengths (f5) then a 70-mm Celestron f 400 (f 5.7), both with acromatic objectives: to bypass the problems arising from the secondary spectrum for shooting in the near UV (CaII K and H) to which the instrument is dedicated, before the focus of the telescope was inserted a narrow band filter (about 50 nm) centered on 400 nm.

The spectroscope optics is a Skywatcher 80 ED, practically the same as the ORION 80 ED of VHIRSS.

The instrument is currently dedicated only to ionized Calcium light CCD shots for which it has been optimized and in this context is able to obtain images of all respect, similar to those of professional observers.

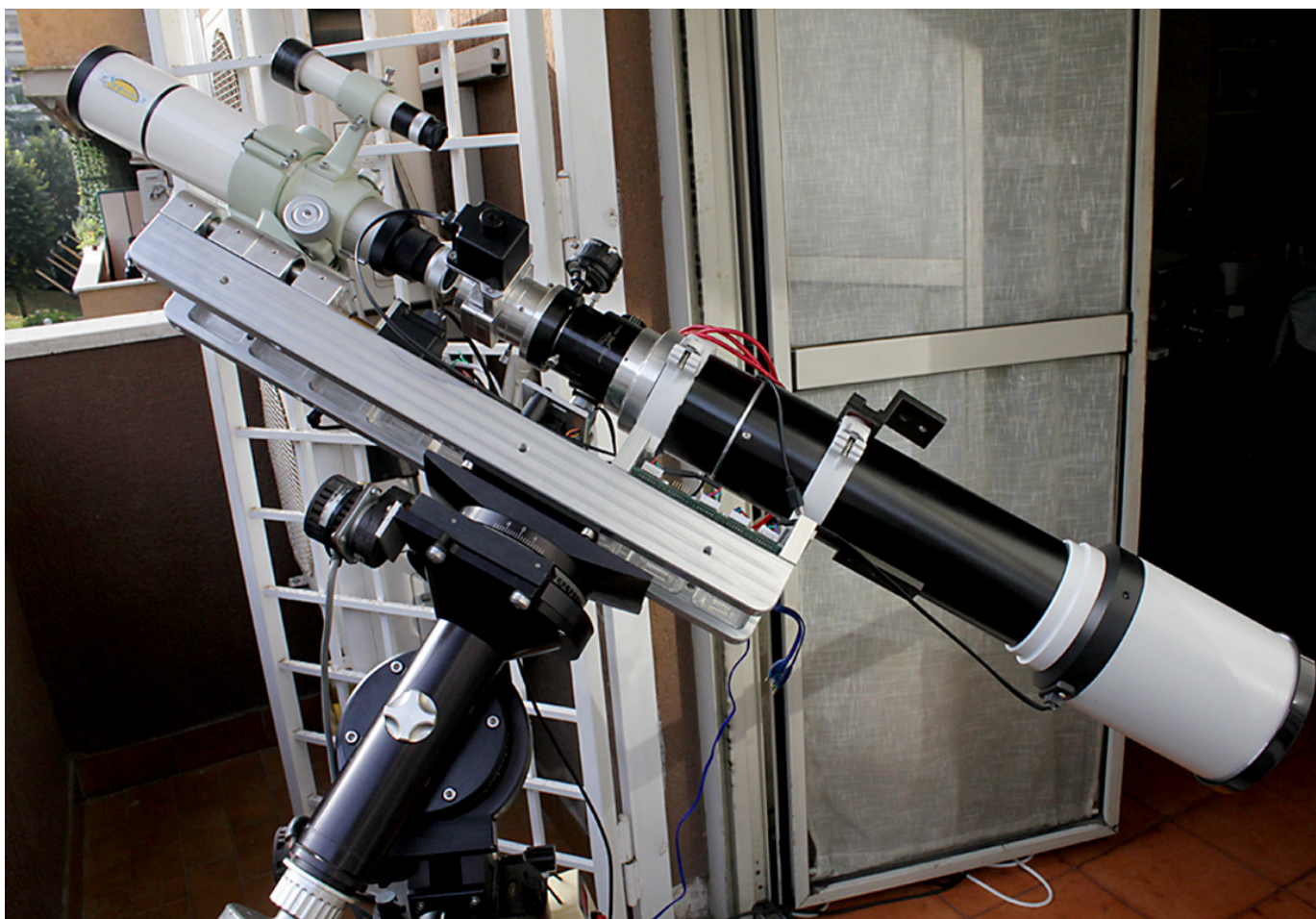


An image of POSS2



### 3- Solarscan

The Solarscan project, which could be realized thanks to the competence, commitment and innovative capacity of Avalon Instruments, a factory of astronomical instruments near Rome <http://www.avalon-instruments.com/>, constitutes the logical evolution of VHIRSS, in the idea of a remote operated spectroheliograph with a specific software in all its functions, from focusing of the telescope and the spectroscope and the opening of the slit, to the movement of the grating with very high-resolution stepper motors. An instrument of such features needed quality components, and therefore I chose a small, but very efficient Takahashi FS 60 C that with its ratio  $F / D$  of 5.9 it was close to that of  $f 7.5$  of the usual SW 80 ED, also present in this instrument as optics of the spectroscope; the grating is always a Edmund holographic one of 2400 g/mm. Of course this instrument, built with professional criteria and tolerances, provided performances of high level, to the point that I later decided to dedicate it to a more challenging activity, such as the measurement of the magnetic fields of sunspots by Zeeman effect.



Solarscan on my Losmandy G11 equatorial mount





Solarscan on a Avalon Instruments M1 equatorial mount

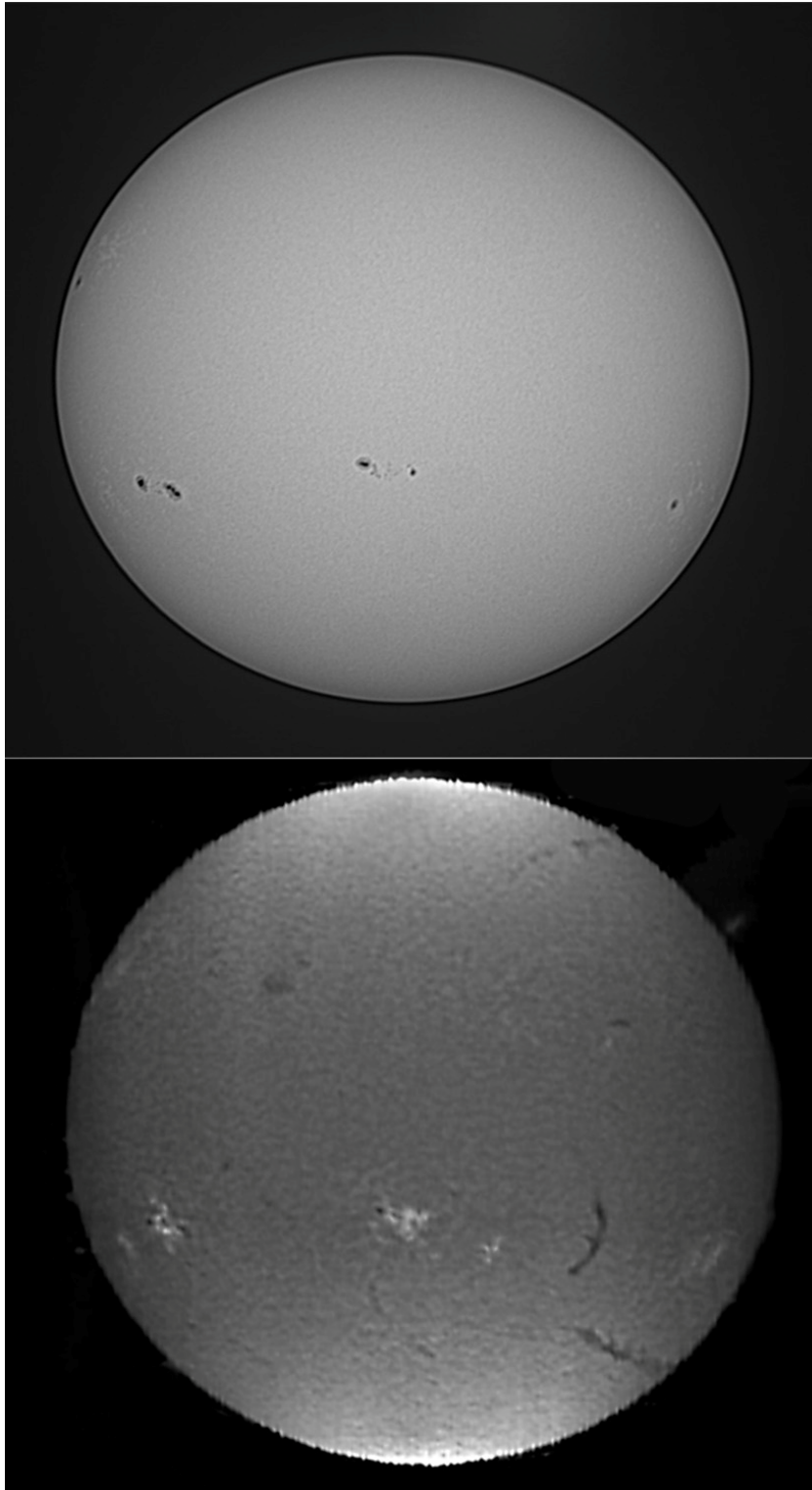


The weight, grown to 15 kg over 110 mm in length due to the sophisticated and robust mechanics, required the use of mounts of a high level and load capacity such as Losmandy G11 and Avalon M1.

#### **4-HIRSS2**

Born as a classical spectrograph, HIRSS (Hi Res Solar Spectroscope 2) was then transformed into an autocollimating Littrow with the usual already tried scheme. The only variation compared to the others similar instruments was the realization in economy, with two acromatic Antares refractors (an 80/400 for the telescope and a 100/500 for the spectroscope) purchased both on the second hand market for a total of 150 €, but of good optical quality, and a 1800 g/mm Thorlabs grating of the cost of 170 €. Ultimately the instrument had cost me, everything included, about € 400 (about 455 \$). In the image below HIRSS2 in a white light solar telescope/ spectroheliograph, thanks to a flip mirror and a Astrosolar filter. With the filter inserted and the flip mirror lowered, it imaged the Sun in white light, while removing the filter and by raising the flip mirror, a spectroheliogram was made in the line of interest. The quality of the spectroheliographic images is not the best and certainly not at the level of the other instruments, but yet acceptable. It is now used by myself exclusively for testing and for some interesting experiments. Last but not least, the acro 80/400 refractor has been replaced with a good 60/415 vintage with less weight and dimensions and similar performances



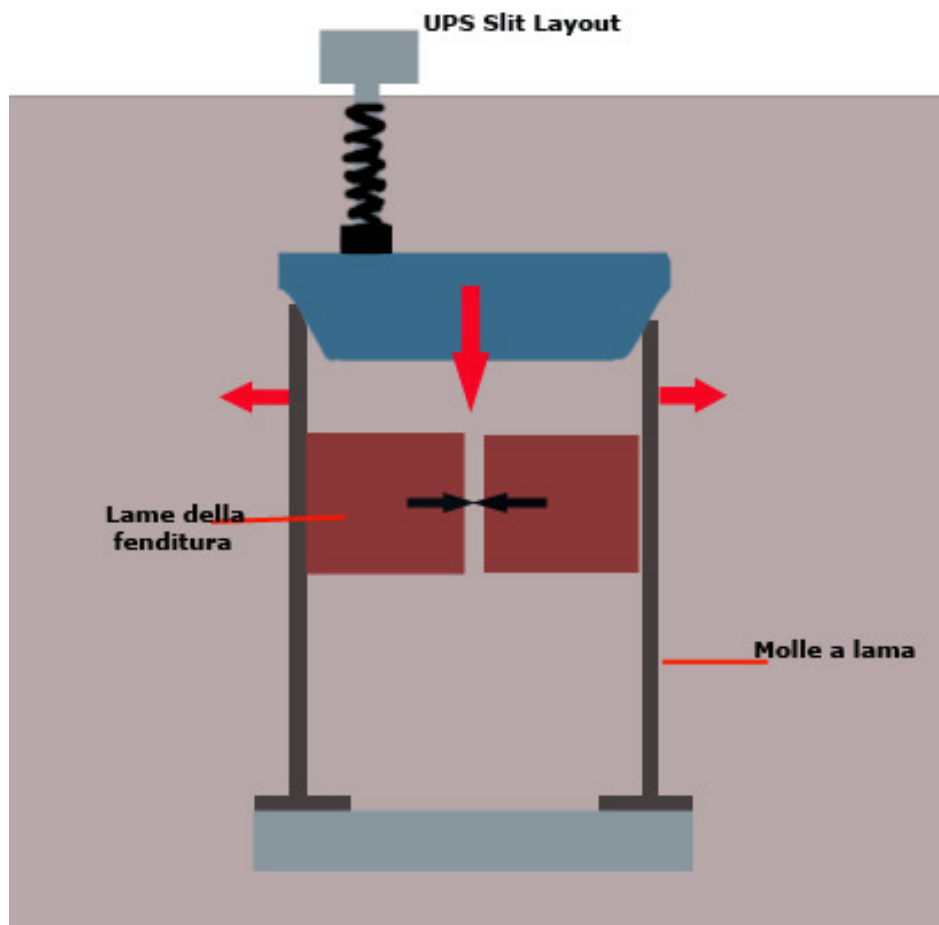


The contemporary shooting of Sundisk in WL and Halpha of HIRSS2

## 5-UPS

UPS (Ultra Portable Spectroeliograph) is the smallest and most manageable of my self-made spectroeliographs, and that's what I normally use when I perform public demonstrations at astronomical events.

Its small size, however, does not affect the performance, which is very respectable despite using a grating of 25 mm and only 1200 g/mm. The optics of the spectroscope, of 36 mm and 300 of focal length, is derived from military surplus and are absolutely excellent, while the optics of the telescope is made up of an equally excellent 60 mm and 420 mm focal length Stein Optics vintage refractor. The particular solution of this instrument is given by the unique slit obtained from the use of components of a professional slit, adapted for astronomical use. Its characteristic, difficult to find at reasonable prices, is that of the simultaneous closing of the jaws in the center, obtained with a sophisticated system of blade springs, as can be seen in the figure A system of this kind is absent on all amateur slits and on most of the professional ones and ensures perfect closure and opening of the blades.







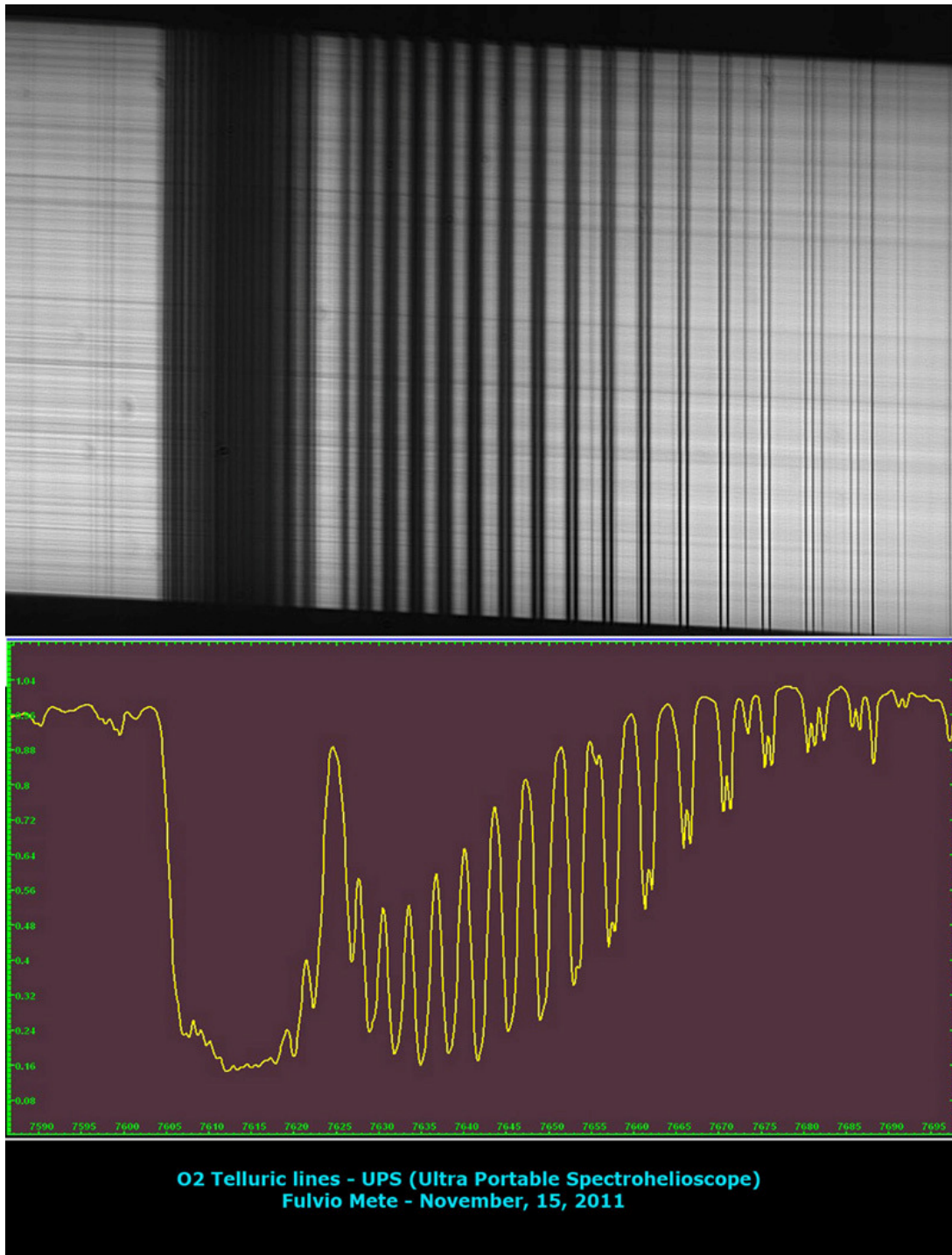
UPS layout



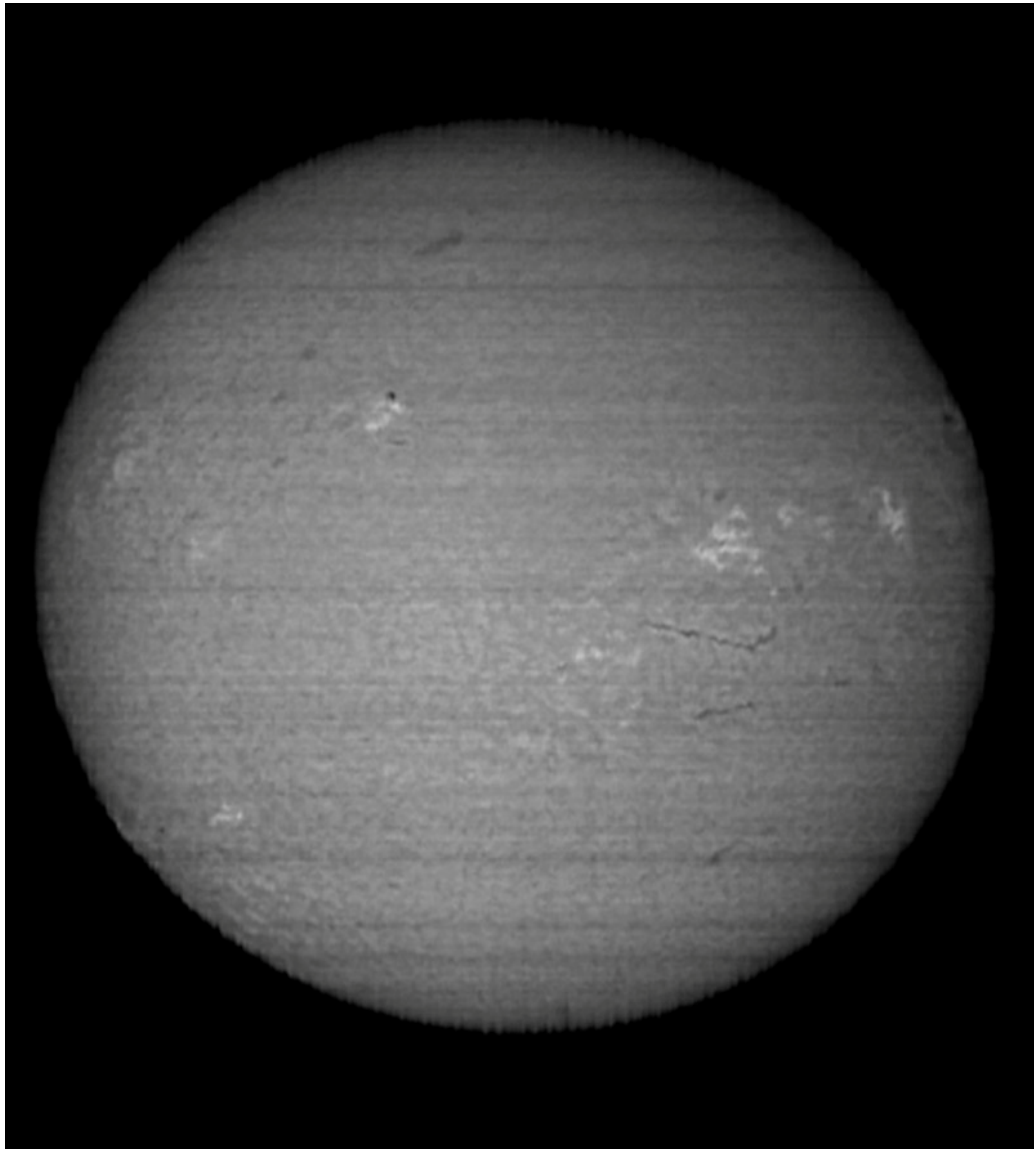
This is a small instrument of only 70 cm in length for 3.5 kg of weight, capable, however, of respectable performance. You can observe, in the center, the box with the slit which has been mentioned.



UPS on the Losmandy G11 mount on my balcony.



The good resolution provided by the instrument on the telluric lines of the O<sub>2</sub> belonging to the Earth's atmosphere.



A spectroheliogram in H alpha light by UPS

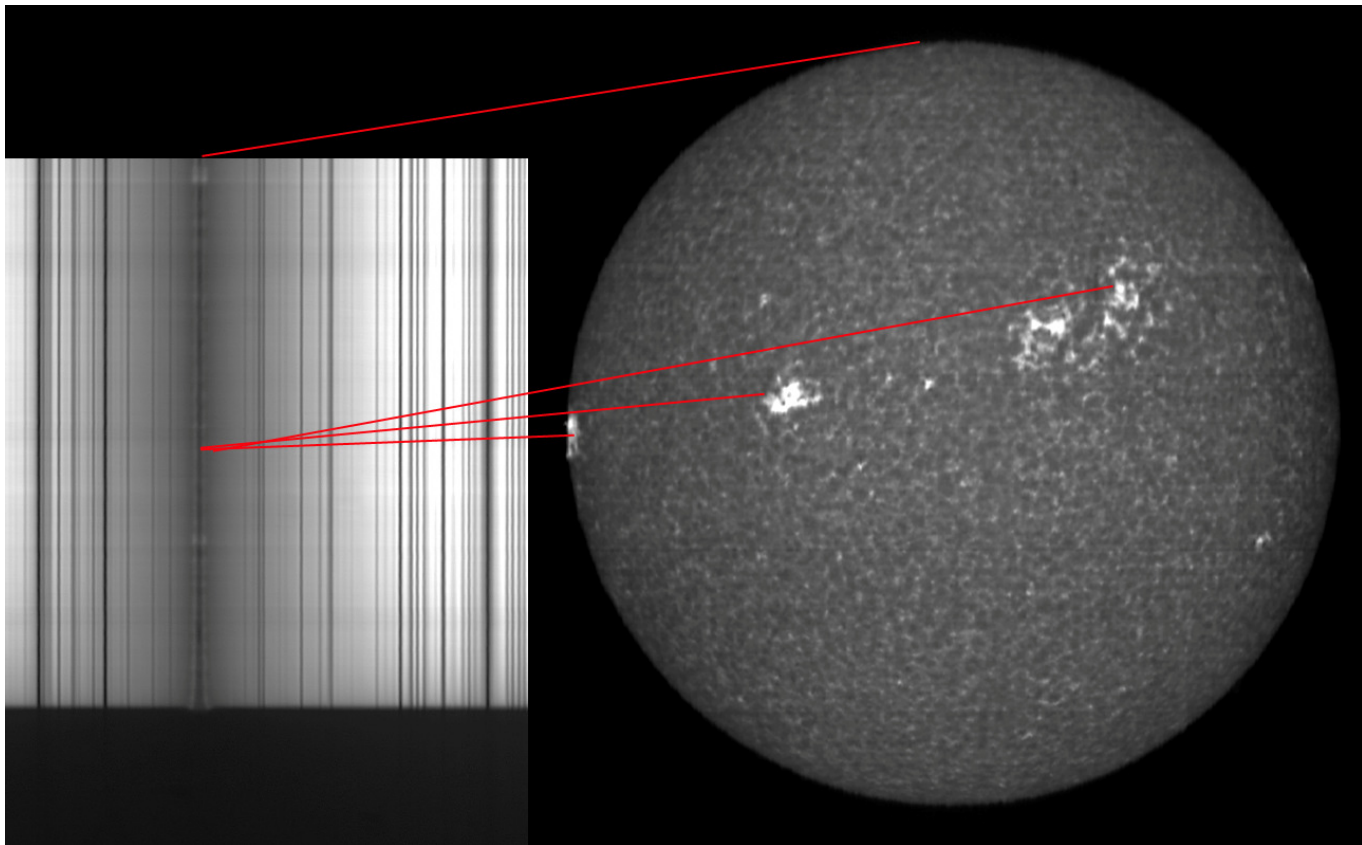
### **Summary of operations to be performed in digital spectroscopy**

#### **1- Focusing**

The focusing of a SHG (Spectro Helio Graph) in Littrow configuration may not initially seem a trivial thing, but once practiced it becomes a routine operation. It is done in steps, focusing both instruments, telescope and optics of the spectroscope, until an optimal focus point is obtained.

But let's see in detail:

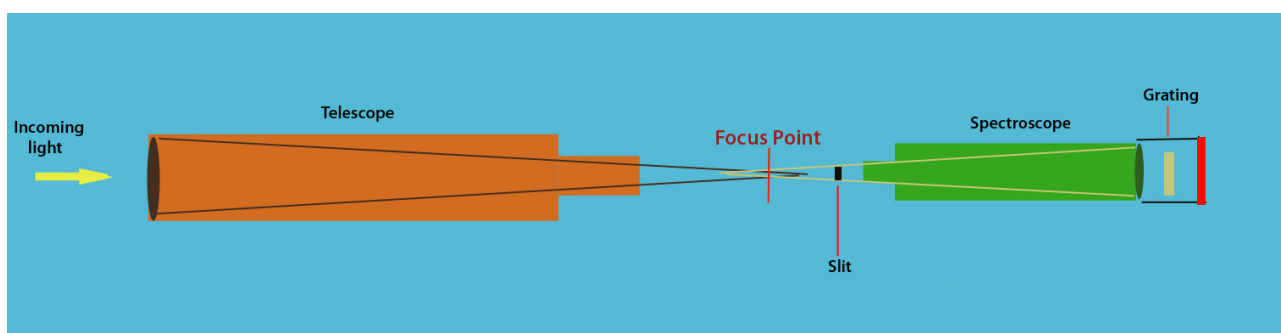
First of all, to understand better, it's necessary to clarify a fundamental point: how the image of the spectrum translates into that of the solar disk after software synthesising operations. In practice, the upper and lower edges of the spectrum correspond to the edges of the solar disk in the final image, while the chromospheric details observed inside the lines constitute the details (faculae, filaments, etc.) that can be observed on the disk, as shown in the following image.



The first focusing operation, once the line of interest is centered and the slit opened to the working position, will be to focus the telescope on the slit itself visually using an eyepiece, until we get an incised spectral image. Once the camera has been inserted into the eyepiece holder, the telescope focusing system will be operated until we see on the monitor an image of the edges of the spectrum similar to that of the figure; probably the lines will not be in focus, then it will be necessary to operate on the spectroscopie focuser (in the case of the Littrow on the focuser of the ED refractor) until the lines are clear and defined and, even more, so are the chromospheric details inside the lines; if, after this operation, the edge of the spectrum has returned slightly out of focus, it will be necessary to make a final readjustment on the telescope, until the spectrum appears as

in the figure, with the edges and the details inside the lines perfectly focused.

All this is explained by the fact that the focusing point (given by the factory layout) of the telescope and the spectroscope intersect each other in the optimal point of focus. In other words, while the focus (at infinite) of the telescope is first placed on the slit, the one of the spectroscope (originally also on the slit) is taken a few cm back to "draw" the telescope focus, this, on the other hand will also go a little back to focus the whole system. For example, in POSS2 the focus point of the system is 370 mm from the 70/400 telescope and 560 mm from the lens of the SW 80/600 refractor.



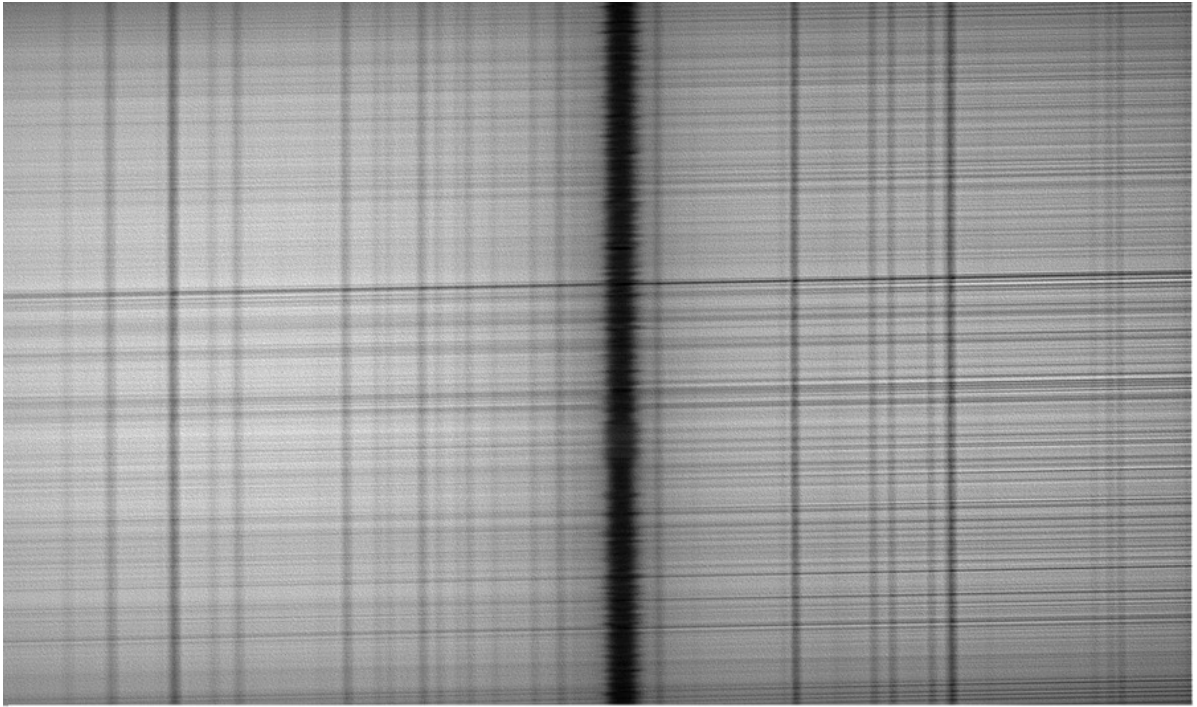
A very common mistake, happened several times to the writer, was forgetting to put the jaws of the slit to the usual 15-30  $\mu\text{m}$  of opening: causing the lines of the spectrum to be blurred and still out of focus, as long as you act on the focuser of the spectroscope, so you will need to close the slit to see them clear and focused.

The image of the line on the PC screen should also be as dark as possible, and the outline overexposed, as in the image of the line H $\alpha$  below. The horizontal jaggedness of the line is due to the plasma columns in ascending and descending motion in the solar atmosphere (supergranulation).

In the case of H alpha, the following must be observed:

After setting the first parameters of the camera the line must appear dark, with horizontal streaks, as we said. In a subsequent phase, before the shooting, the line must be overexposed until observing the chromospheric details inside the line itself, on which the final focus will be carried out.





## 2- The acquisition of the video

I now move on to the operations necessary for a good acquisition of a solar image with a digital spectroheliograph of the type illustrated above, assuming that it is placed on a motorized equatorial mount.

### Time and time of the year

First of all, it is hardly necessary to mention that it is important to choose the hours when the negative effects of seeing, which affect the images, are less noticeable. The morning hours, when there is no need to monitor a given phenomenon in other hours, are in my opinion, preferable. Obviously the season and the height of the sun on the horizon are of great importance; the best results are, based on my experience, in late spring and early autumn.

### Localization

The location of the instrument is also important: for those who can choose it, a garden or a grassy lawn are much better than a balcony or a terrace, to avoid rising of hot air masses.

### The acquisition

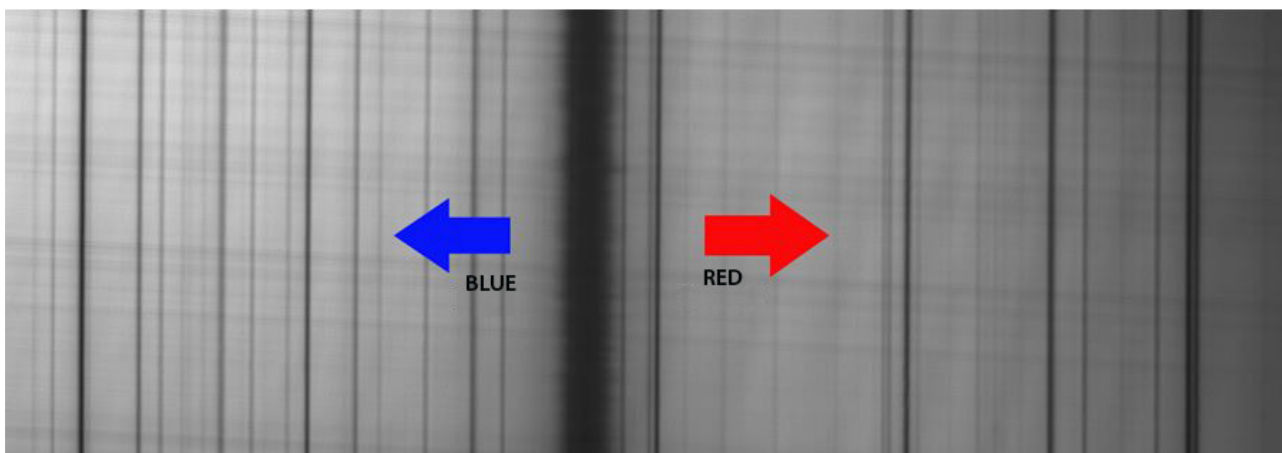
Once the Sun is pointed so that the disk projected from the telescope optics appears onto the slit, insert the camera into the eyepiece holder with the long side of the sensor parallel to the AR axis, identify the line of interest oriented along the Y axis, (along the short side of the screen) and carry out the focusing operations described above. At this point it is necessary to check the appearance of the spectrum that is shown on the monitor, paying attention to the following points:

#### a) Spectrum orientation

It should also be kept in mind that the positioning of the camera corresponds to a correctly oriented spectrum, ie with the blue on the left and the red on the right of the image on the monitor, as in the figure

below. Online catalogs are useful for checking orientation , among which, in addition to that of Moore, the following is very useful:

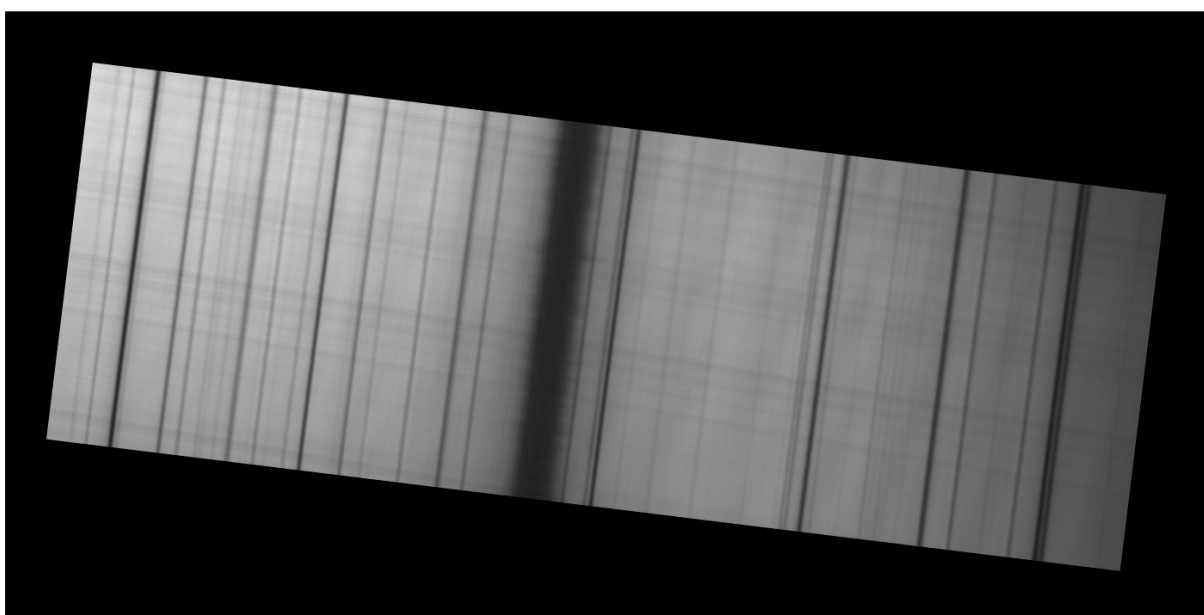
[http://bass2000.obspm.fr/solar\\_spect.php](http://bass2000.obspm.fr/solar_spect.php)



The correct orientation of the spectrum

b) The "Tilt" of the spectrum

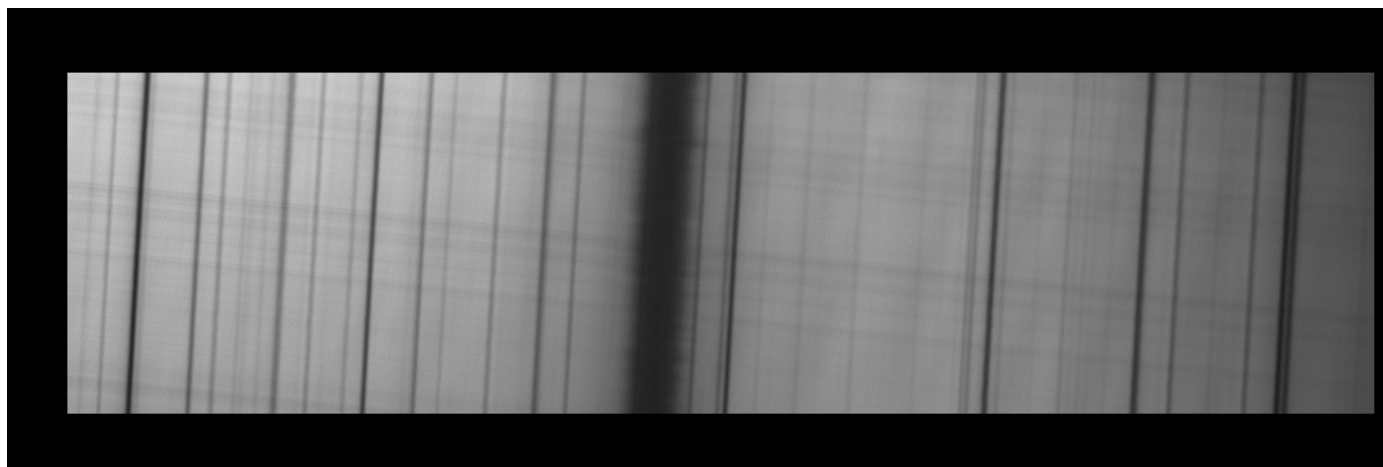
It may happen that the camera is not correctly oriented with respect to the spectrum and that this does not appear straight on the monitor as in the figure that follows; do not worry, just turn the camera slightly to the left or right to straighten it up.



A tilted spectrum

### c) The "Slant"

If, after performing the tilt correction operation, the spectrum appears straight, but the lines inside are slightly inclined with respect to the vertical axis of the spectrum itself, then it is "slant", and the correction must be made by trying to make the slit plane exactly parallel to the rotation axis of the grating, by slightly turning the slit on its own axis. In any case, some computer programs such as IRIS, BASS and Vspec, allow to correct the slant via software.



The Slant

### d) The "Smile"

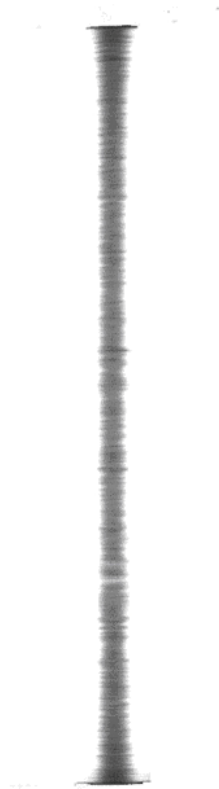
The Smile consists in the curvature of the lines of the spectrum, especially when using slits of a certain length. In the Littrow used by myself this phenomenon has hardly ever appeared; however it can be corrected via software with some programs like Spectral Line Merge.

### e) The orientation of the line along the axis

Some amateurs place the camera so that the line of the spectrum is oriented along the X axis instead of the Y as in the previous images, to gain in resolution. Personally I find this solution not convenient and, from tests done, I think it does not lead to appreciable gains in the final image: in any case, the choice is left to the habits of the amateur astronomer.



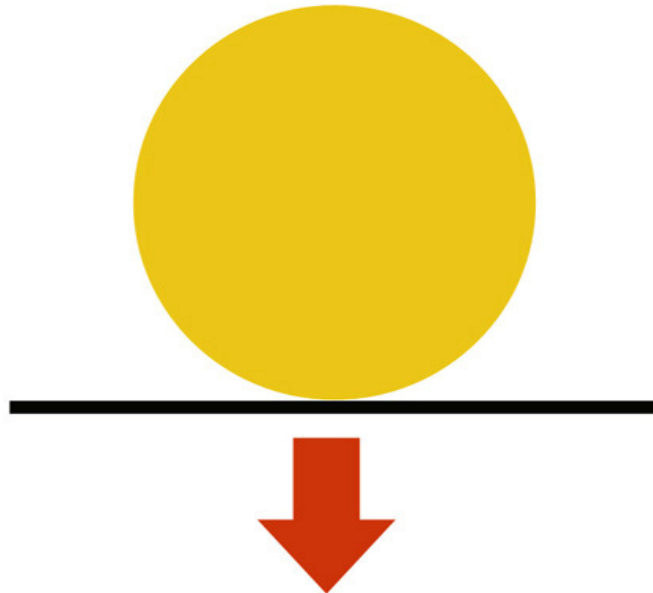
Immediately before the acquisition, the spectrum of the line (in the example always the H $\alpha$ ) after selecting the ROI, will appear roughly as shown:



After having possibly corrected the anomalies of the spectrum, focused on the chromospheric details of the overexposed line, and selected the line itself with the ROI like in the image above, you'll bring the solar disk tangent to the upper edge of the slit using the fast motions of the mount and pressing the W (West) button of the hand controller (in the case of the FS2 controller this is the case but it should also be the same in the other motorisations): the spectrum image will shrink and disappear from the PC screen. Then, you'll launch the acquisition of an AVI video (other formats are not generally supported and must therefore be converted). As Codec you can use the Y800 or other, according to the software of the camera, but in any case it is recommended to make a selection ROI (Region Of Interest) around the line, which greatly decreases the weight of frames to download; the frame rate will depend on the camera and the

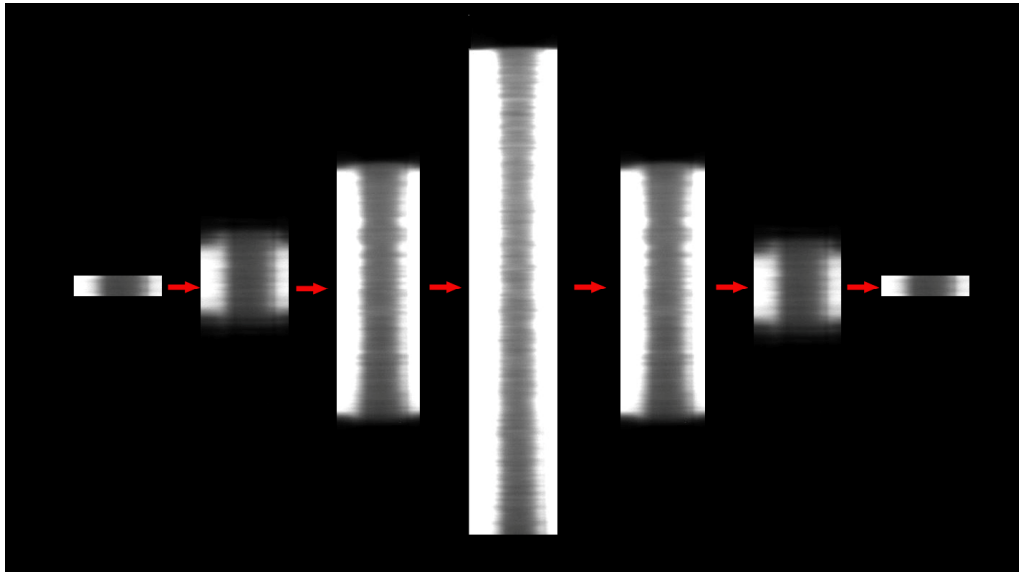


power of the PC: I normally use with the DMK 41 a frame rate of 7.5 or 15 and with the DMK 51 a FR of 7.5 or 12 fps, with good results. Contemporarily to the launch of the video you must stop the RA motion of the equatorial mount, letting the solar disk sliding slowly onto the slit, from east to west.



As this happens, you will observe the spectrum that grows, reaching the maximum size, then shrinks until it becomes a thin line disappearing from the screen. At that point, after another 3-4 sec you can stop the video and eventually turn on again the motorisation of the mount, by pressing the W key of the controller to bring the spectrum back to the center of the slit and again visible on the PC screen.

In the image that follows an example of how the selected line appears (in the example the H alpha) as the scan proceeds. At the beginning and at the end of this the screen is dark, finishing the outlines of what will then be the final image of the solar disk.



A scan lasts an average of 120 sec (plus a few additional seconds for the black part of the image), and the image size will depend, as we said, on the used frame rate.

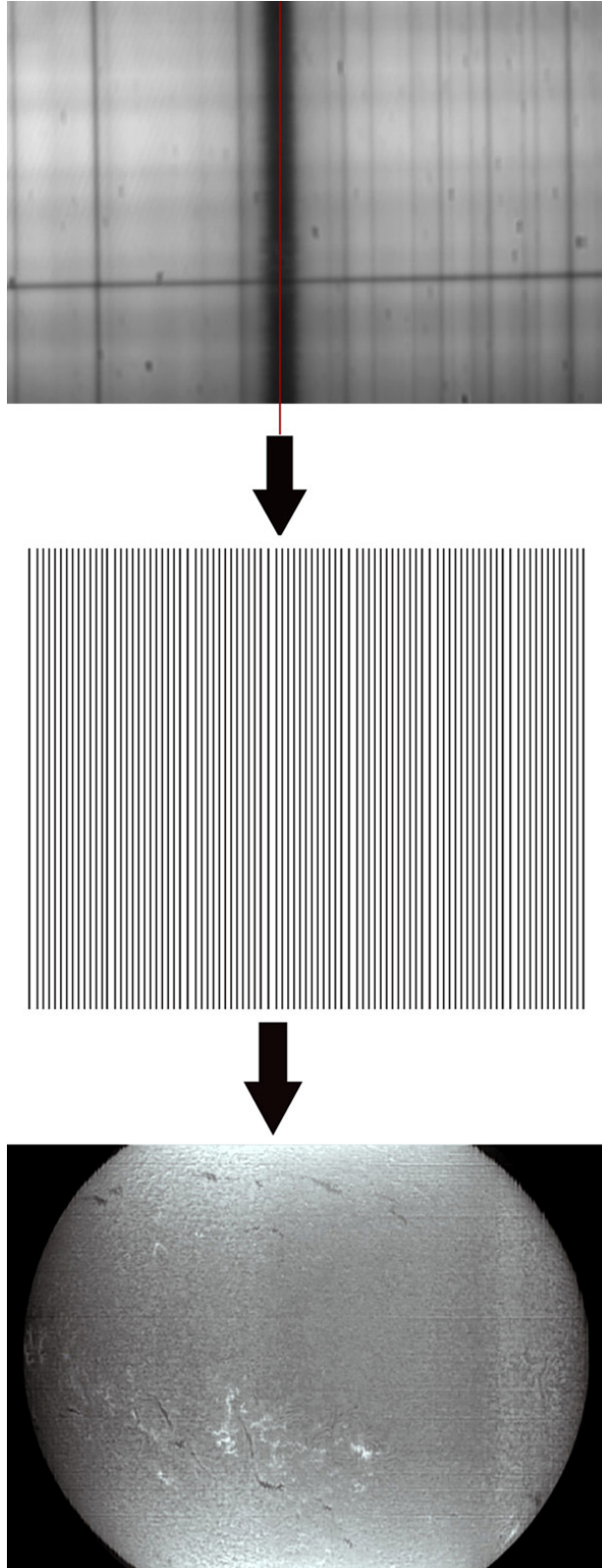
### Digitization and image construction starting from the spectrum

Before talking about the software, a mention of the methods of execution of the algorithm that provides for the construction of the final image, and which replaces the output slit and synthesizers of the traditional spectroheliographs.

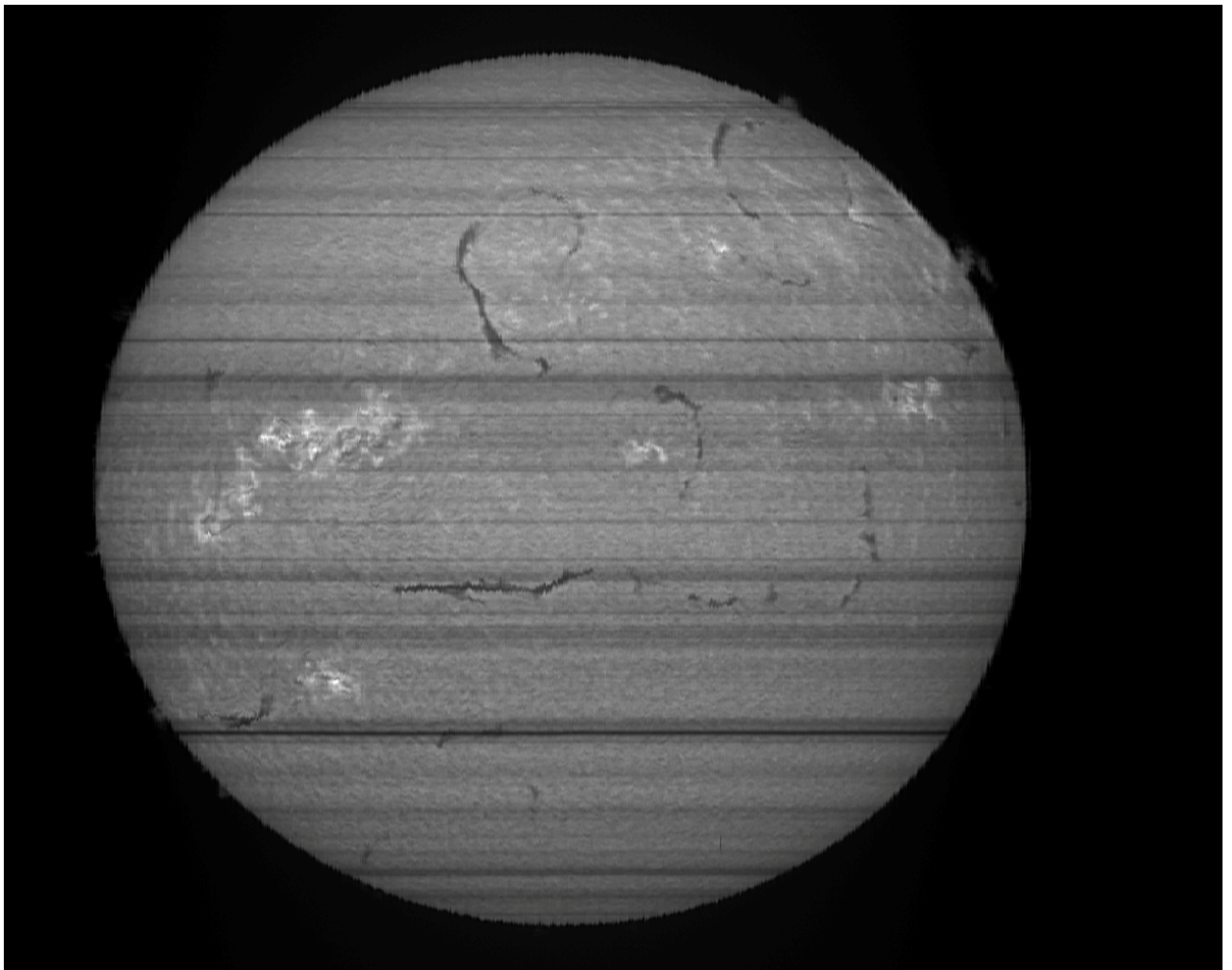
In practice, once you have chosen the column of a pixel corresponding to a point of the spectrum, usually the center or the edges of the line of interest, all the different software do nothing more than adding to that column all the others of the same pixel for all the frames that make up the video. Therefore, for example, assuming that the total frames of the video obtained with the scan are 1200, we will have an image of 1200 pixels on the x axis and as many pixels as those native to the camera chip on the Y axis.

The procedure therefore allows the total emulation of a conventional type spectroheliograph, allowing to associate to each pixel of the image of the spectrum along the X axis and therefore to a given wavelength of very small dimensions (with VHIRSS and a DMK camera with pixels of 4.65 microns, it is equal to about  $0.029 \text{ \AA}$  in violet and  $0.019 \text{ \AA}$  in deep red) the corresponding solar image. While the format of the Y axis of the image is that native of the used camera, that along the X axis is given from the frame rate chosen in relation to the duration of the scan: if, for example, the native image format is  $960 \times 1280$  pixels, the images that will be obtained will have a resolution of  $960 \times (T_o \times \text{Fps})$  where  $T_o$  is the duration time in seconds of the solar disk scan and Fps is the number of frames per second of acquisition.

Therefore, assuming that  $T_o = 160$  sec and  $Fps = 7.5$ , the image format of the X axis will be  $160 \times 7.5 = 1200$ . We will have therefore, in the example f Act, of the  $960 \times 1200$  pixel solar images. This last consideration leads us to reflect on the importance of the used camera, the field it covers its resolution and its frame rate. In the figure that follows the visualization of the process, from the video to the final image.



The final image depends, in addition to the quality of the optics, on the processing quality and the closure of the slit, which, as we said, decisively influences the resolution of the spectrum and therefore the quality of the solar image itself. If you close to the minimum possible the slit you get very good images and minute details, but also very large and deep transversal lines (transversalium) difficult to eliminate via software. The following image is the most evident demonstration of this situation. Then the best choice is to close the slit to the minimum compatible with the quality of the spectrum, or with the minimization of horizontal lines due to imperfections of the slit and diffraction. It is a compromise solution, which is however essential with low-cost commercial slits. A solution more sophisticated, but not too difficult to achieve, is that of modifying the beforementioned slits by working their blades as we said earlier, closing them to the minimum opening in order to obtain both resolution and good image quality.



Closing the slit to the limit gives detailed images, but also many horizontal lines

## **The software**

It is easy to understand how the video processing software takes on a crucial role in this category of spectroeliographs, as it is able to supply the final image of the solar disk in the line of interest, according to the methods described above.

### **1 - SpecHelio Bas**

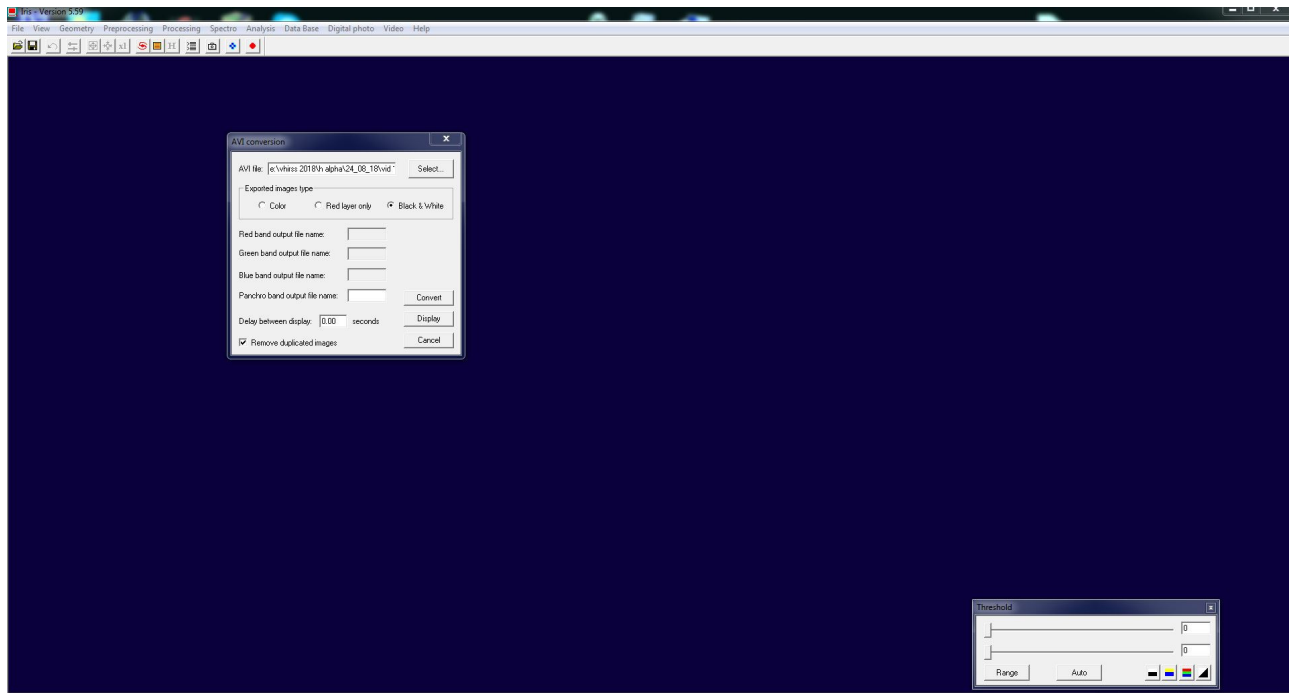
The French amateur astronomer Daniel Deforneau was the first to have the idea of introducing, with a spectroheliograph based on a traditional spectroscope, the digital amateur spectroheliography. His ability also extended to the computer aspect, with the creation of an ad-hoc software written in Visual Basic for converting a series of BMP files into a final mosaic image. However, you need first to convert AVI video files to BMP files, but there are some free programs that do it, like IRIS and Virtual Dub. Personally I have never tried this program, but it is still advised to read the instructions and the tutorial before installation and use.

<http://astrosurf.com/ciieldelabrie/sphelio/program/>

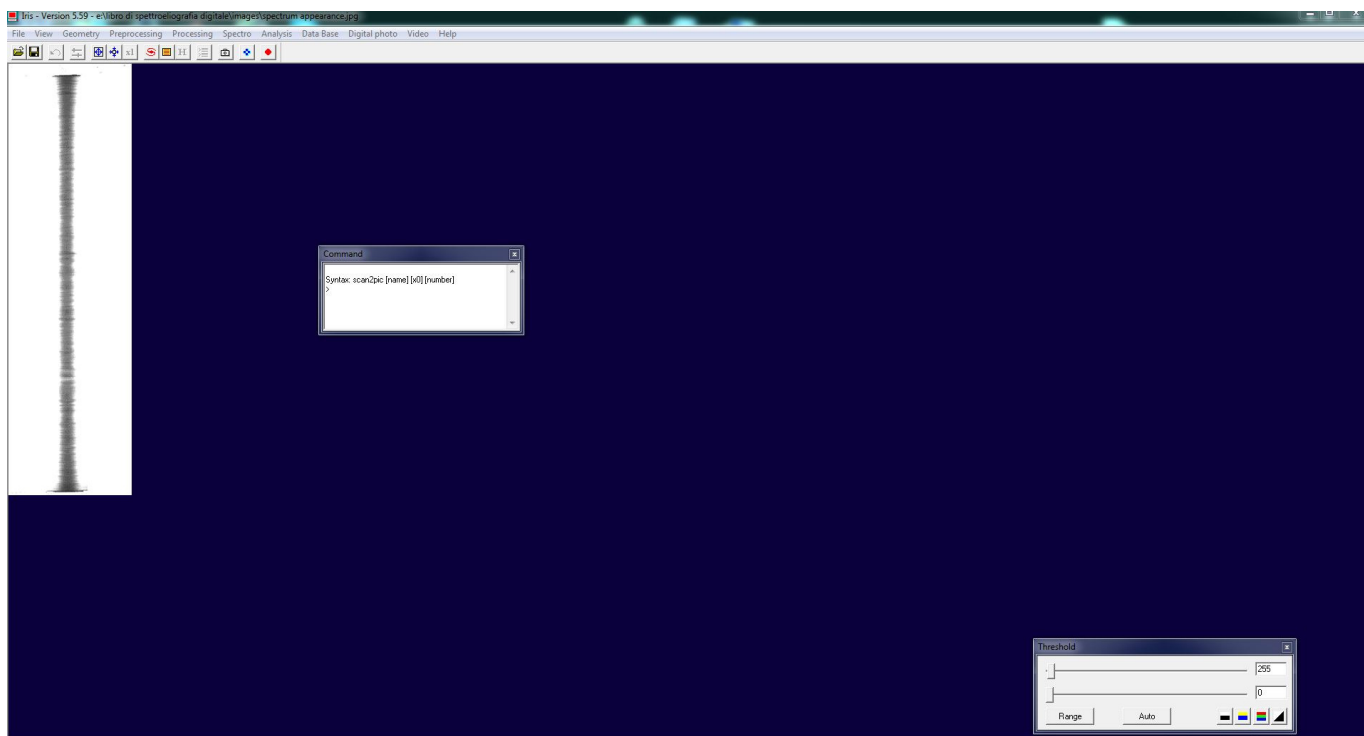
### **2 - IRIS**

The famous and very popular C.Buil program allows, with some routines and a specific command, the conversion of AVI files into monochromatic fits. It is advisable to convert it into an ad hoc folder of disk C (eg C / SpecHelio) selecting it like working directory and moving the AVI file into it.

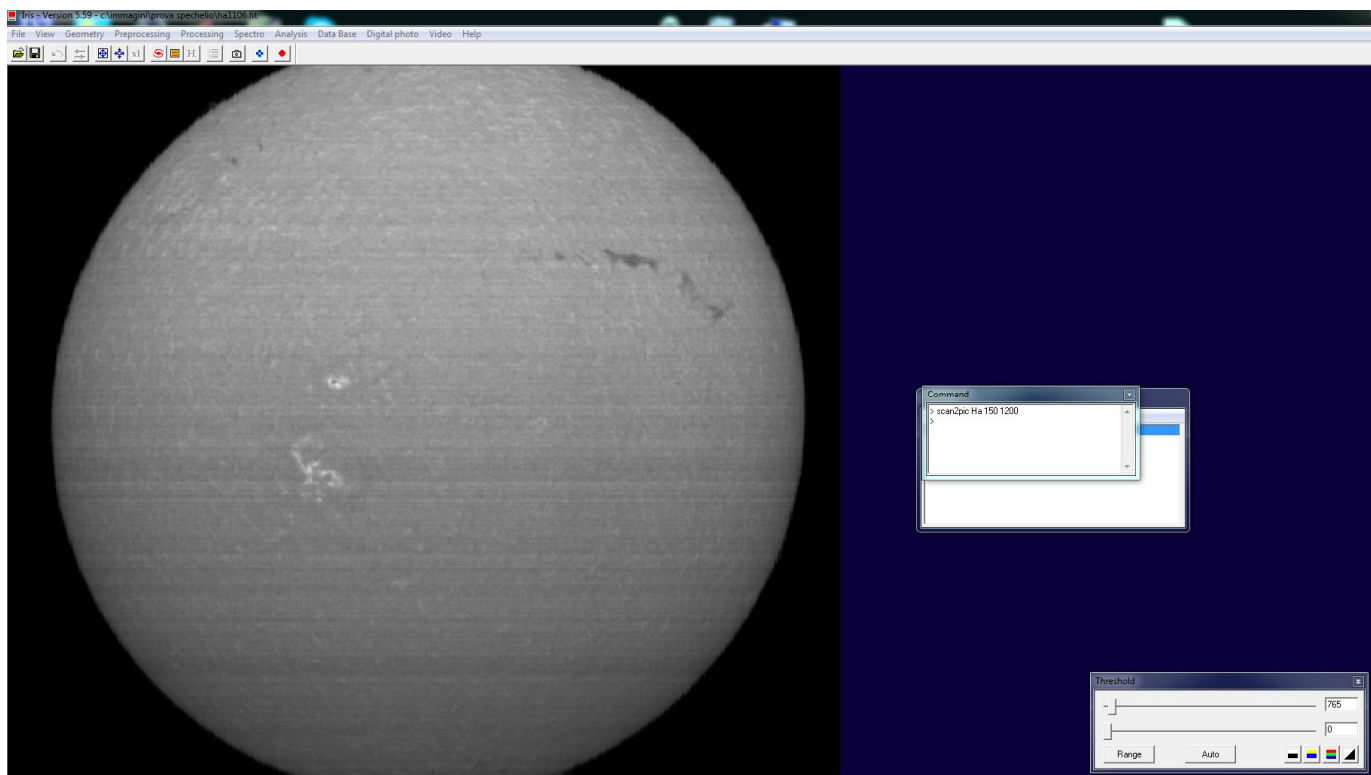




The Fits files obtained from the conversion generally correspond to the number of frames generated by the video, except for the loss of some: assuming that these are 1200, select and load a central one in the program, examine it, and choose a column corresponding to a pixel of the line of interest (generally the central one). You can then launch the "scan2pic" keyboard command making the sum of the pixels for all the frames of the video and obtaining in this way the final image.



The keyboard command has the following syntax: "scan2pic [name] [x0] [number]" where [name] is the file name, [x0] is the pixel corresponding to the chosen column, and [number] is the total number of the images actually converted into Fits by IRIS, which appears in a small window. So, assuming that you have obtained from the conversion of the AVI (BW) 1200 Fits file into the appropriate folder, and having named them "Ha", you upload a central one, as in the above figure (for example the 650, which will show the whole line), after having carried out any rotational operations and possibly slant and smile corrections, the pixel number X corresponding to the center line column (or possibly other) is selected. Imagine it is the 150 (shown in the window at the bottom right of the program window) and then launch the command: "scan2pic Ha 150 1200". The program will then register all the columns of the pixel 150 for all the 1200 Fits, obtaining the mosaic of the final image corresponding to the selected pixel.



This command does not seem to like long file names, so it is advisable to use a short name working directory (eg C / SpecHelio)  
The routine works very well, and the only negative points are, in my opinion, the number of files generated and saved that takes up a lot of disk space, and the fact that you can only act on a single pixel, sub-sampling the final image.

### 3 - Spectral Line Merge

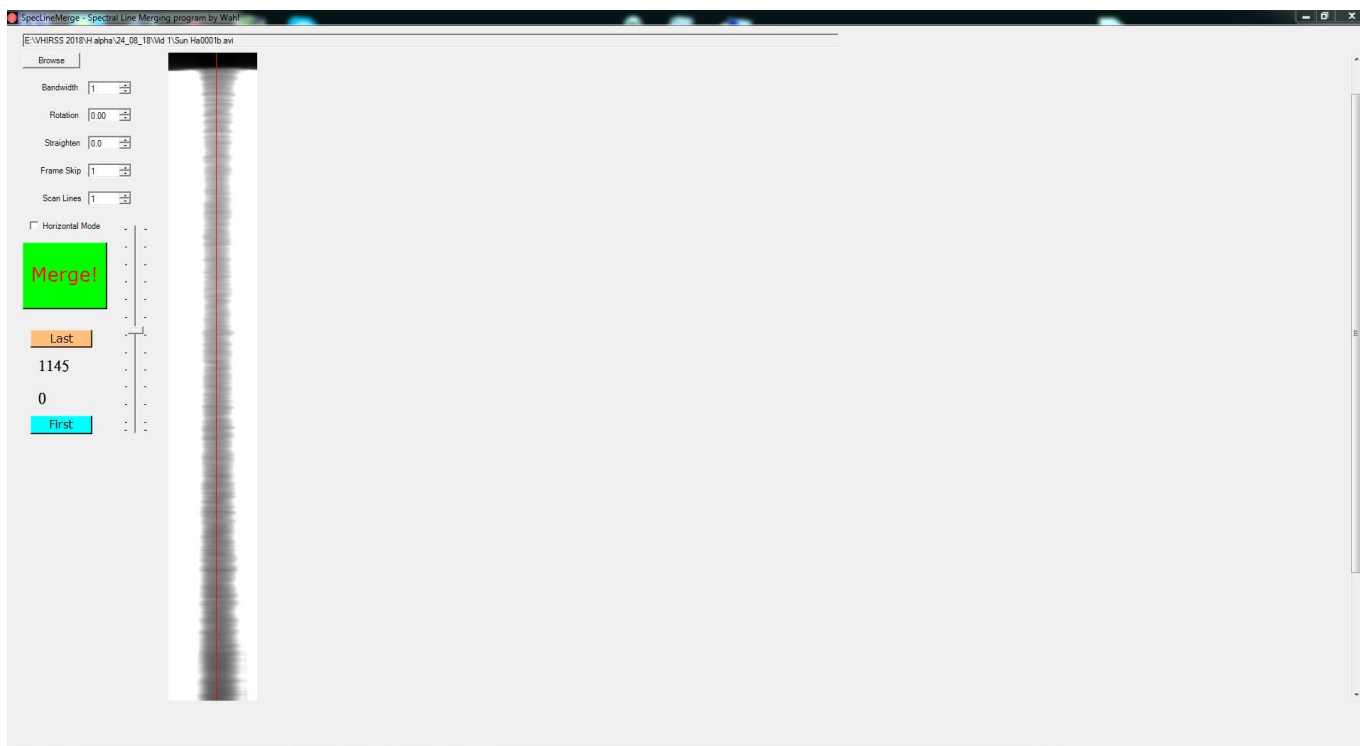
The Chinese amateur astronomer Wah-Heung Yuen has created a specific program for digital spectroheliography, with many interesting features, despite its extremely simple and "user friendly" interface.

<http://www.hkastroforum.net/viewtopic.php?t=29425>

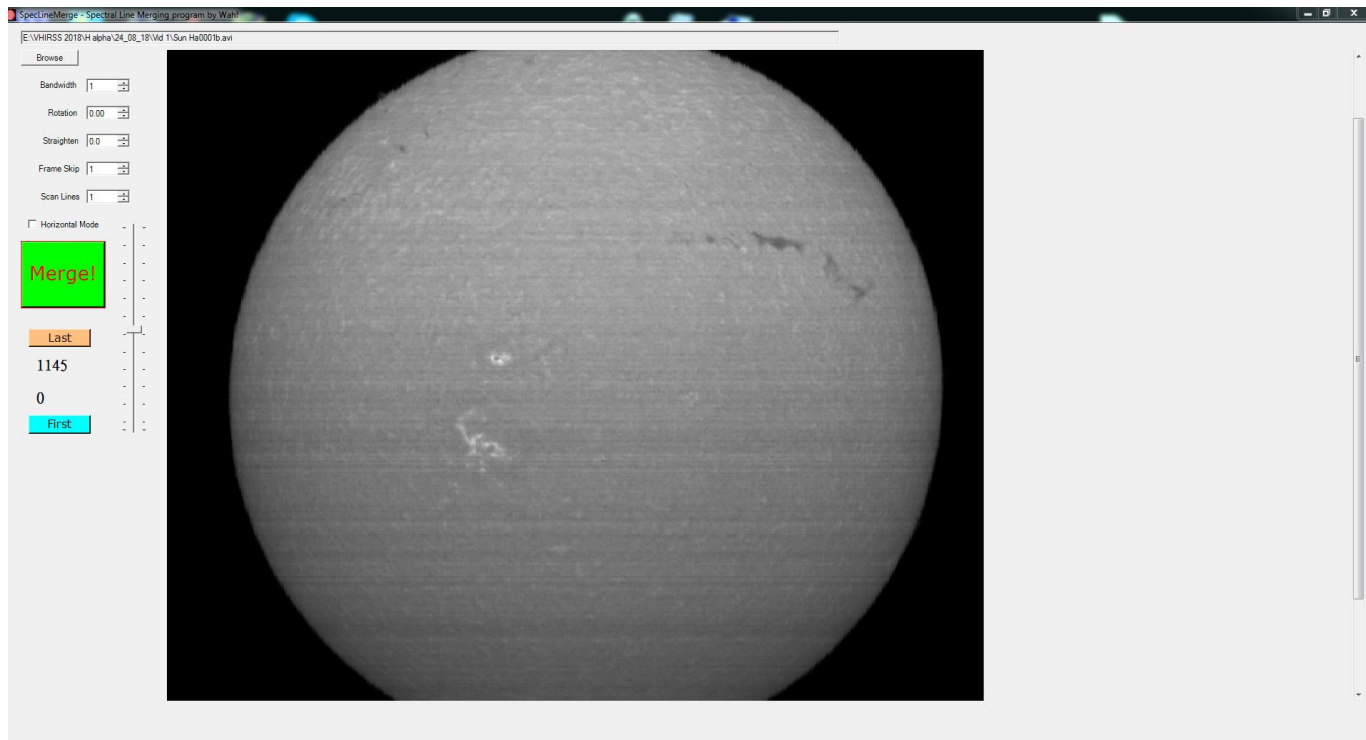
The latest version can be downloaded from the Solarchat forum:

<https://solarchatforum.com/viewtopic.php?f=7&t=21608>

However, the program requires a pre-processing of AVI files (cropping) with the well-known freeware program Virtual Dub. In practice, you need to load the file on VD by making a crop along the X and Y axis (Video> filters> add> null transform> cropping) then save it to make its transformation into an image with Spectral line merge.



The Spectral Line Merge screen: by placing the red line on the pixel of the desired line, the program will produce the final image on the column corresponding to that pixel (figure below). However, unlike IRIS, the software can select a band wider than 1 single pixel, that is the conversion of several pixels contiguous to that chosen obtaining a series of images with benefits on the final sampling. The program also allows the rotation of the line and the possible correction for smile (curvature).



Spectral Line Merge is therefore a simple and complete software, with a reduced and friendly user interface. It is currently my favorite program for the production of spectral images: the only drawback is, in my opinion, the procedure for the elimination of the transversalium that the author describes in his tutorial, a bit too laborious for common users.

#### 4 - BASS Project

BASS project is a well-known and complete program developed by John Paraskeva (UK) for amateur spectroscopy, which also has special routines, in which I have also collaborated, for the extraction and treatment of spectroheliography images. The program is currently at its version 1.9.8 beta. For download go to:

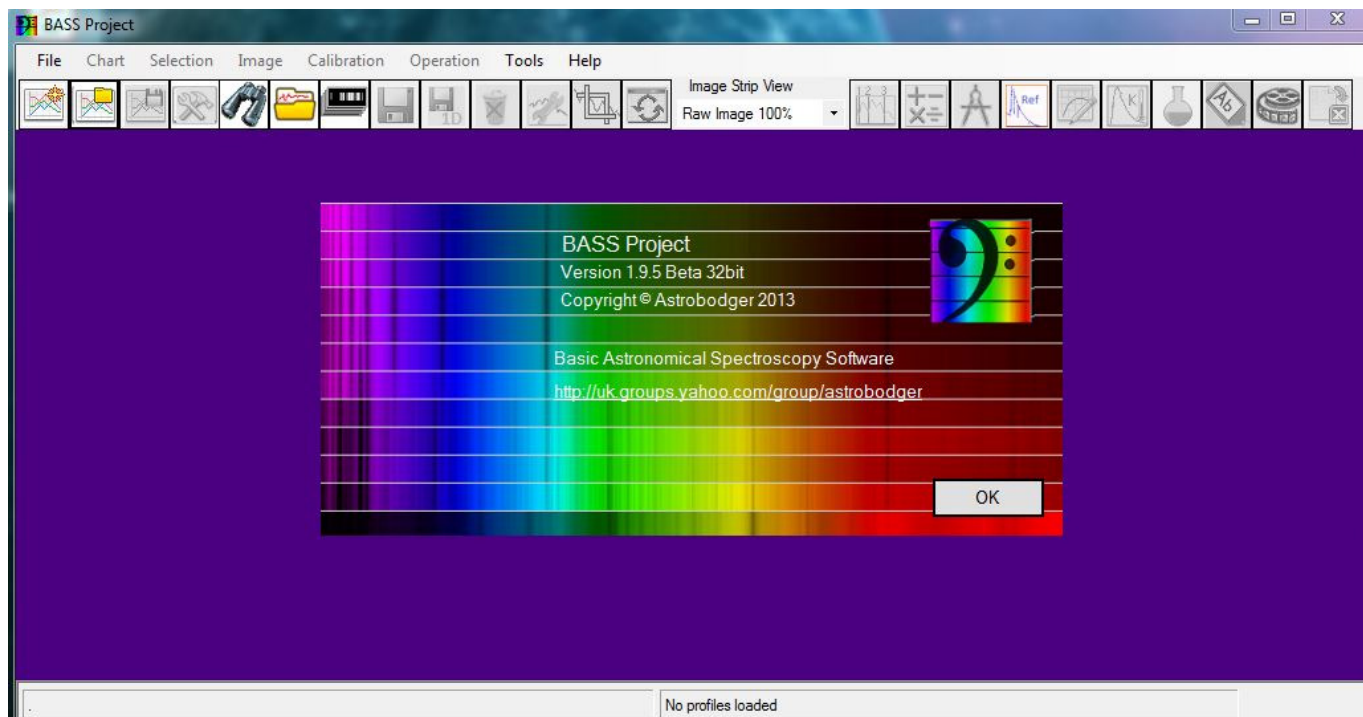
<https://www.dropbox.com/s/utayfo60g9kggjf/BASSProject198b7.exe?dl=0>

(32 bit)

<https://www.dropbox.com/s/ntbd7uavfdejy8/BASSProject198b7-64.exe?dl=0>

(64 bit) - For info:

<https://uk.groups.yahoo.com/neo/groups/astrobodger/info>

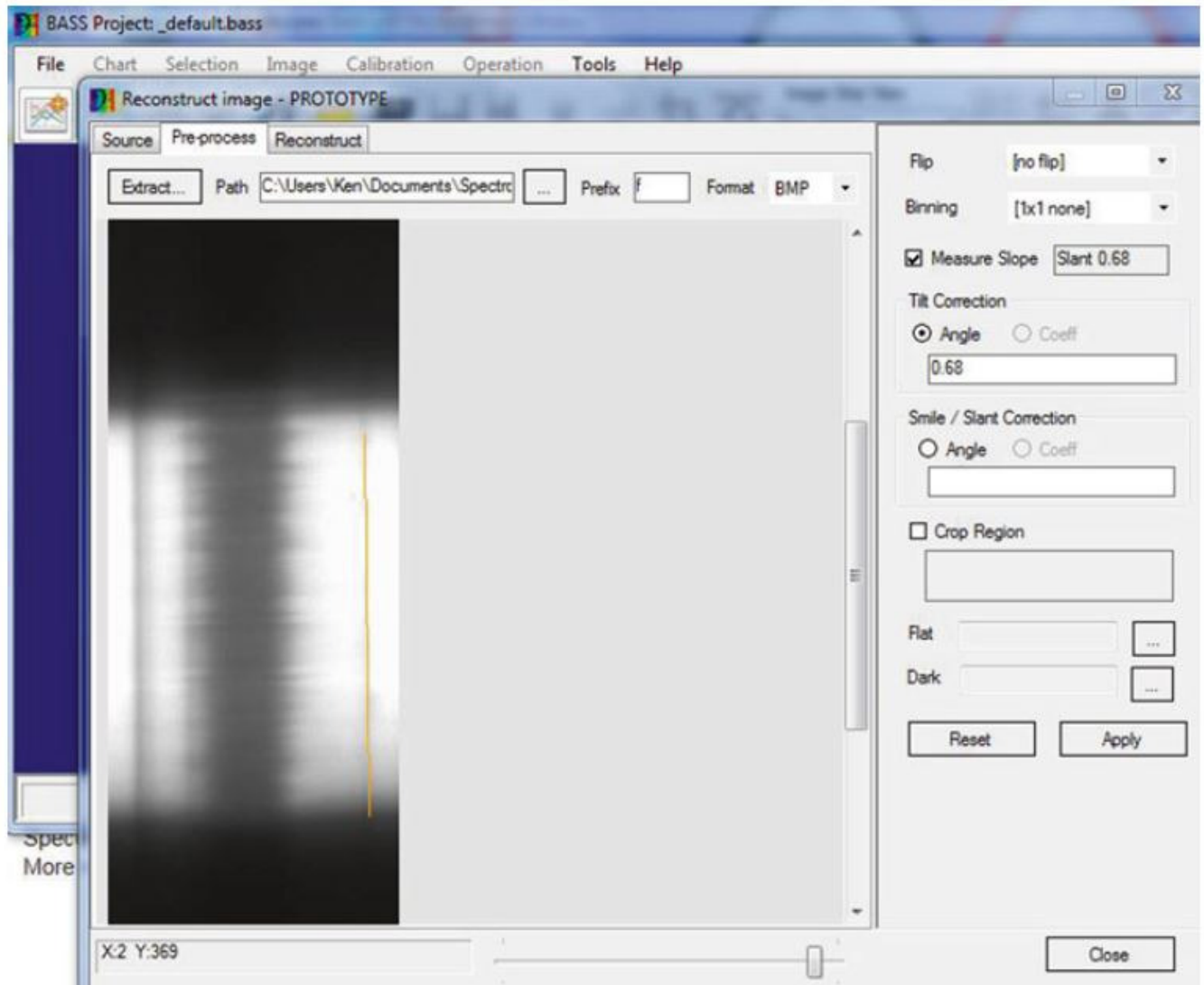


The operating procedure is as follows:

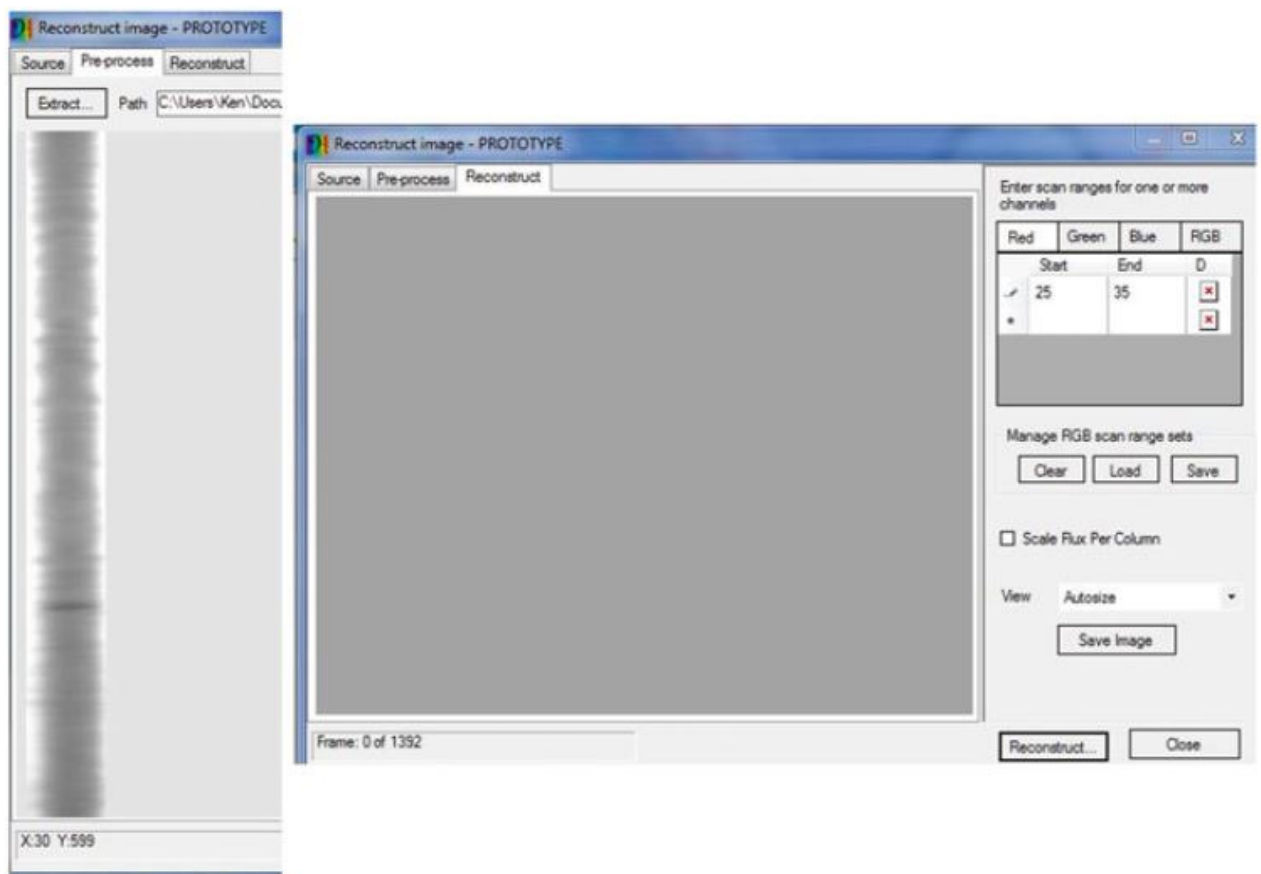
In the TOOLS menu, open the "Reconstruct" routine and import the AVI file to be processed.

Using the slider, load a frame in which you can clearly see the line in absorption by the interest, and still use the slider to go on a frame that shows visible the transversalium to correct the tilt, and another line near the one of interest to correct the slant if necessary, then press the "Apply" button. Immediately afterwards go to "Extract" and extract the video frames to the selected directory. At this point BASS behaves like IRIS and extracts all the frames of the video. Place the cursor in the middle of the line of interest and note the X value of the central pixel (eg 30).

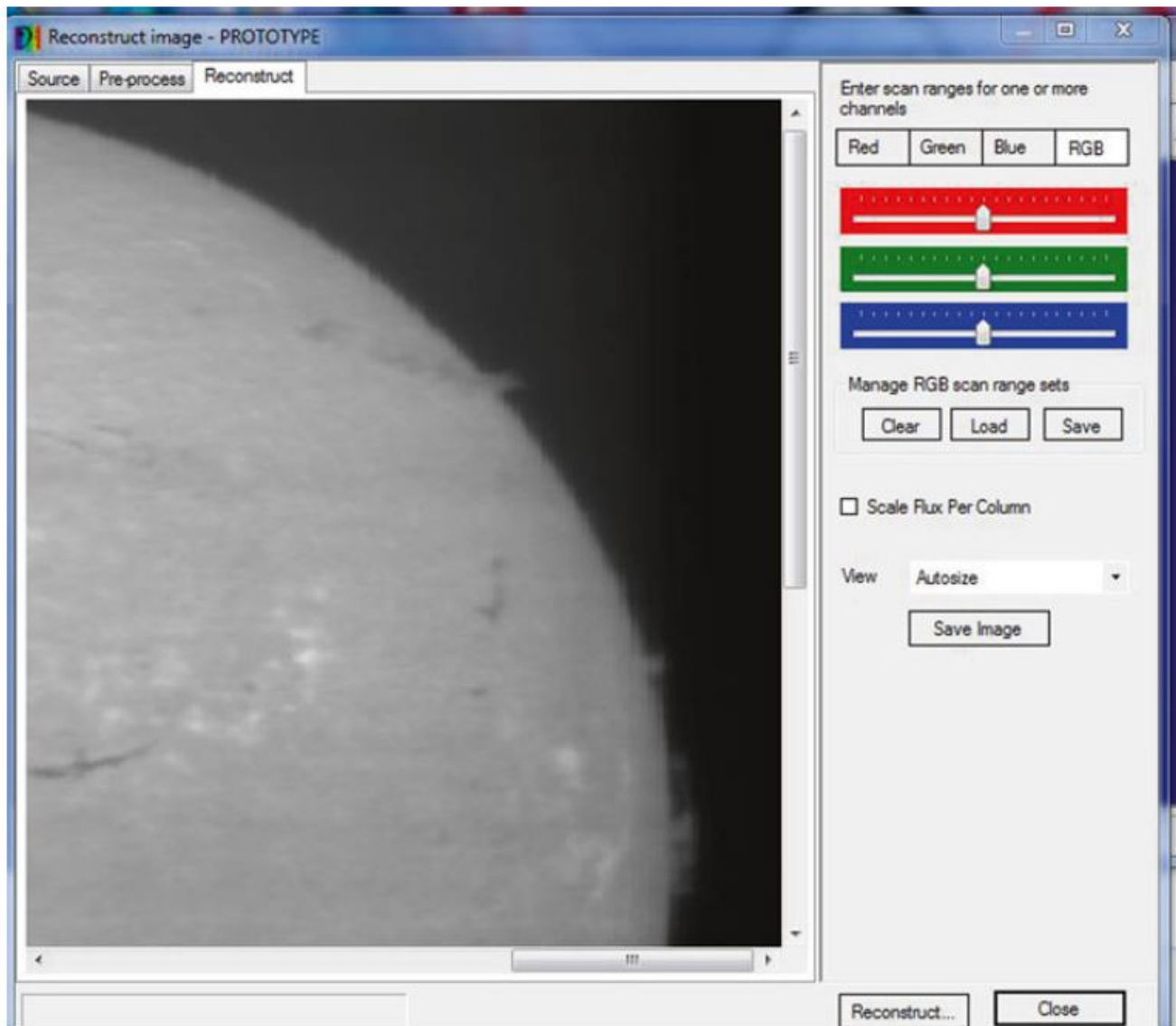




Then go to the "Reconstruct" menu (image below) and indicate, in the "enter range for one or more channels" window, the pixels relative to the columns that will be used in the image. If, as said before, the central pixel of the line is the 30, then writing 30-30 we will use only this in the reconstruction, while writing 25-35 we will use 10 pixels and the final image will be better sampled.

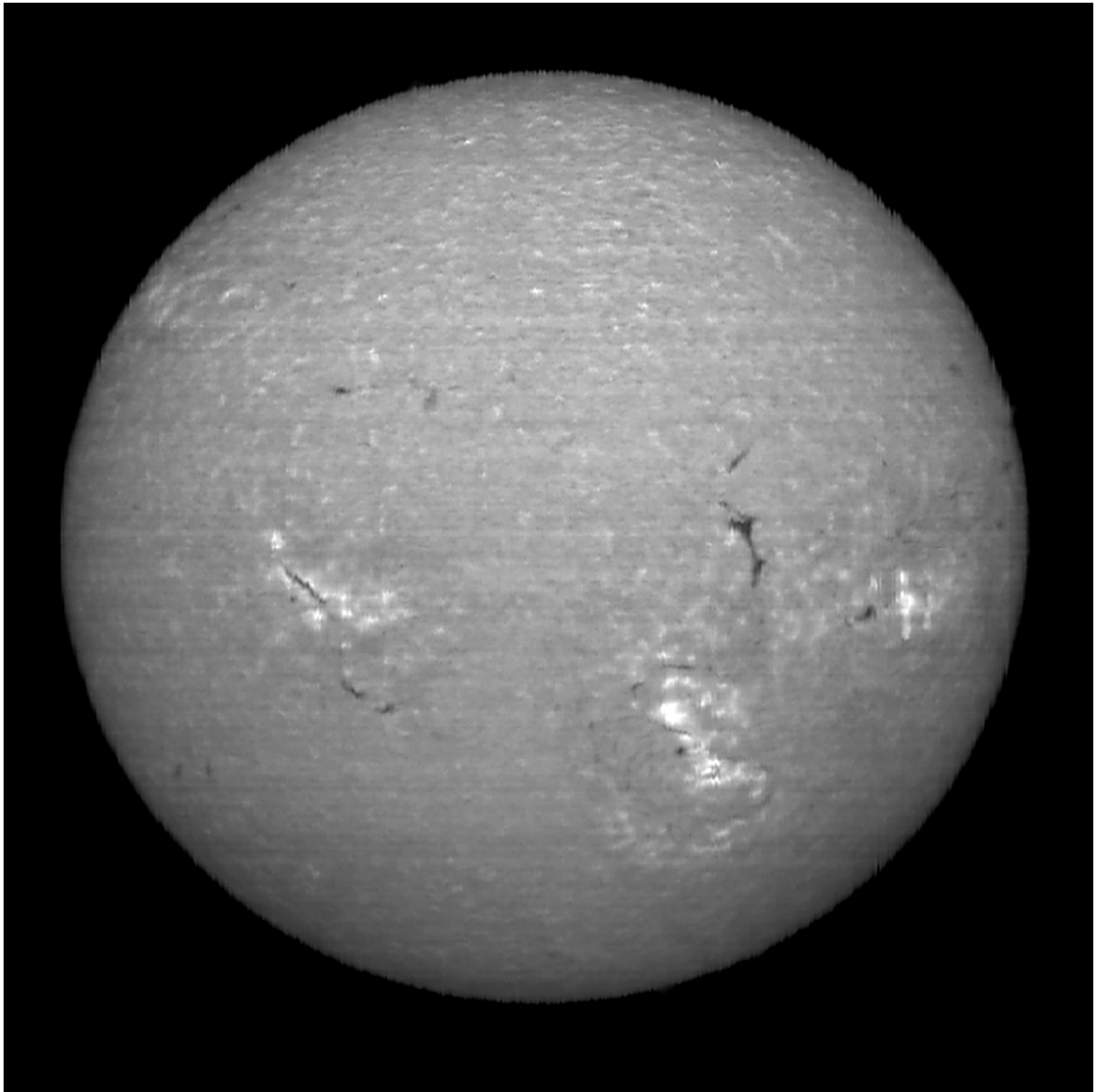


I must say that the functionality of the routine, at first glance a bit complex, is very good and produces good images: the only flaw is, in my opinion, the processing time in a medium power computer maybe a little long, superior to those of IRIS (which nevertheless allows the reconstruction on a single pixel) and, even more so, of Spectral Line Merge which is certainly the fastest of those examined. Once you get used to the BASS procedure, it works well and also has an accurate manual available, where all of its numerous functions, dedicated not only to spectroheliography, but to spectroscopy in general, are explained. It also includes a procedure to suppress the transversalium with a synthetic flat.



Below, an alpha H image obtained by the writer with the processing of an AVI file with BASS, without applying any flat: the final result is more than good.

The characteristic that distinguishes BASS from the other software mentioned is that the same constitutes an excellent and complete spectroscopy software, which the writer often uses in addition to Visual Spec for the treatment and processing of stellar and deep sky spectra.



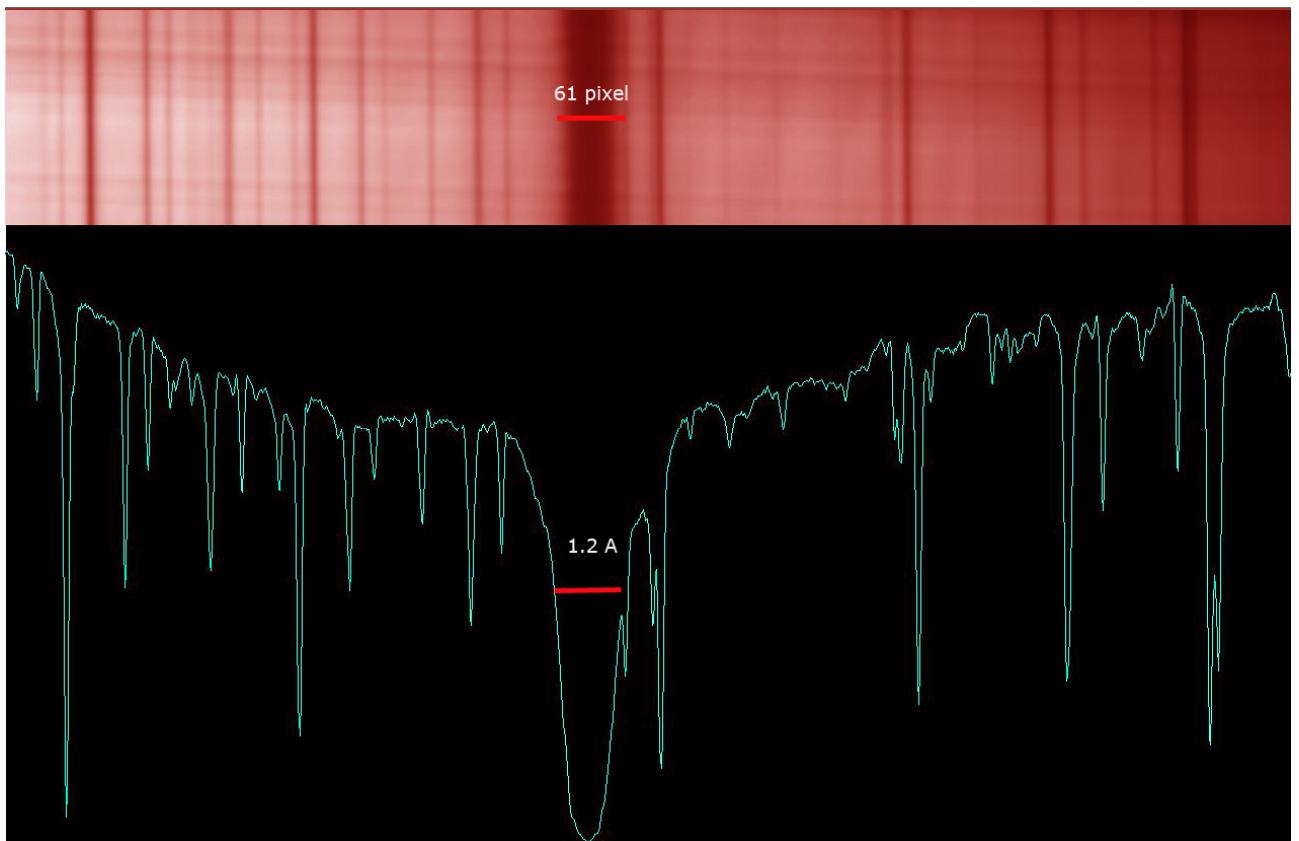
**Results obtained in digital spectroheliography by a double-pass  
Littrow spectroheliograph**

Let us now examine some results obtainable in full-disk solar imaging with a self-constructed Littrow-type spectroeliograph like those previously discussed. First, however, it is good to examine some aspects not known to all.

The first question that the solar observation neophyte can do is of the type: "but what a spectroheliograph could be used for, given that the images in H alpha and CaIIK light of the commercial filters are very beautiful and detailed, and aesthetically superior to those of the spectroheliographs ?".

The answer is simple: the strength of the spectroheliographs is the very high level of spectral resolution achievable, even with modest instruments such as those mentioned: to clarify this, the following consideration holds: a normal amateur commercial Halpha filter generally has a bandwidth between 1 Å and 0.3 Å; beyond this limit, the cost, already very high, become prohibitive and accessible only to professional users.

Spectroeliographs such as VHIRRS or Solarscan reach without any problem on average a resolution oscillating between 0.03 and 0.019 Å / pixel (depending on the wavelength) with a camera like DMK, with pixels from 4.65 or 4.4 μm: this because we generally use only one pixel to construct the image and in practice the resolution of image itself equals the dispersion of the spectroscope. In practice, therefore, hypothesizing the average resolution of 0.025 Å, this is 40 times that of a 1 Å filter and 20 times one of 0.5 Å. Ma the thing does not end here: the very high level of dispersion per pixel causes the H alpha line , eg, at 0.0195 Å / pixel appears wide 61 pixels wide on the screen of a PC, as shown in the figure, with a bandwidth well 51 times narrower than a 1 Å filter and with a resolution level of final image 51 times higher!





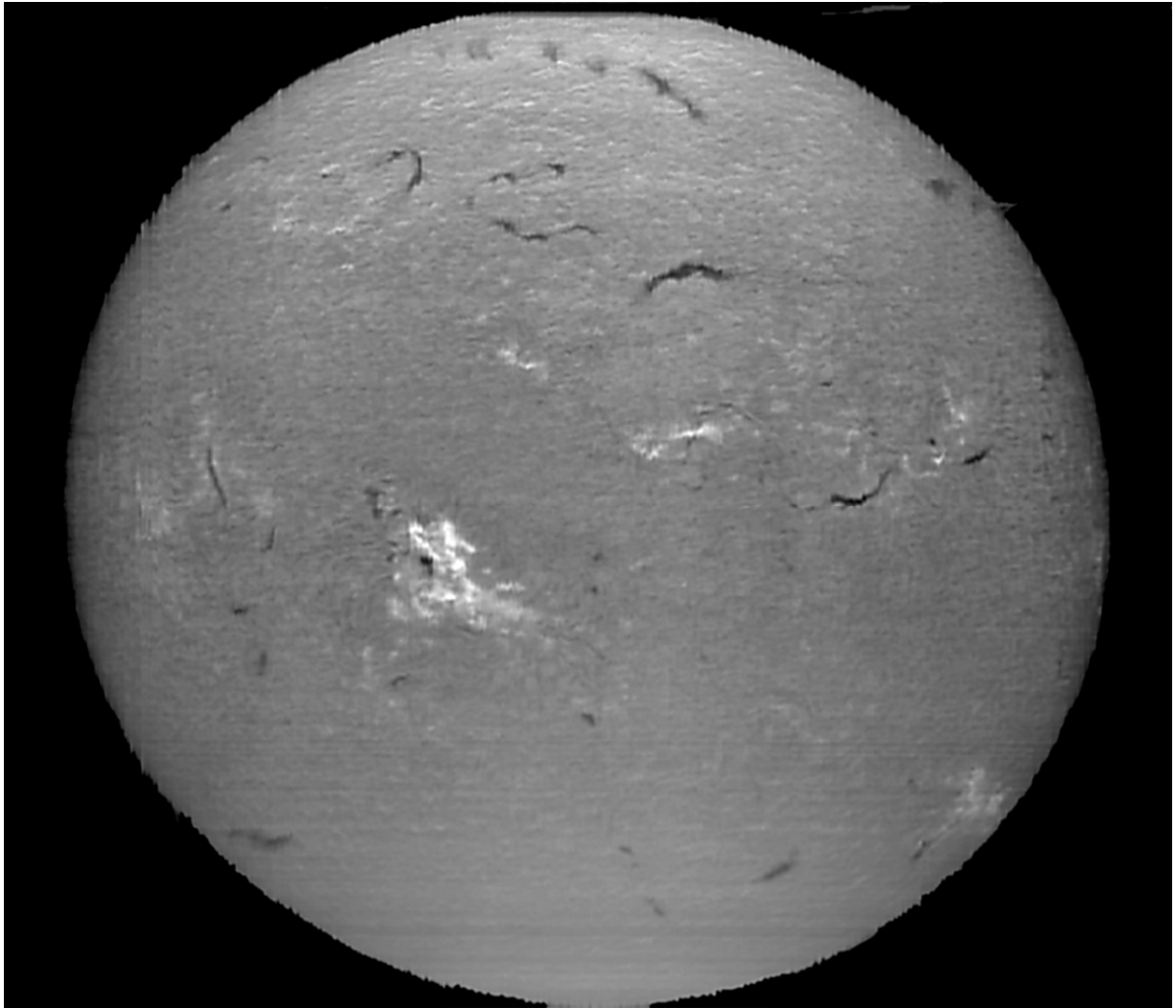
This has the important consequence that it is possible to position the 1 pixel image acquisition column at 30 pixels from the center of the very center of the line, thus obtaining as many as 61 images of the H alpha line from the center to the wings: 1 in the center, 30 towards the blue and 30 towards the red. Identical thing for the line CaII K, CaII H and so on. But this allows us to go from the lower chromosphere, to the borders with the photosphere, up to the highest part of it, thus operating a real tomography of the chromosphere itself, which is impossible with commercial filters.

Moreover, this peculiarity opens the door to the scientific study of the solar chromosphere, such as the shift doppler, the measurement of solar magnetic fields, the differential spectroscopy, not to mention that the instrument also serves as a mere spectroscope, for demonstrations and didactics purposes.

It is a new world, so far explored only by professionals with equipment too expensive to be accessible to amateurs, which opens itself to those of them endowed with tenacity and good will, at least until instruments such as those described will be available on the market. But now let's see some of the possible observations.

## **Ha 6562.8 Å**

The following is a solar image taken with VHIRSS on May 12, 2012, in a period of atmospheric stability and good seeing. Media of the images obtained from 22 pixels distributed on the sides of the center line. Incredible the number of visible details.

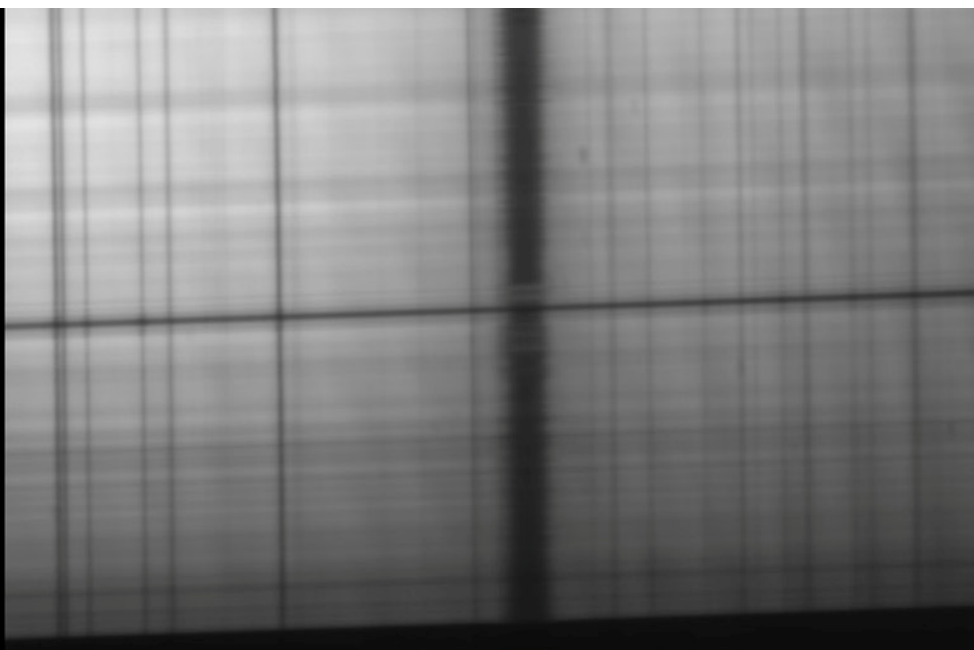


This image can be considered an example of the difference between spectroheliograms and traditional amateur imaging: the details visible in the first are clearly higher than those of the second, where the image quality is lower.

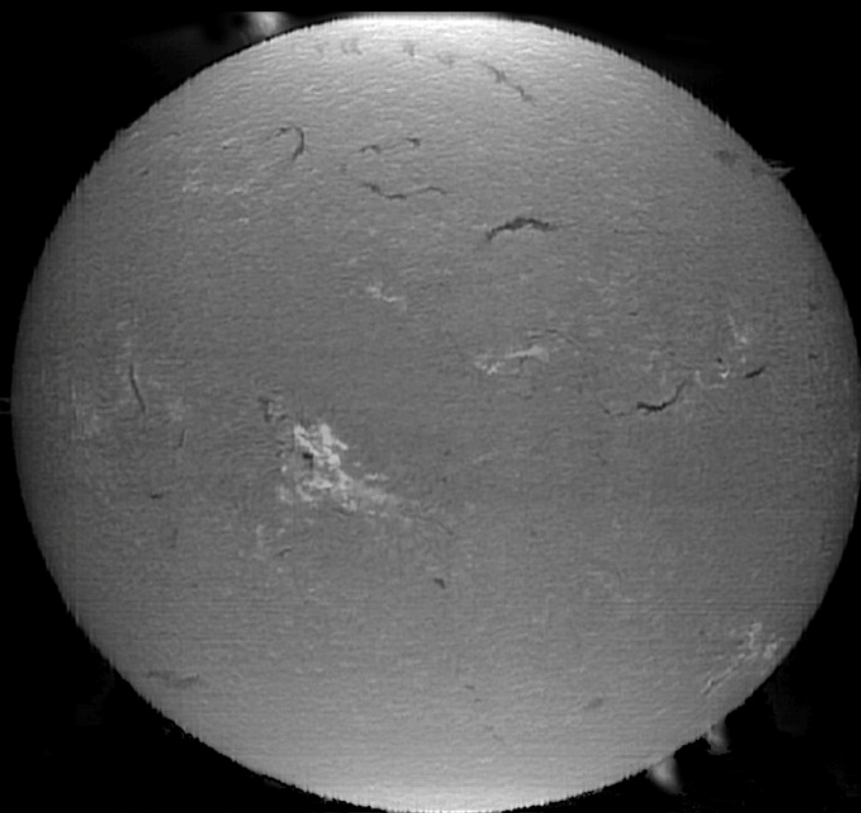
This implies that from a purely aesthetic point of view, imaging with narrow band solar filters is a winner, while from the scientific point of view the spectroheliogram is superior.

Below the same image with better observable prominences.

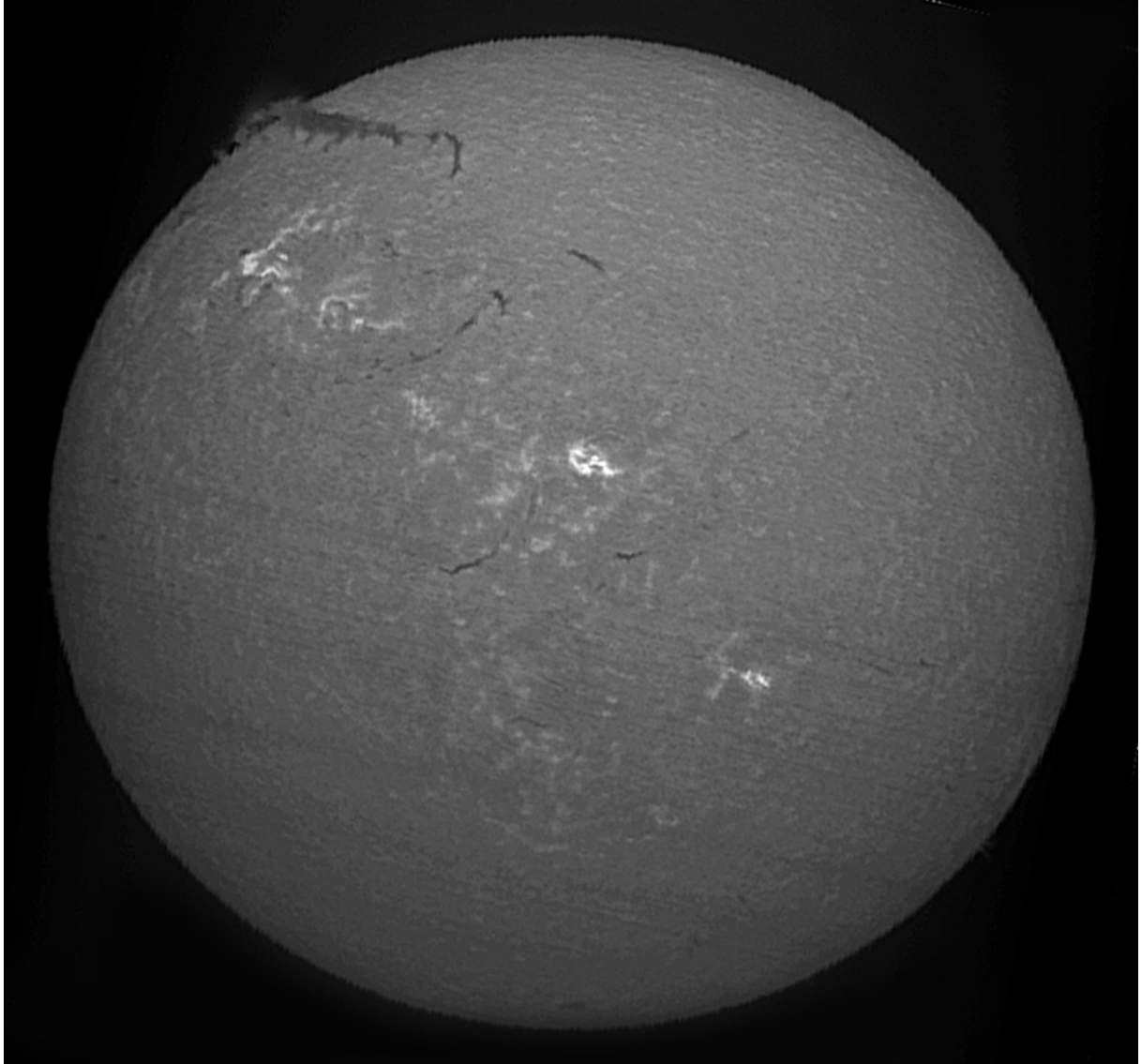
AR 1476 →



Sun Ha May 12 2012 h.8.10 UT  
VHIRSS Spectrohelioscope mode  
Fulvio Mete  
Rome, Italy

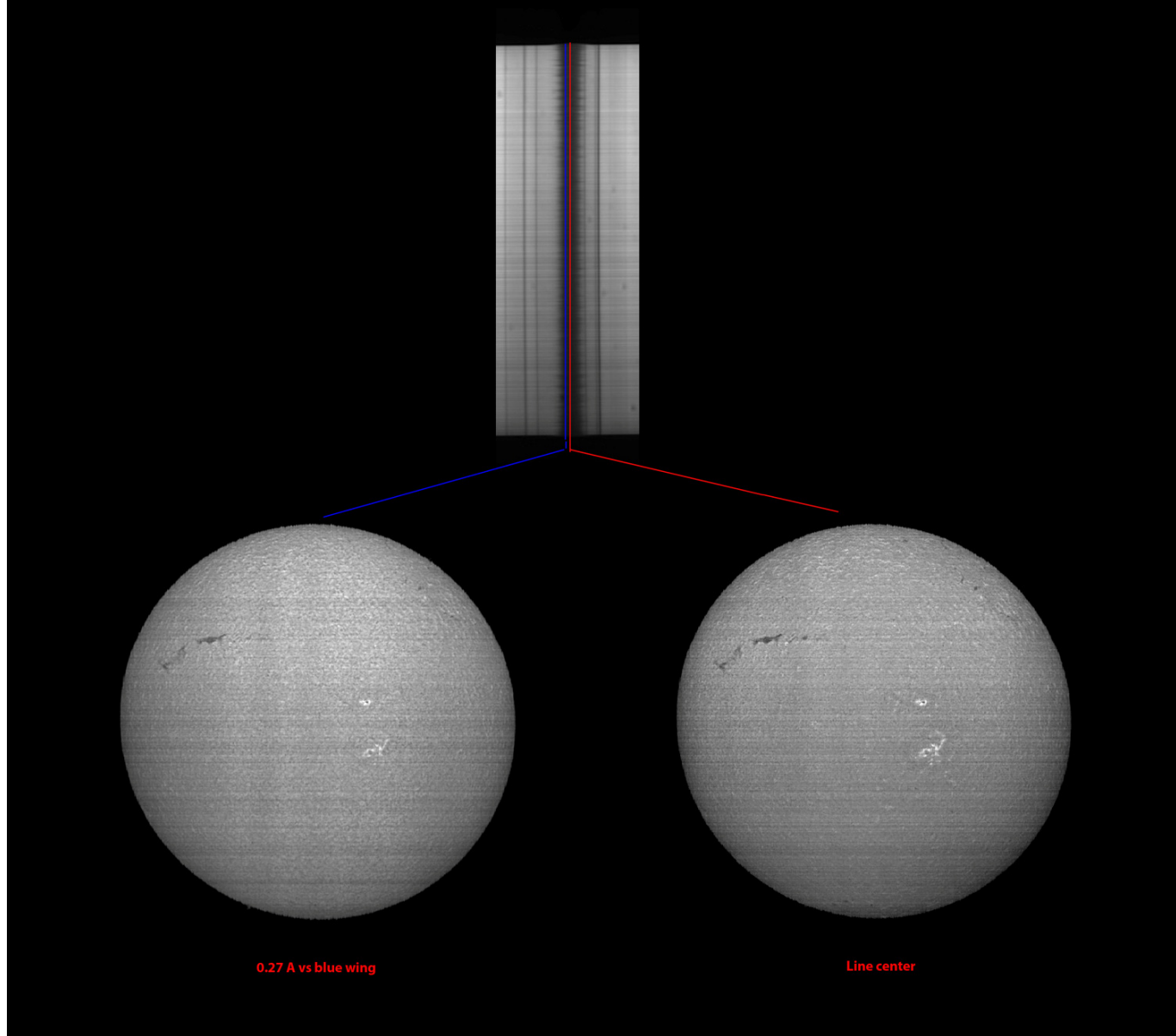


Below, a characteristic image of the sun with a gigantic prominence that extends from the disk, where it is visible as a filament, to the edge, vaguely resembling a centipede.



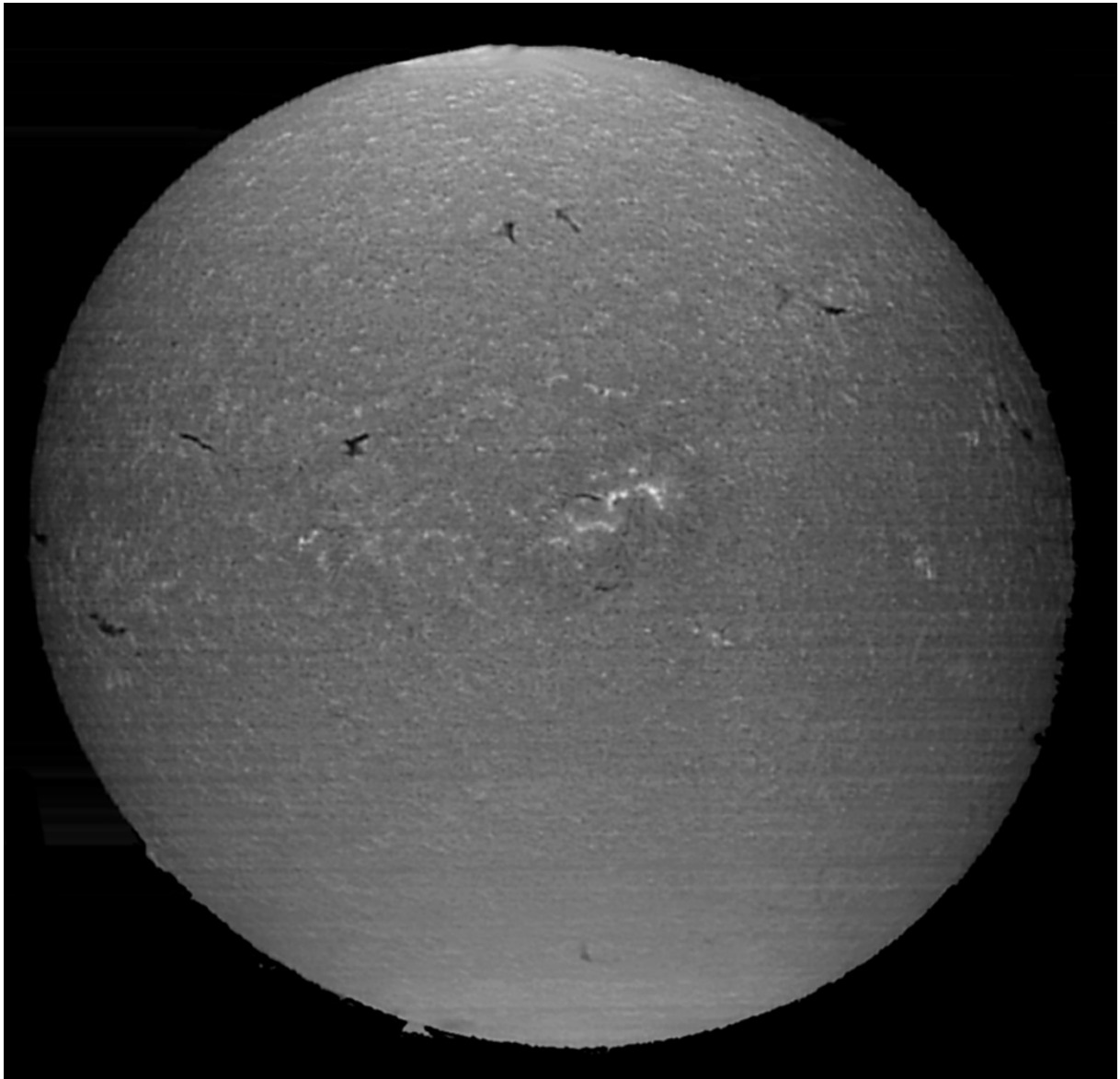
The image below shows instead the change in the appearance of the solar disk in H $\alpha$  light with spectroheliograms taken in the wing towards blue ( $6562.53 \text{ \AA}$ ) just  $0.27 \text{ \AA}$  with respect to the center of the line, , and another in the very center of the line ( $6562.80 \text{ \AA}$ ). It is only about a quarter of  $\text{\AA}$ , but it is already enough to visualize the changes in the visibility of the chromospheric details passing from the wing to the center of the line. This is how much going from the continuous towards the wings and then towards the center line one passes from the borders with the photosphere at the low and then the high chromosphere.

Sun Image in H $\alpha$  line, at the very center (6562.80 Å) and 0.27 Å shifted toward the blue (6562.53 Å) Despite the moderate shift, the difference in visibility of solar disk features is noticeable. VHIRSS High resolution spectroscope in spectrohelioscope mode dispersion 0.018 Å/pixel camera DMK 51 R = 59750 at 6573 Å, Fulvio Mete, Rome, 08 24 2018



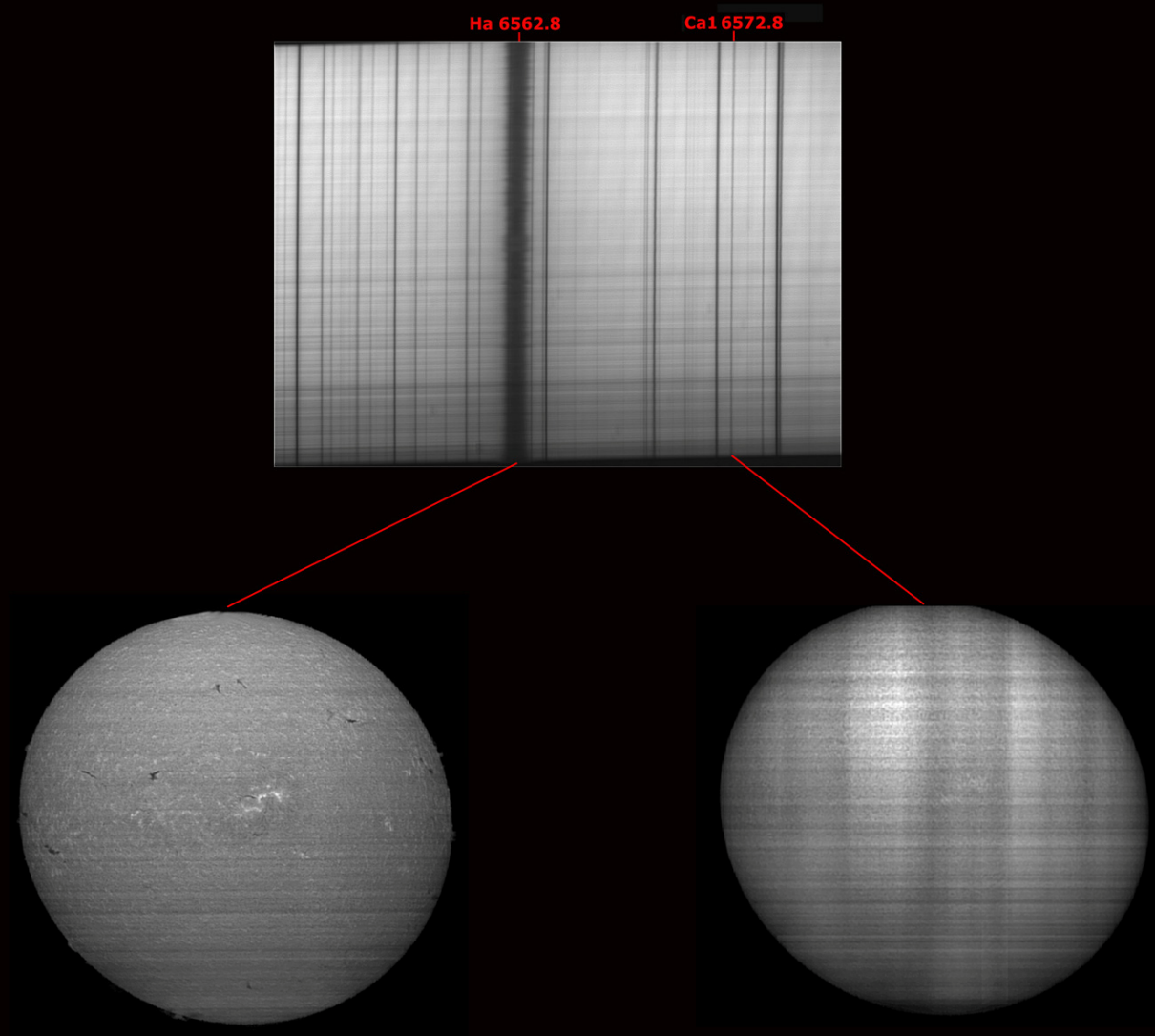
Another H $\alpha$  image by VHIRSS on august,21 2016, to which a synthetic flat was applied to eliminate transversalism.

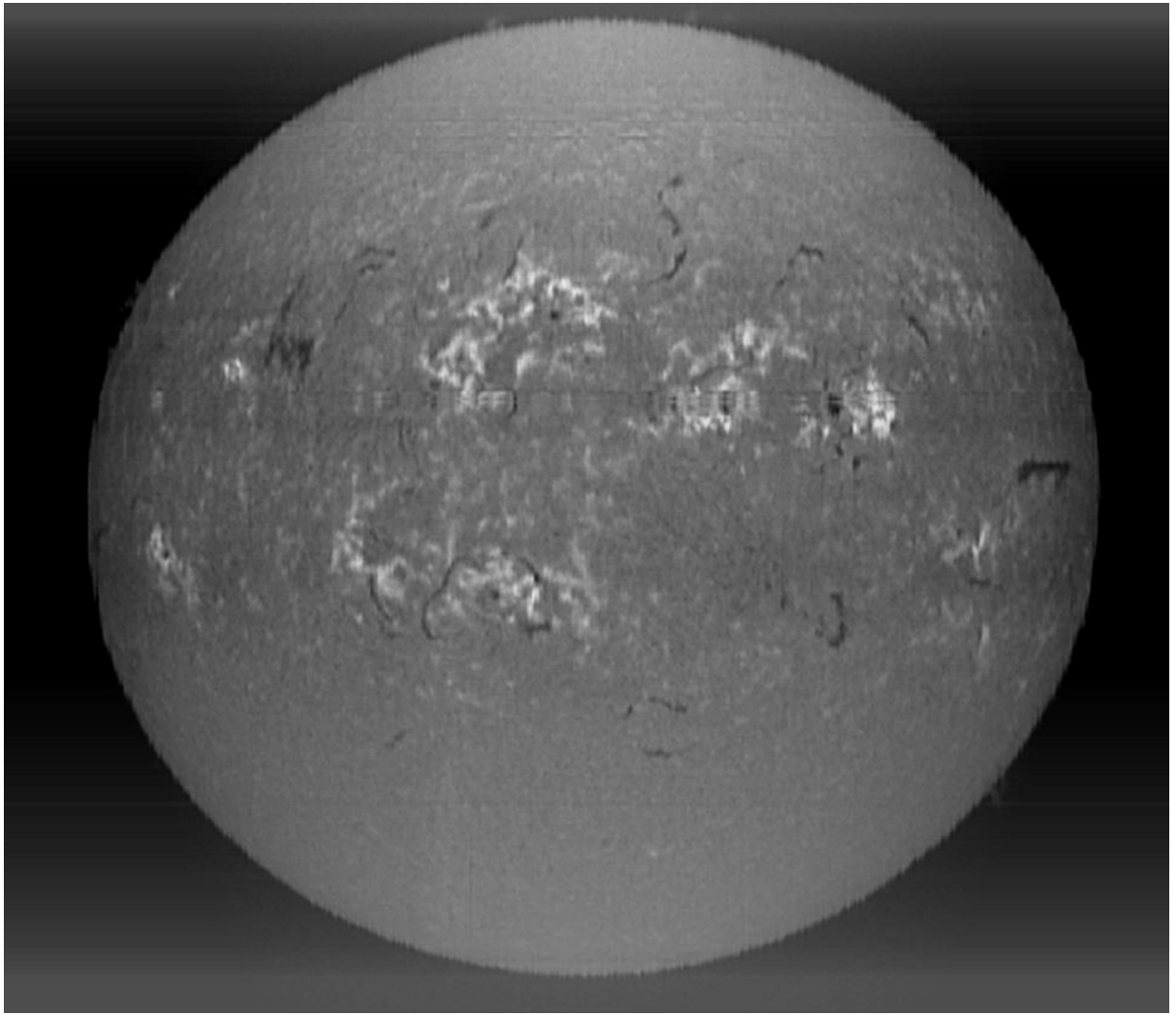




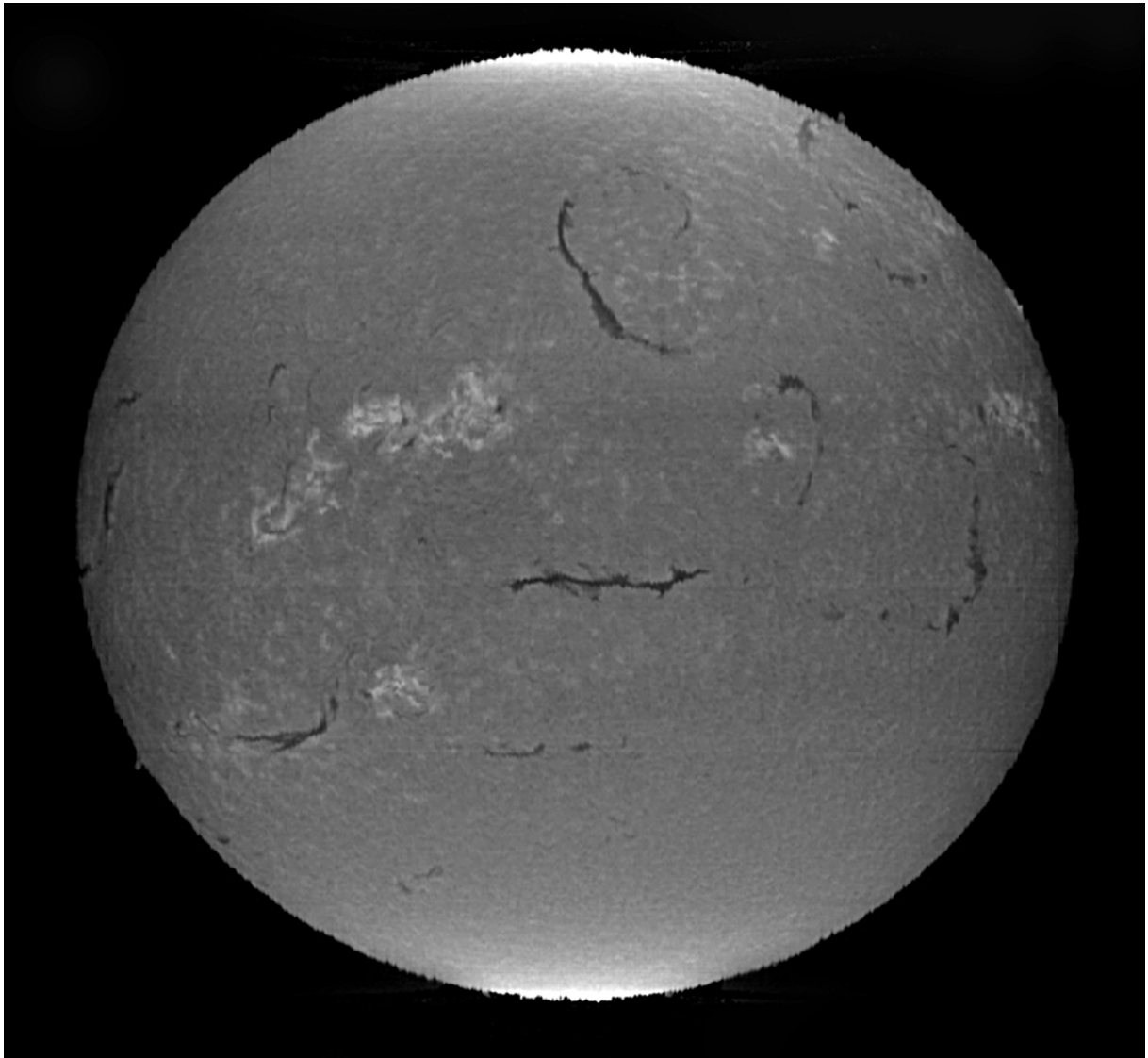
In the composition that follows, the previous H $\alpha$  image was compared with one in neutral Calcium (CaI). The poor sensitivity of this element to the magnetic fields in the active regions is observed, as opposed to what happens for the once ionized calcium (CaII).

**Comparison between Hydrogen Alpha and neutral Calcium (Ca I) images - VHIRSS in spectrohelioscope mode - camera IS DMK 41 Fulvio Mete, Rome, Italy**





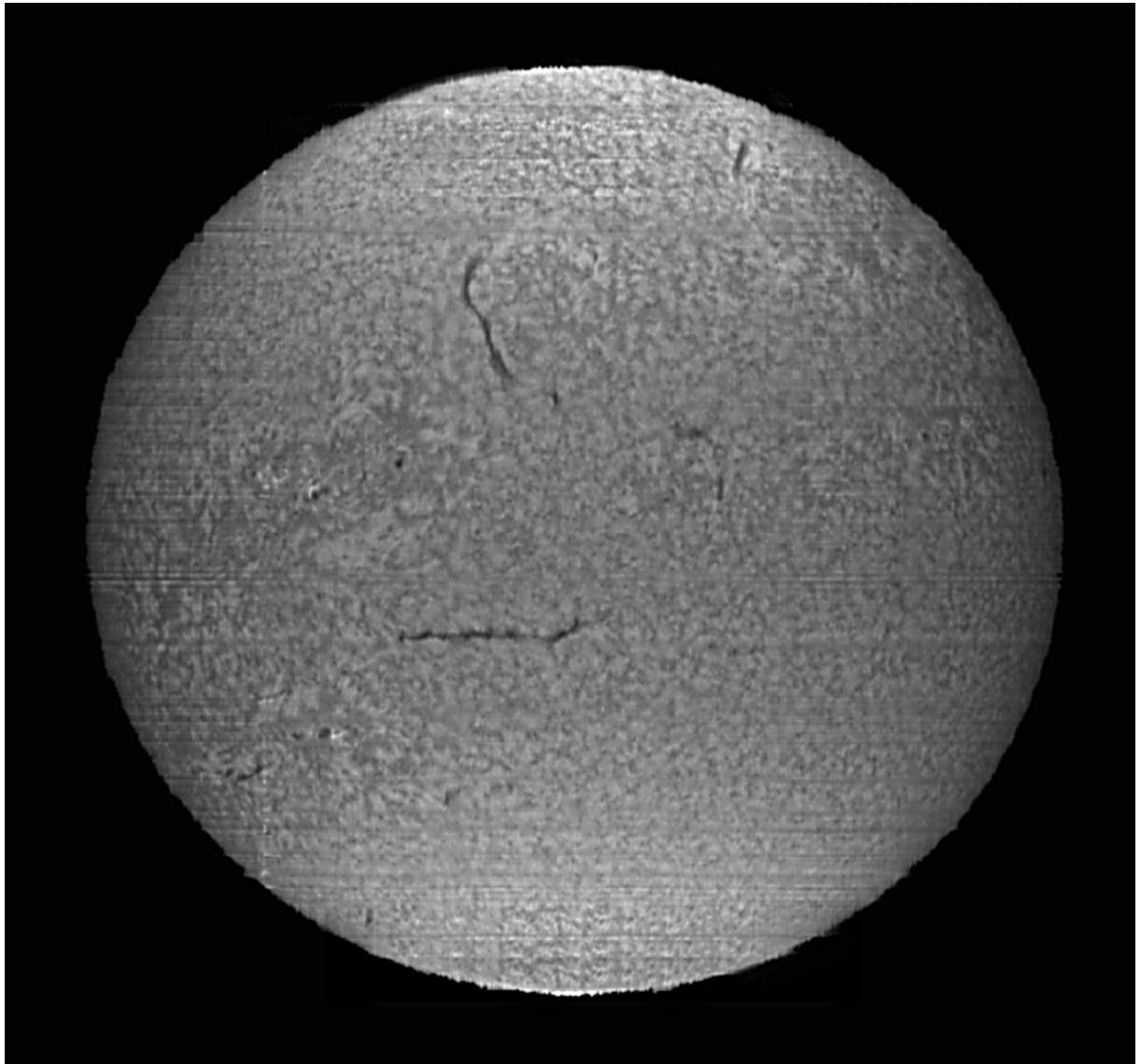
The impressive amount of visible details: POSS2, scan of July 6 2014



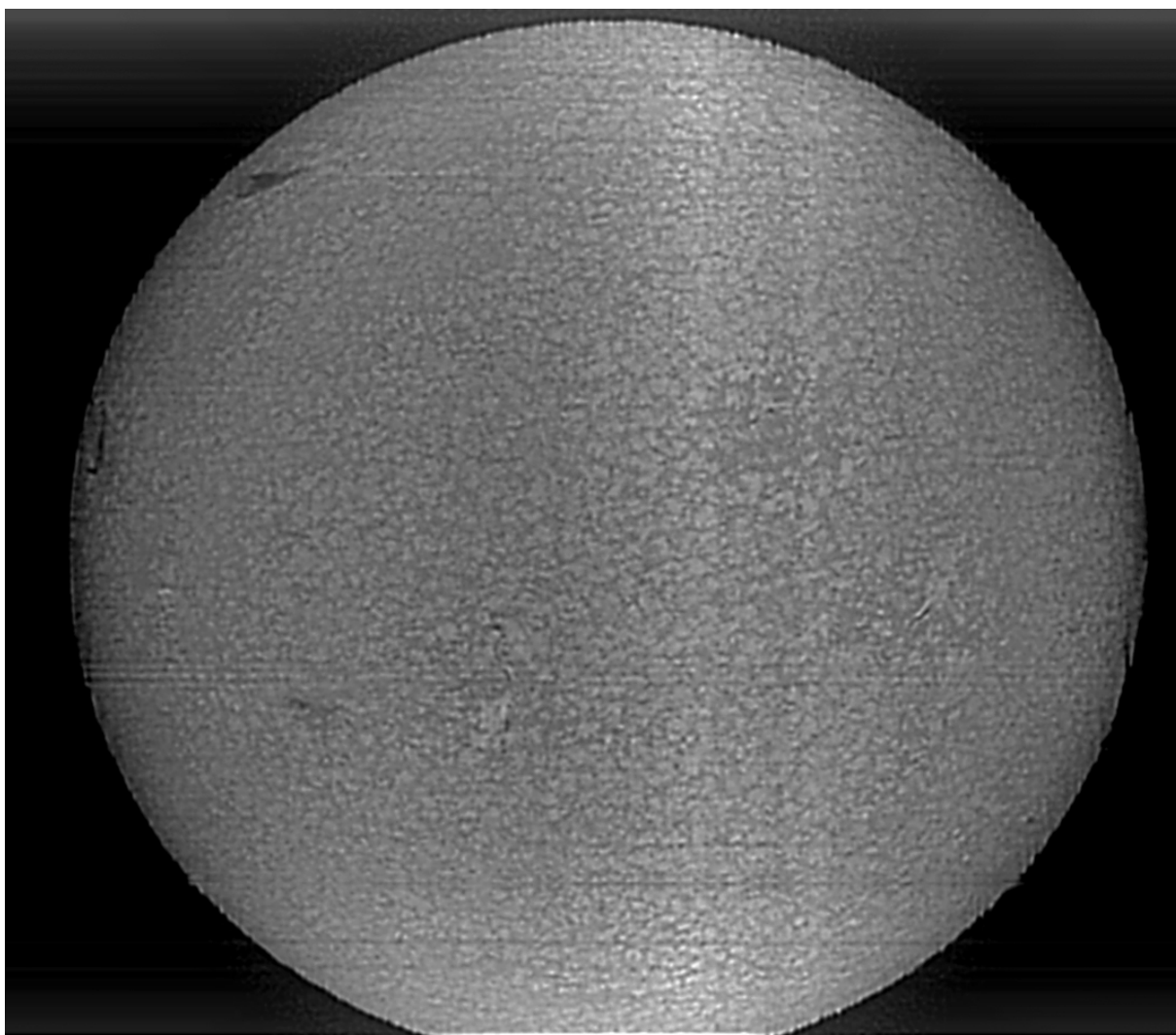
A highly contrasted Solarscan image in H $\alpha$  light of September 27, 2014: the saturated points at the north and south of the image are due to the flattening procedure with Astroart 3.

### **H $\beta$ at 4861.34 Å**

The diversity of the shots in H $\beta$  light is twofold: with regard to the ability of the cameras to record the chromospheric details, this is considerably intensified due to the position of the line, in a spectral area where most of the sensors have the highest Quantum Efficiency: however, it is not all gold what shines, as this results not only in the better reading of the chromosphere inside the line, but also in the intensification of the transversalium, ie the transversal lines due to manufacturing errors or grains of dust on the slit jaws. It therefore imposes, even more than the H alpha, the use of well-worked slits and / or synthetic flat lines. Following two images in this wavelength.





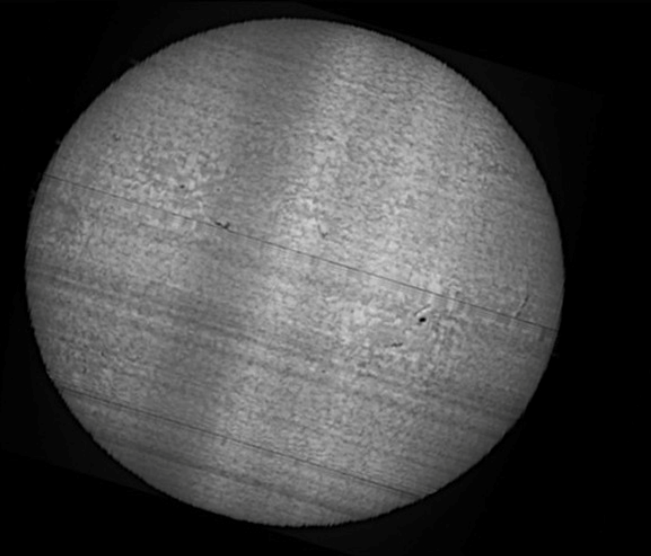
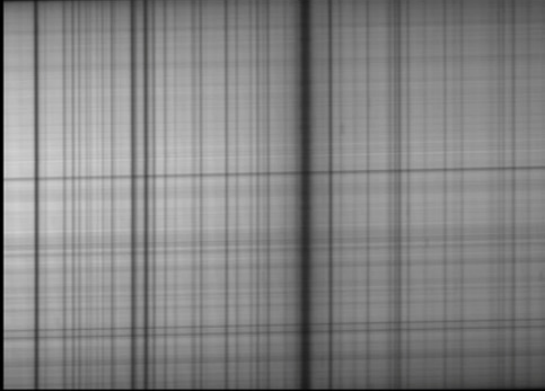


The second feature, which was previously mentioned, is the minor observability of some chromospheric details, such as the plages of the active regions, which appear dark rather than bright as in H alpha, and the greater, on the other hand, evidence of supergranulation. Below is a comparison between H $\alpha$  and H $\beta$  images in which this feature is evident.

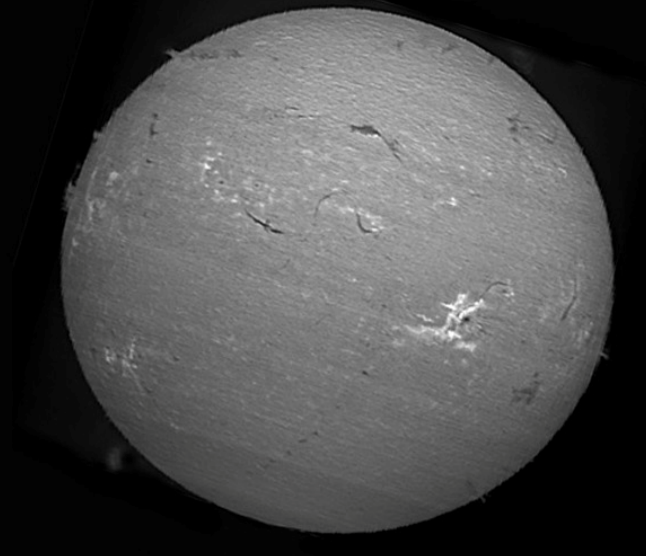
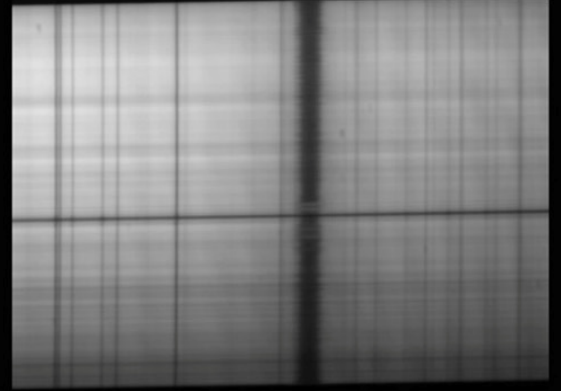
## Sun disk Hydrogen beta- Hydrogen alpha comparison

VHIRSS spectroscope in spectrhelioscope mode May 13 2012  
Fulvio Mete, Rome, Italy

H beta  
4861 Å

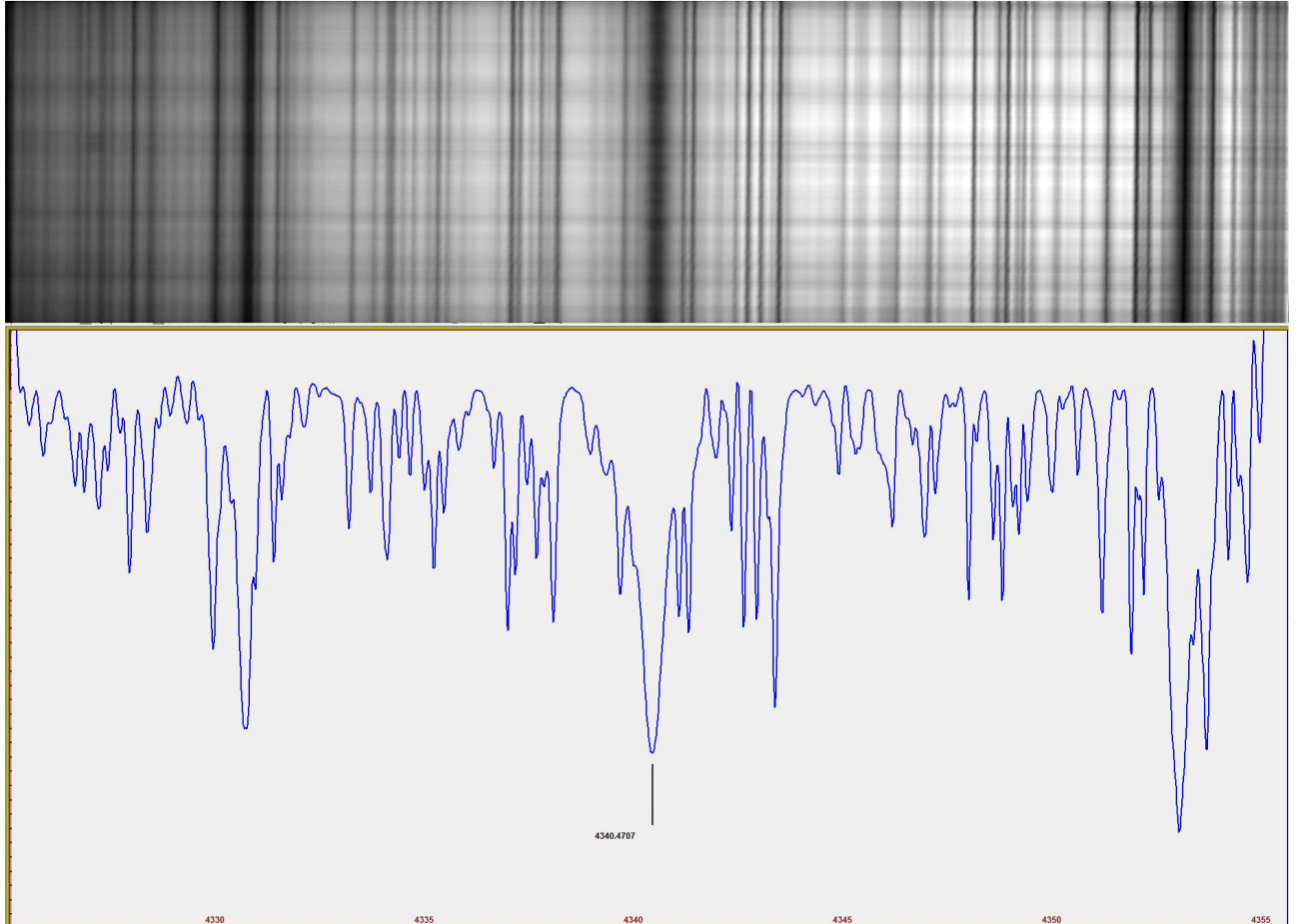


H alpha  
6563 Å

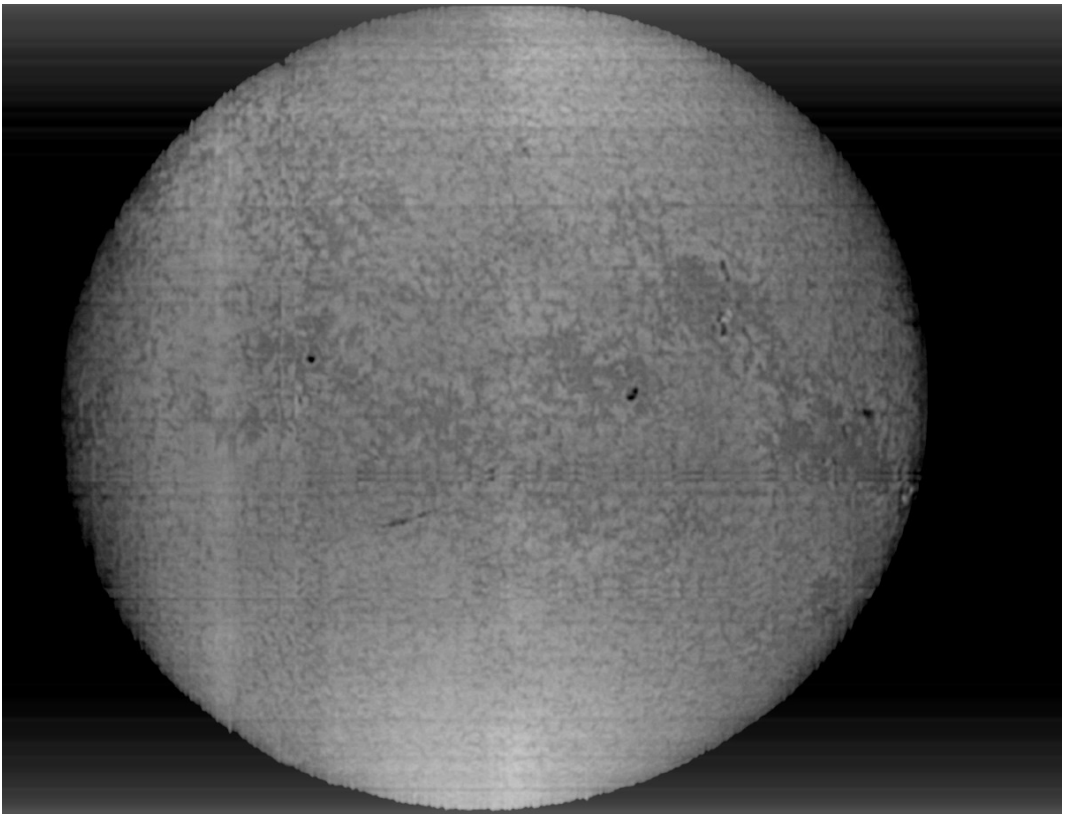
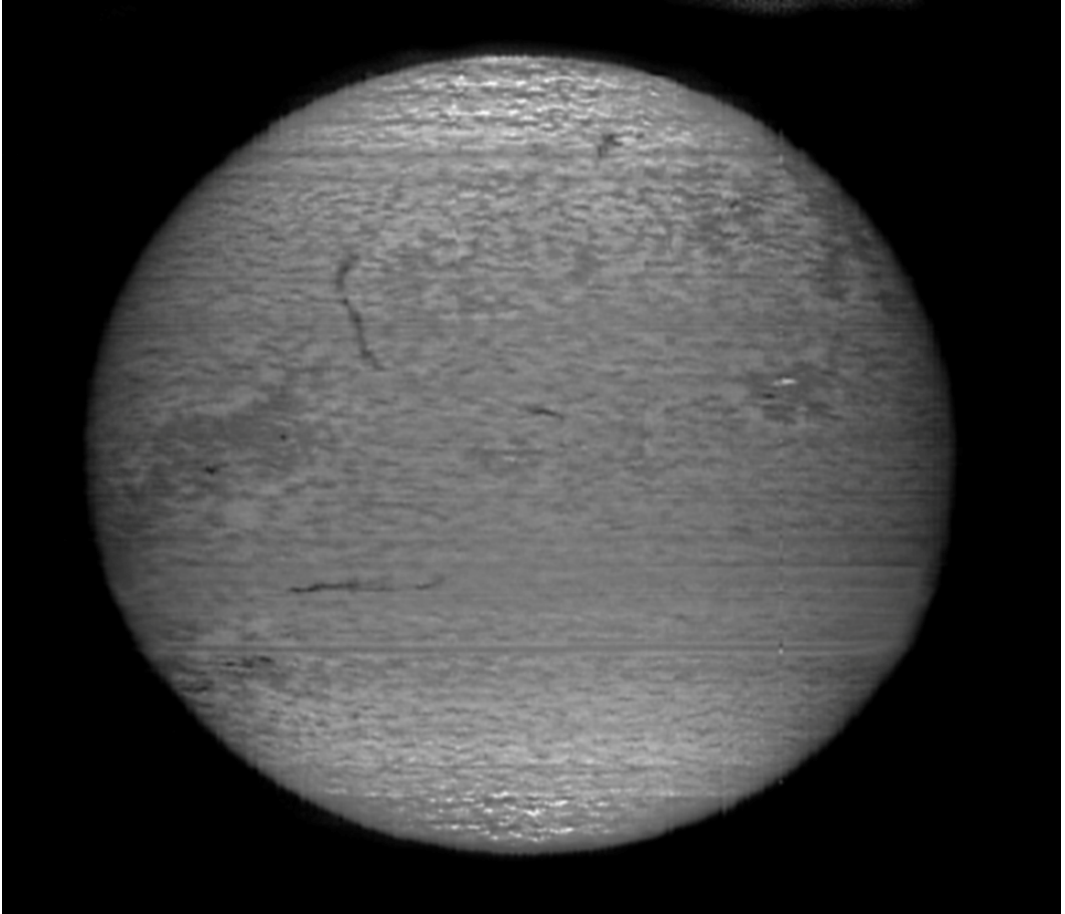


## H $\gamma$ at 4340.47 Å

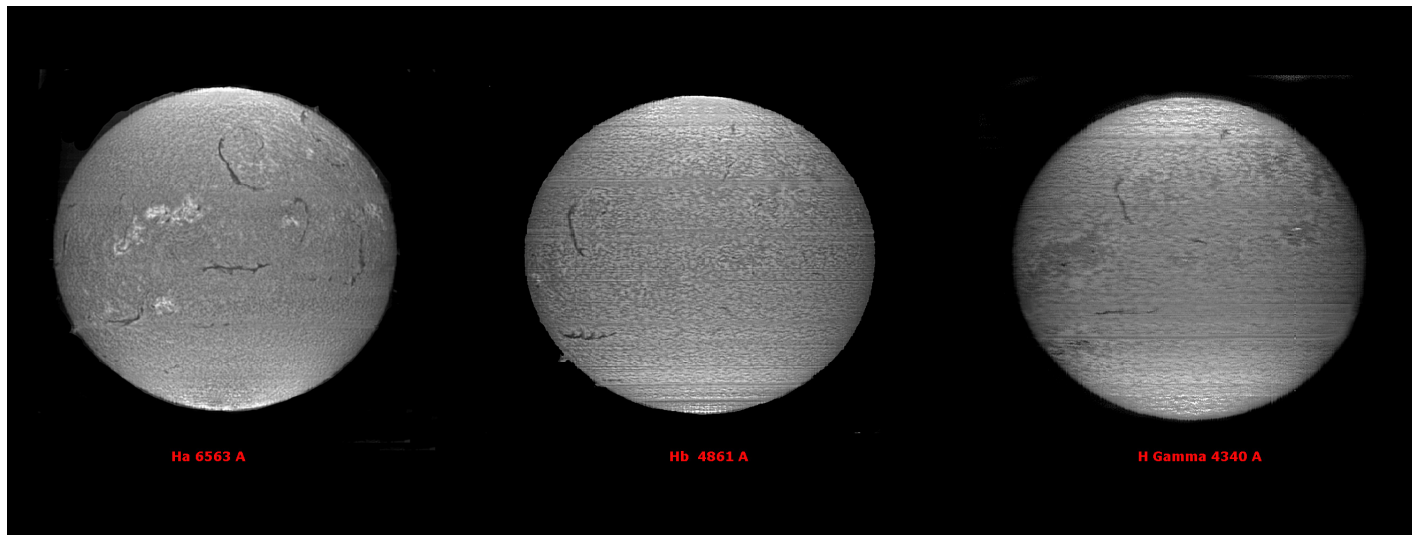
Making spectroheliograms in H $\gamma$  light is not trivial, due to the relative poor extension of the line and its thin optical window in the chromosphere.



The features of minor observability of the plages and in general of the active regions in H $\beta$  light, however, are now more evident in the images of the solar disk in H $\gamma$  light at 4340.47 Å, as observed in the following images, taken with Solarscan and VHIRSS:



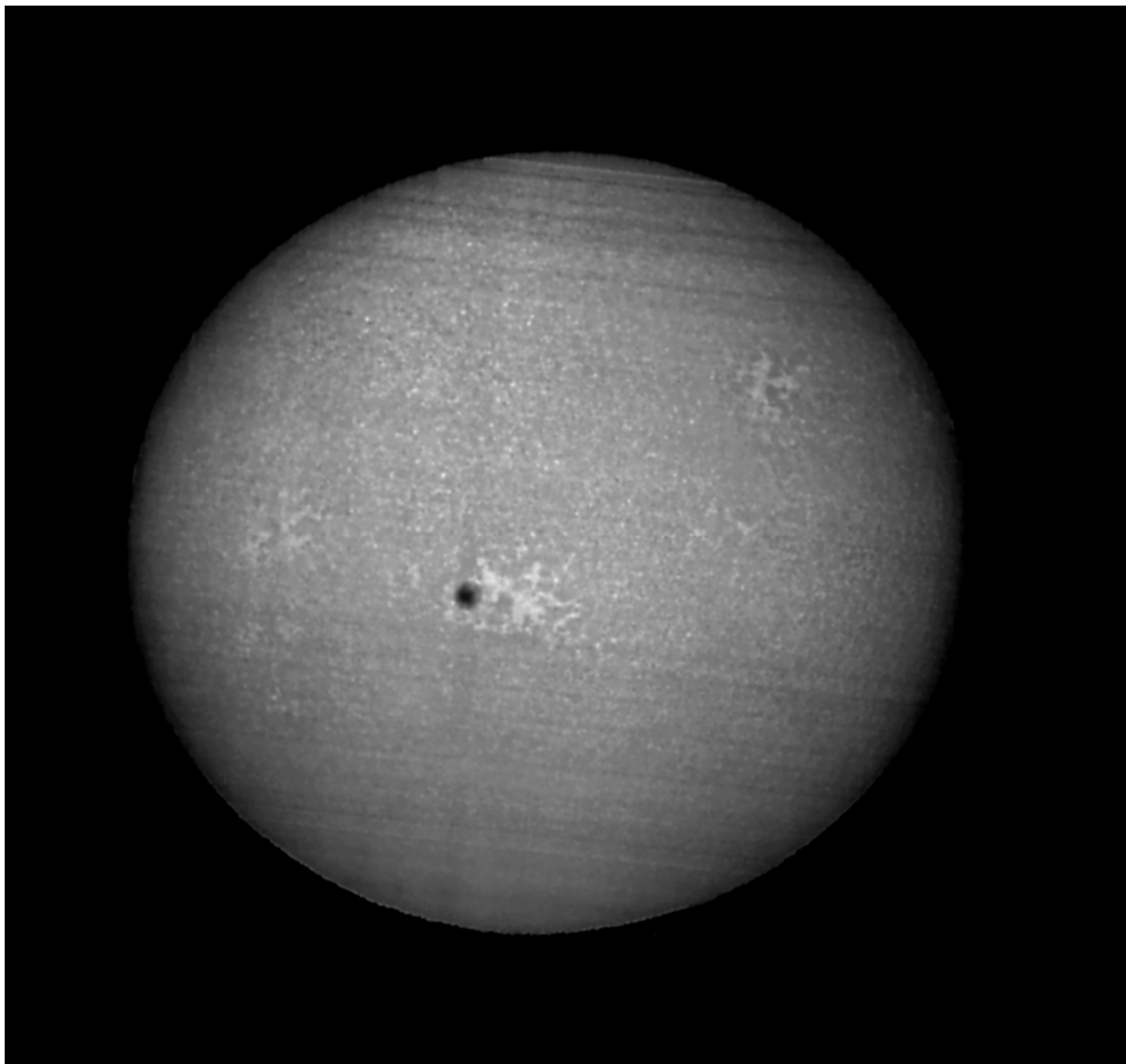
The image of the solar disk in the main lines of Balmer serie of ionized hydrogen, H $\alpha$ , H $\beta$ , H $\gamma$  confirms the trend described in the appearance of active regions, which pass from the bright white feature of the plages in H $\alpha$  to the gray of H $\beta$ , and dark gray of H $\gamma$ , while the very dark gray of the filaments of the H $\alpha$  becomes more and more tenuous in the H $\beta$  and in H $\gamma$  spectroheliograms. It is not only a matter of optical depth, but also of different collocation of the lines in the chromosphere and the difference of temperature.



### **Na D1 and D2 lines at 5889.75 e 5895.94 Å**

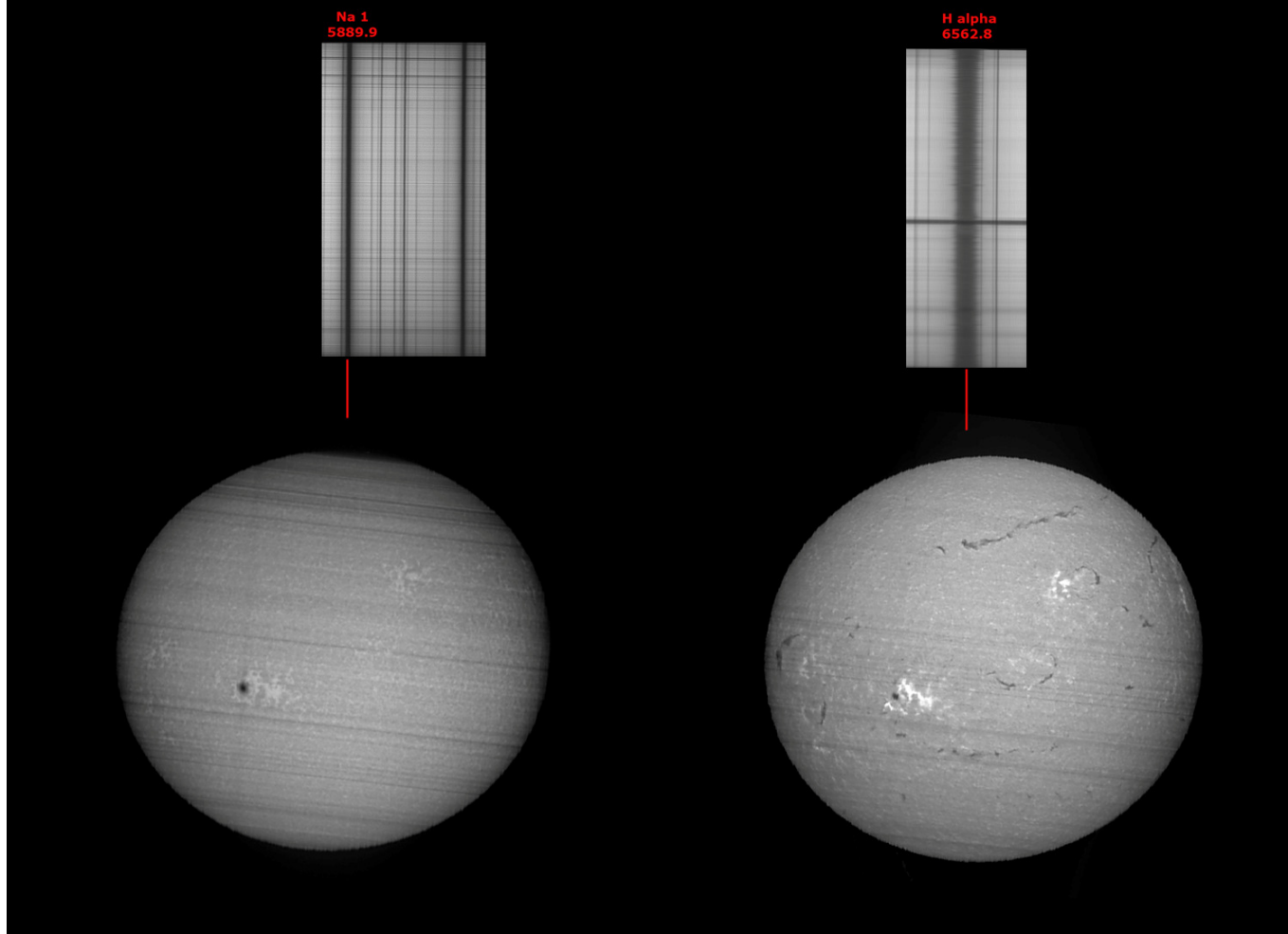
A spectroheliogram in Sodium (Na D1) at 5889.75 Å light taken with Solarscan on May 22, 2016 we note a facular appearance and granulation in some ways similar to that in light Ionized calcium, although much more attenuated.



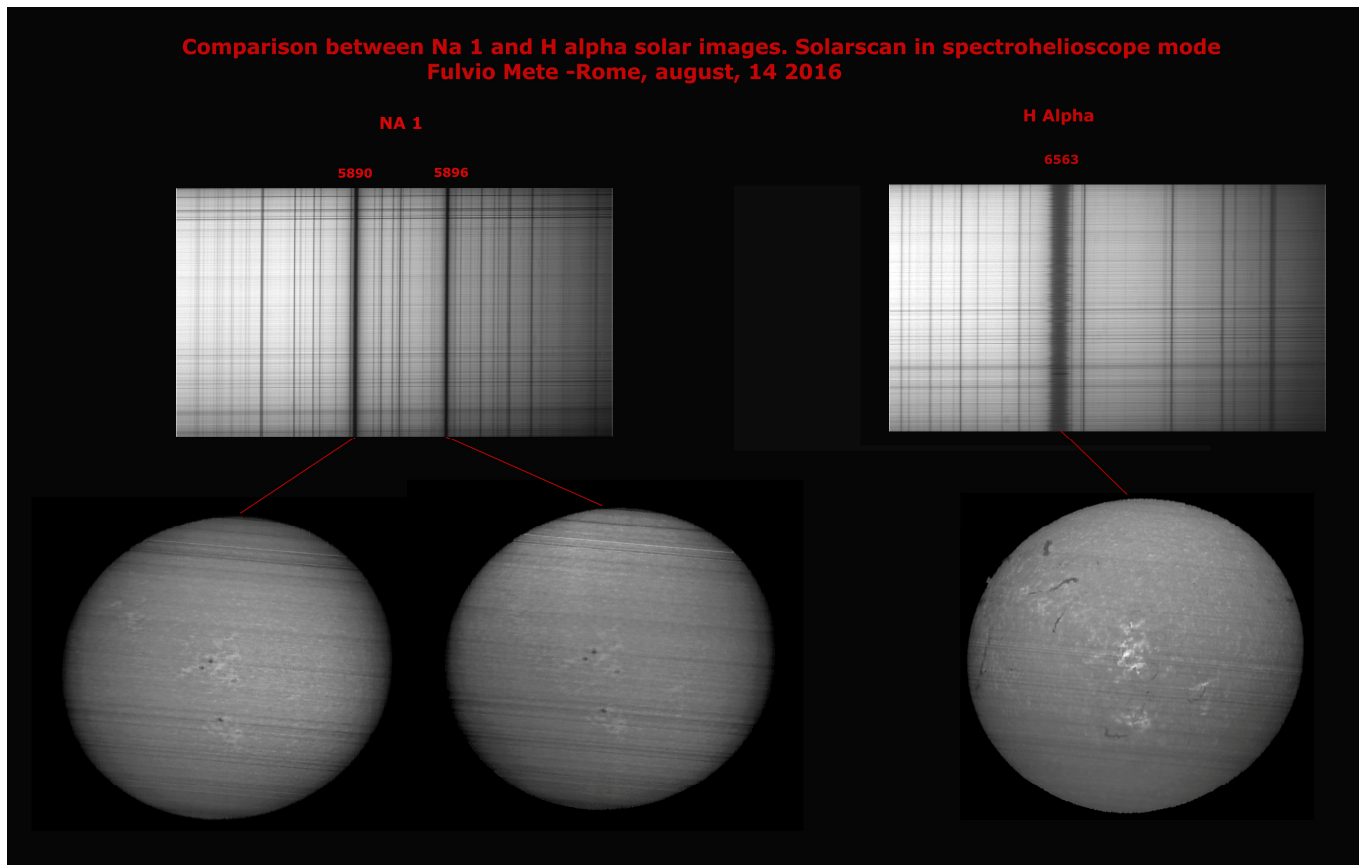


Subsequently, a comparison between the aforementioned image and a spectroheliogram in H $\alpha$  light carried out on the same day. The plages are clearly visible, although less brilliant than in H $\alpha$ , while the filaments on the disk are almost absent.

**Appearance of sundisk in Na 1 line at 5889.9 Å and H alpha at 6562.8 Å: a tomography of cromosphere  
Solarscan in spectrohelioscope mode- May 22 2016 - Fulvio Mete Rome Italy**



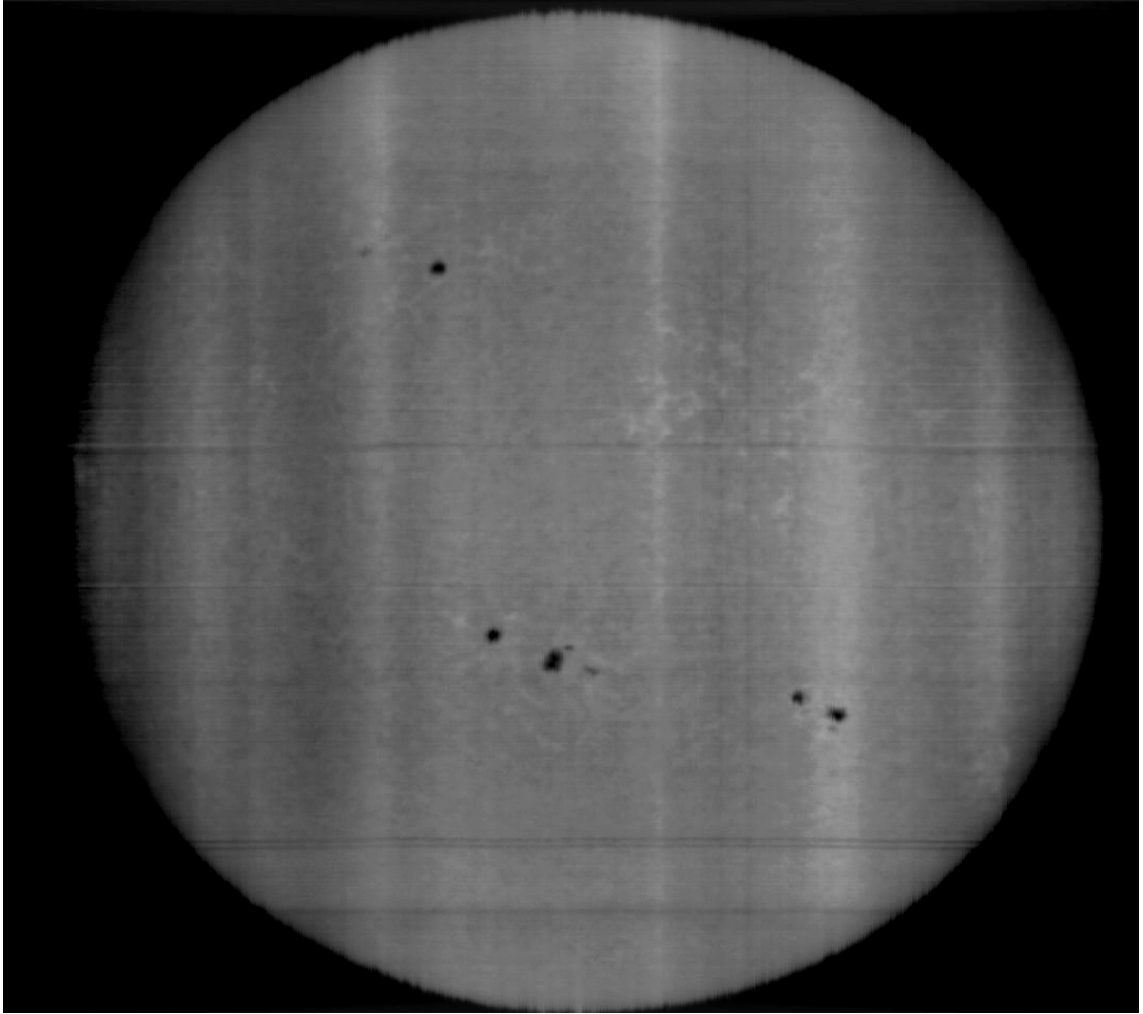
Another interesting observation was that of August 14, 2016, in which the comparison was made between the images, at the chromospheric level, of the solar disk in Sodium Na D1 and D2 light and then between these and the Hydrogen Alpha one.



## **FE 1 4957.61 Å**

A test aimed at recording images in a line of Iron, the one at 4957.61 Å, near the H $\beta$ .

You can observe the plage areas around the sunspots and a hint of supergranulation.



### **The lines of ionized calcium:**

As we have seen, these lines provide elements for a deep and complete observation of the solar chromosphere in the nearby UV, in addition to the H alpha.

**CaII K a 3933.68 Å**

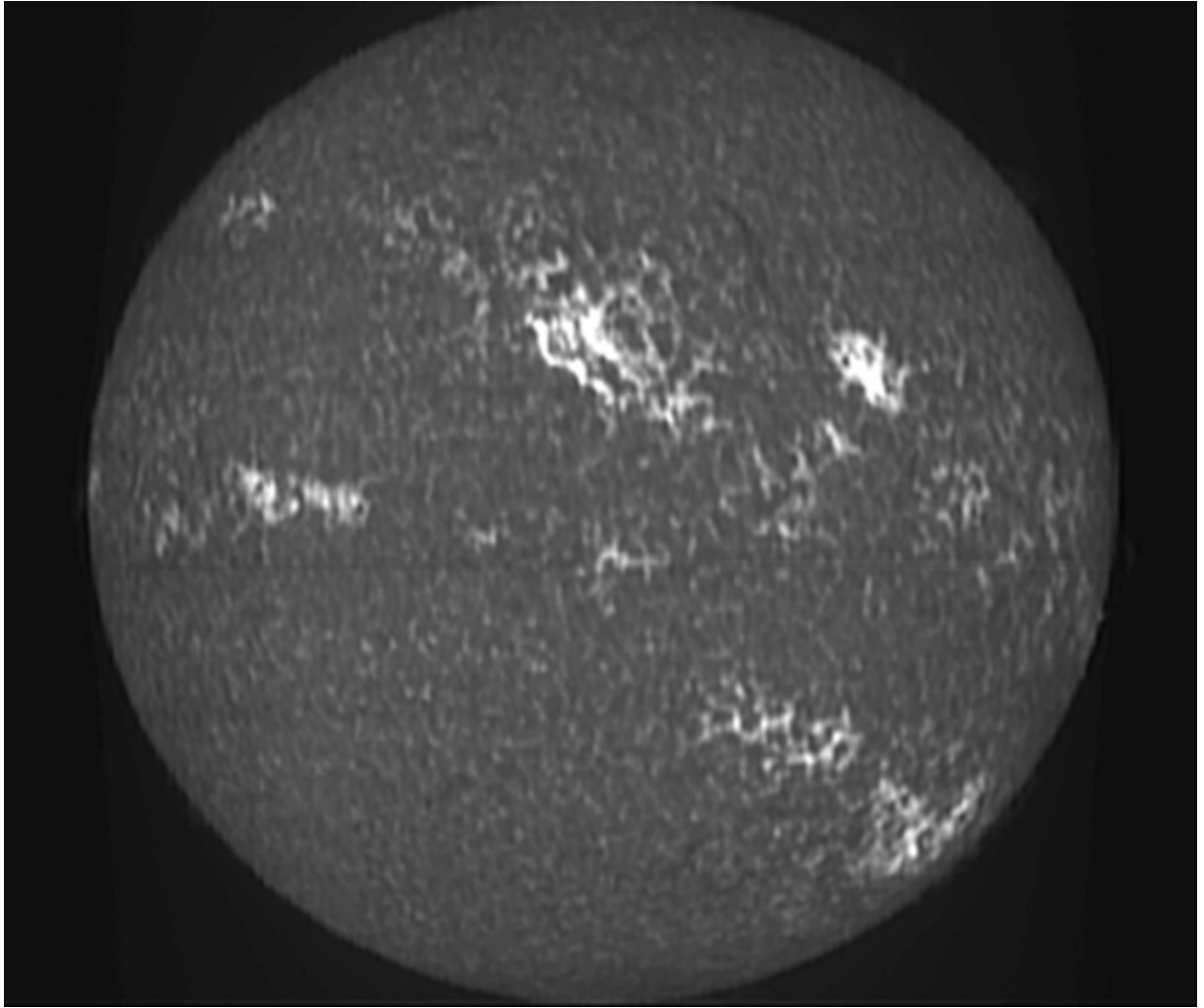
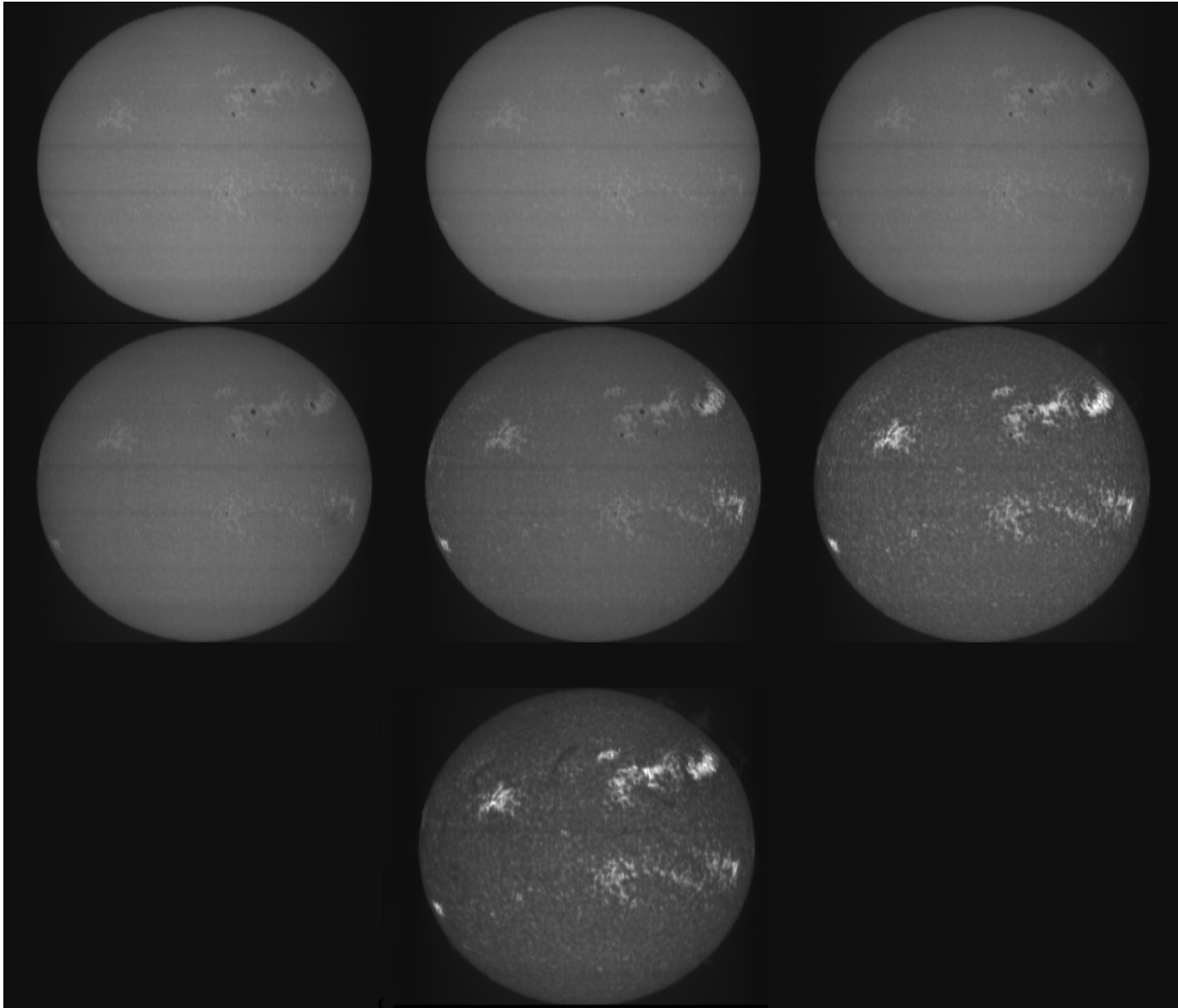


Image of the sun in light CaIIK3 (center of line) taken on July 28 2012 by VHIRSS.

The following image shows the succession of 7 frames  $0.029 \text{ \AA}$  each of bandpass in the violet wing of the line, spaced out by  $0.174 \text{ \AA}$ , which then goes from  $3932.61 \text{ \AA}$  to  $3933.68 \text{ \AA}$  (center line K3), in which there is also the image of the stationary point K1v at  $3933.32 \text{ \AA}$ . Considered that the coefficient of absorption of a line with respect to the continuous is a function of the height with respect to the base of the photosphere and varies continuously with the wavelength, the variation of the absorption coefficient of the line from the wing towards the center allows to perform a sort of tomography of the height of the chromosphere zone observed until reaching more than 2000 km from the photosphere in the very center of the line K3. Each frame would therefore correspond to a zone of the high chromosphere. Dramatic the change in the appearance of the chromosphere itself within a single Angstrom, first of all with regards to

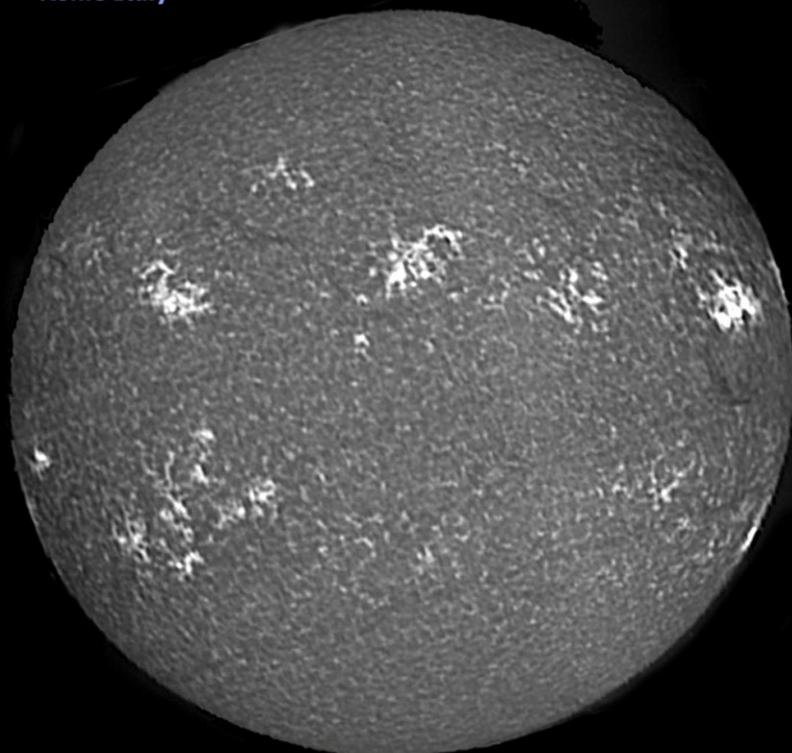


the variation of the sensitivity of the line to the magnetic fields in the active regions, with the passage from absorption into emission, and then to the visibility of the filaments and the protuberances.



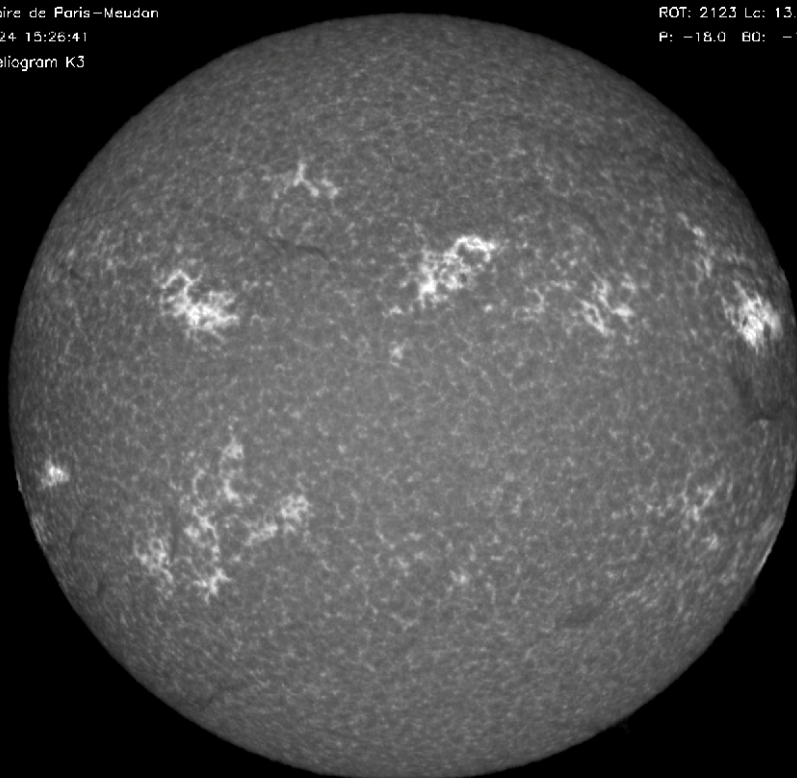
In the following image a comparison between a CaIIK solar light image obtained by VHIRSS and one with the Paris-Meudon Observatory spectroeliograph, mentioned previously: the difference is less than one might imagine.

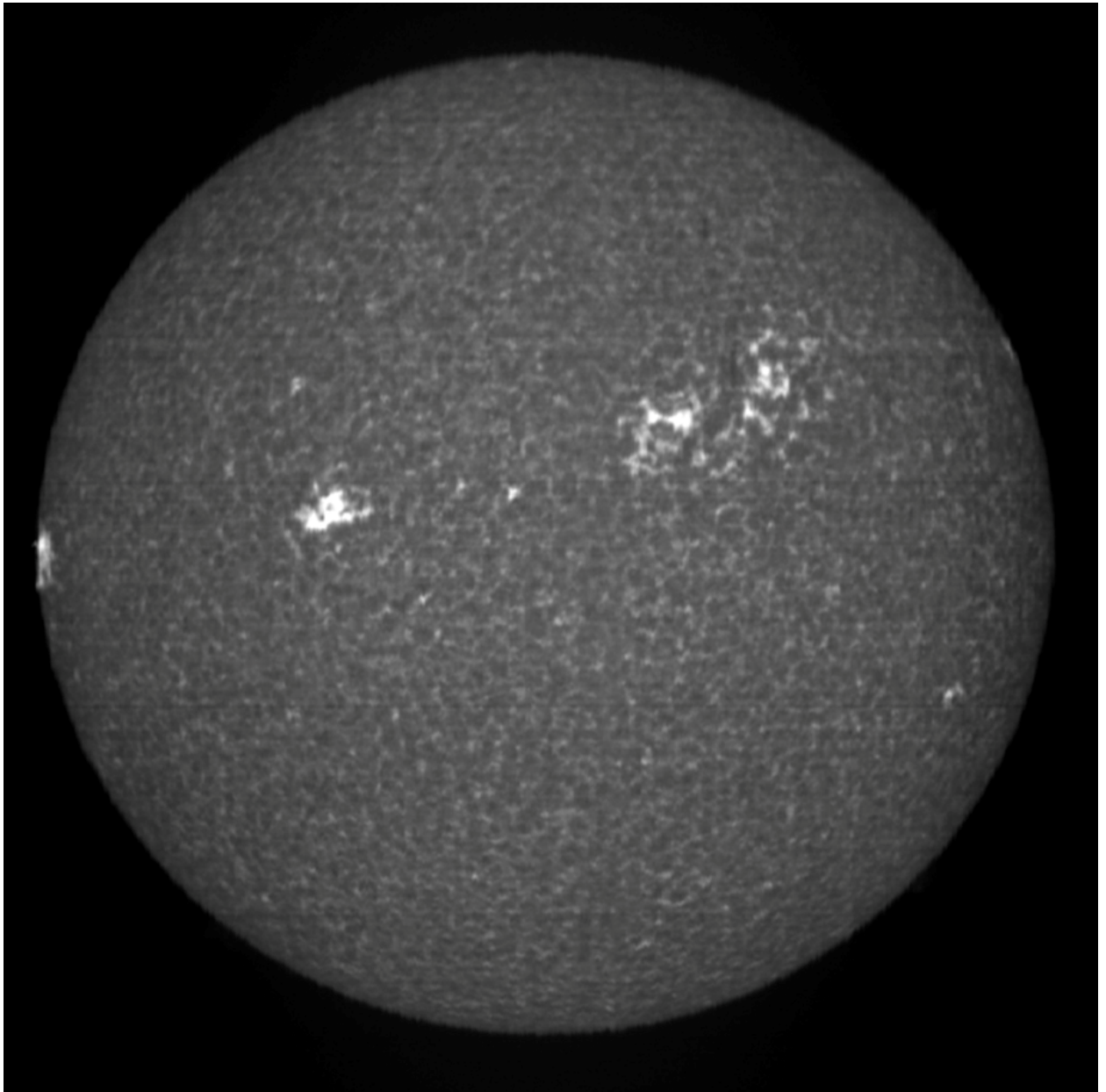
Sun CaII K VHIRSS  
24-05-12 Fulvio Mete  
Rome Italy



Observatoire de Paris-Meudon  
12/May/24 15:26:41  
Spectroheliogram K3

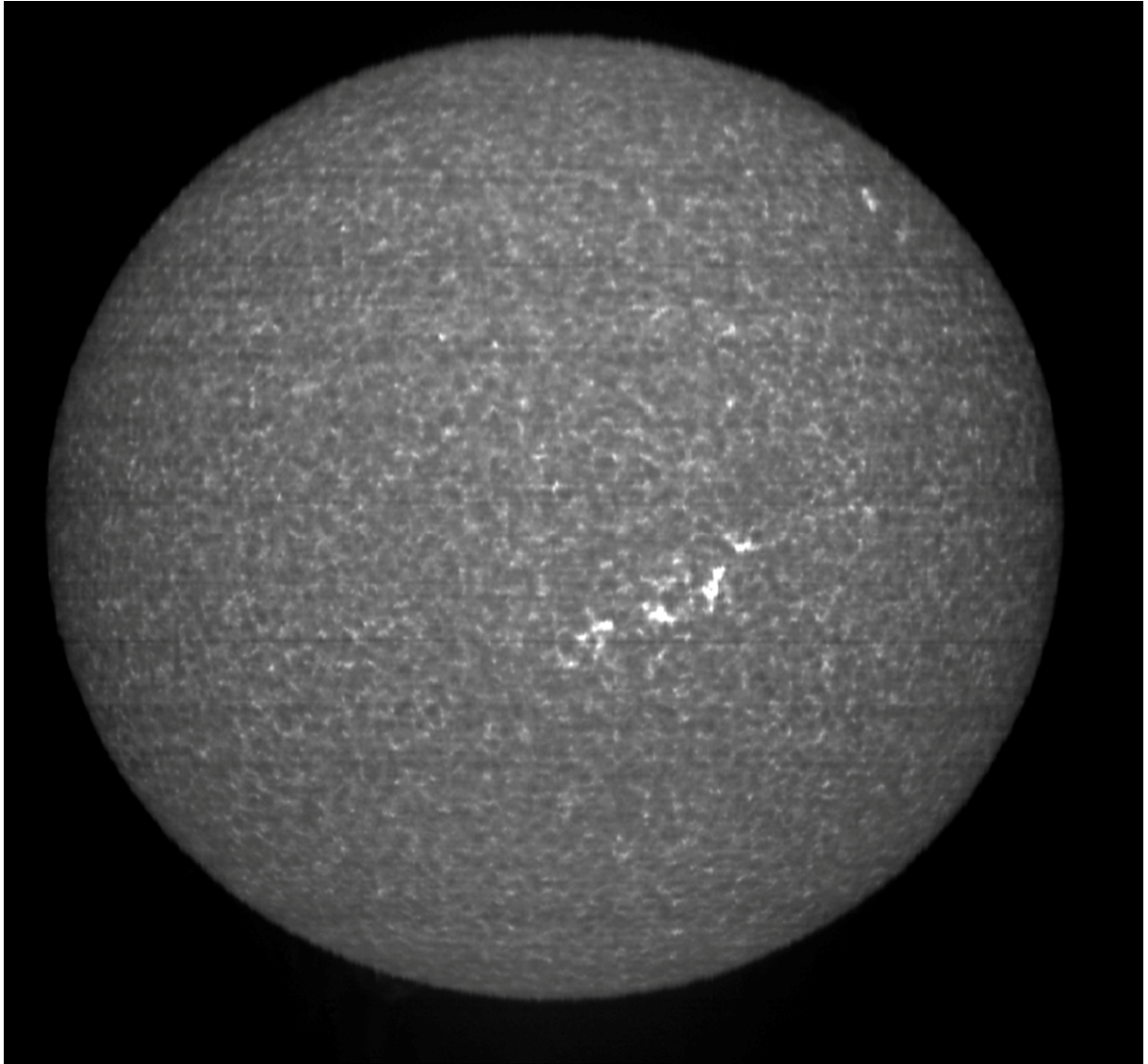
ROT: 2123 Lo: 13.8  
P: -18.0 B0: -1.5



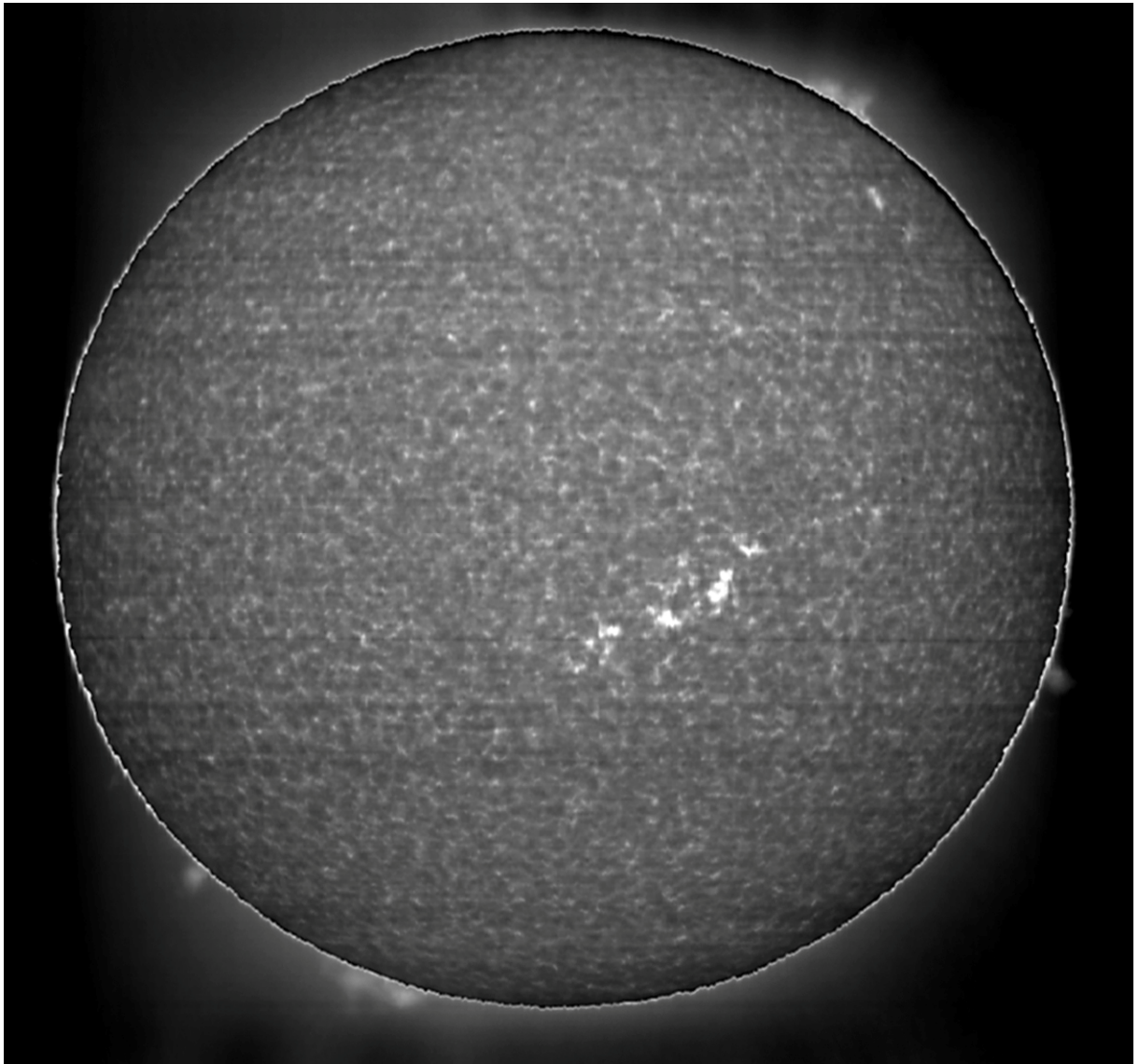


A nice image in CaIIK3 (center line at  $3933.68 \text{ \AA}$ ) of June 24 2018 with POSS2, bandwidth  $0.037 \text{ \AA}$ . Note the practical impossibility to obtain such images of the center of the line with the amateur interference filters CaII K, for their bandwidth too wide (about  $2.2 \text{ \AA}$ ).

Below another detailed image of solar disk in CaIIK3 light shot on october 18 2018 by POSS2 spectroheliograph.



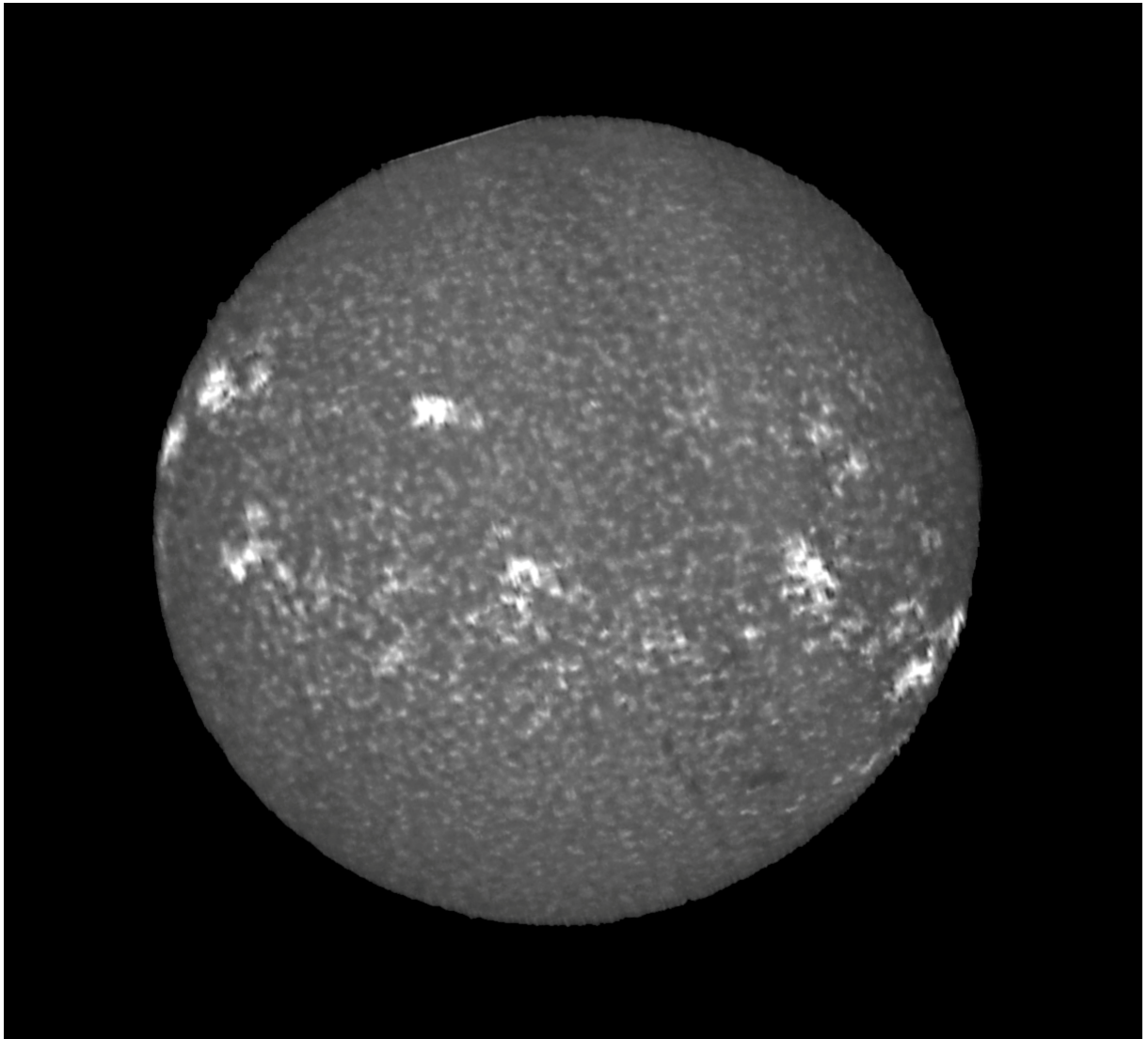
The same image with two exposures, one for the disk and one for the prominences, superimposed by software.



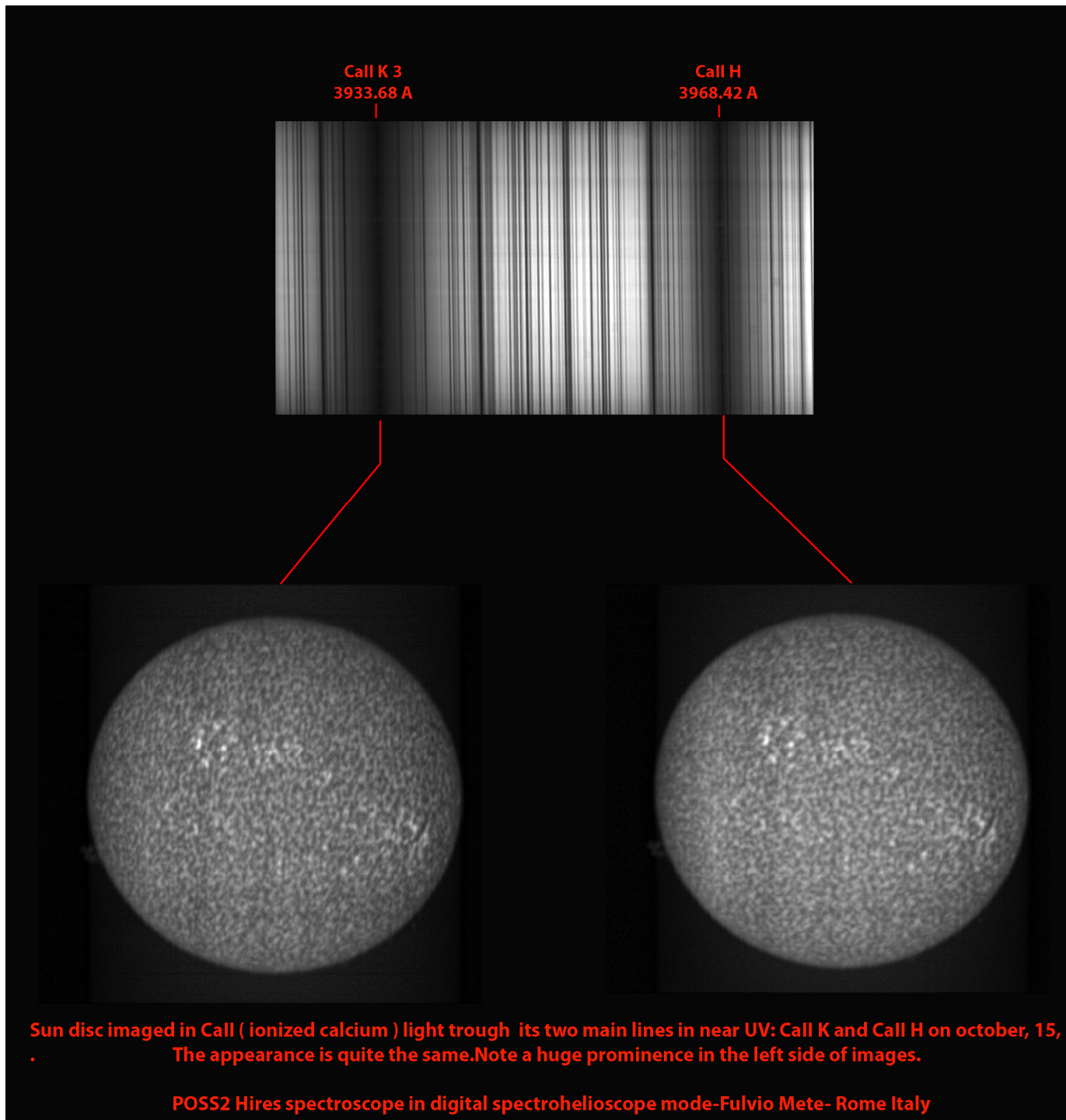
### **CaII H at 3968.49 Å**

It is the second line of ionized calcium in the near UV.

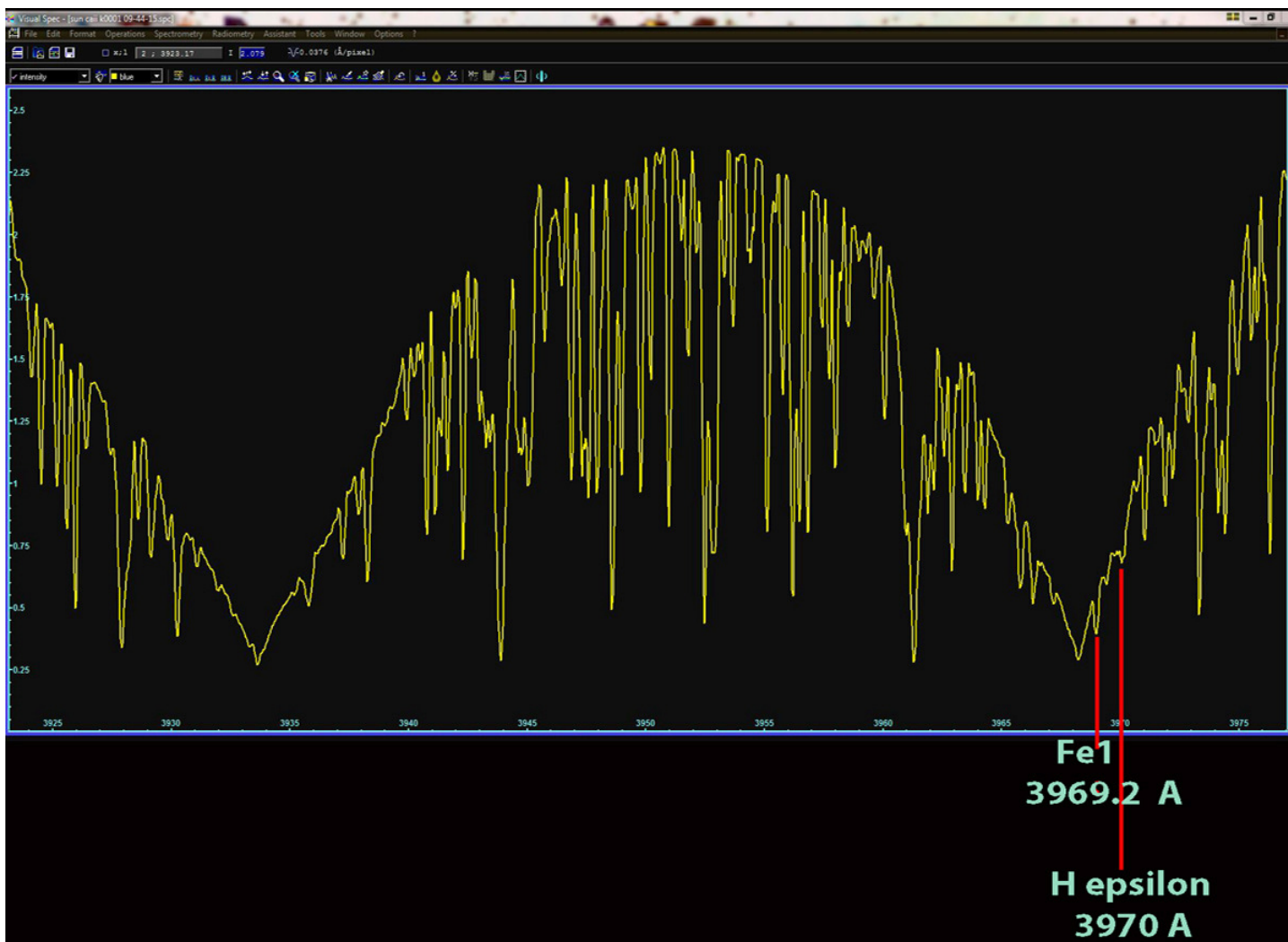




Observing it, the question arises about the difference between that and the best known CaII K. At first sight none, as can be seen from the following comparison:



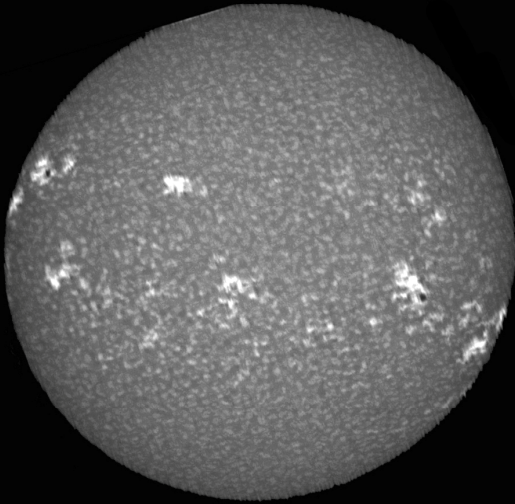
The two images, obtained from a column of 1 pixel of  $0.037 \text{ \AA}$  in bandpass on the center of both lines, do not show substantial differences. In the case of a wider bandwidth, however, the line would risk to be observed in blend with that of iron at  $3969.2 \text{ \AA}$  and of the Epsilon Hydrogen at  $3970.0 \text{ \AA}$ .



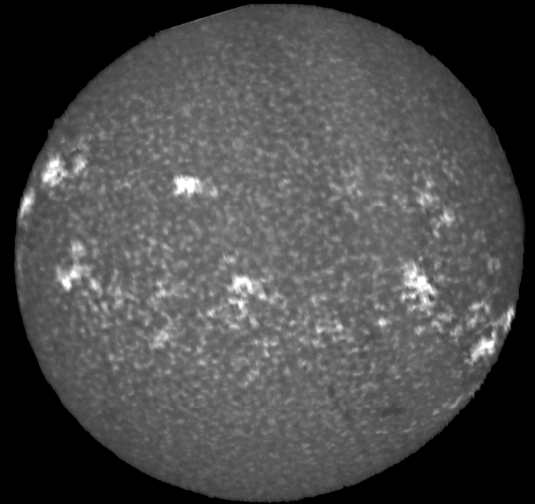
In the following image, of year 2014, a comparison between two CaII H light solar images obtained with the average of frames corresponding to 0.2 Å and 1.44 Å, both centered in the middle of the line: the difference is minor, but visible.

Spectroheliogram in Ca2h light at 3968.49 Å in 1.44 Å and 0.2 Å bandwidth- VHIRSS in spectrohelioscope mode  
Fulvio Mete- Rome- May 06 2014 8.15 UT -

1.44 Å



0.2 Å



## Processing and flatting of spectroheliograms

The processing methods that I will go to exemplify are the exclusive result of my experiments on the subject, and certainly the computer experts will find better ones, but they seem to work in an acceptable way, improving not only the overall appearance of the images, but also the visibility of chromospheric details.

### 1- processing

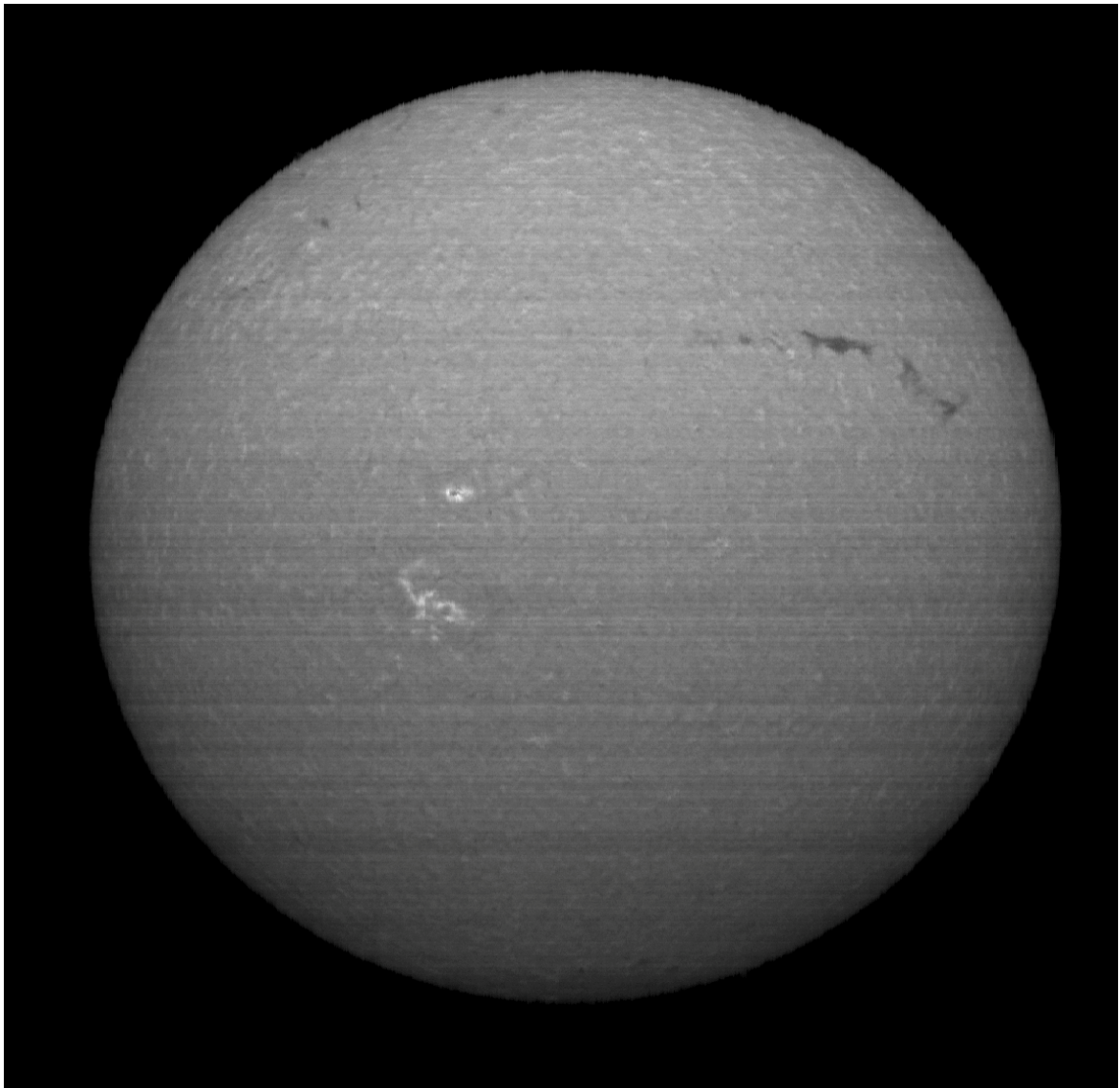
By processing I mean only a few cosmetic steps to make the images more pleasant from an aesthetic point of view. Obviously modifications to these file (Fits, PNG, BMP) make them unusable for any scientific activity.

An elaboration that I do not use often, but aesthetically pleasant, is to modify with Photoshop the central image of a series, multiplying it by the ones (or the one) at the ends of the series itself.

Let me explain: we admit that from a given solar scan video treated with one of the software mentioned above, I get, by hypothesis, 41 images of the H alpha line (this is certainly possible with Spectral Line Merge that converts the filmed in a number of png files up to 100) each of a pixel, one centered on the center of the line and then 20 towards the blue and 20 towards the red.

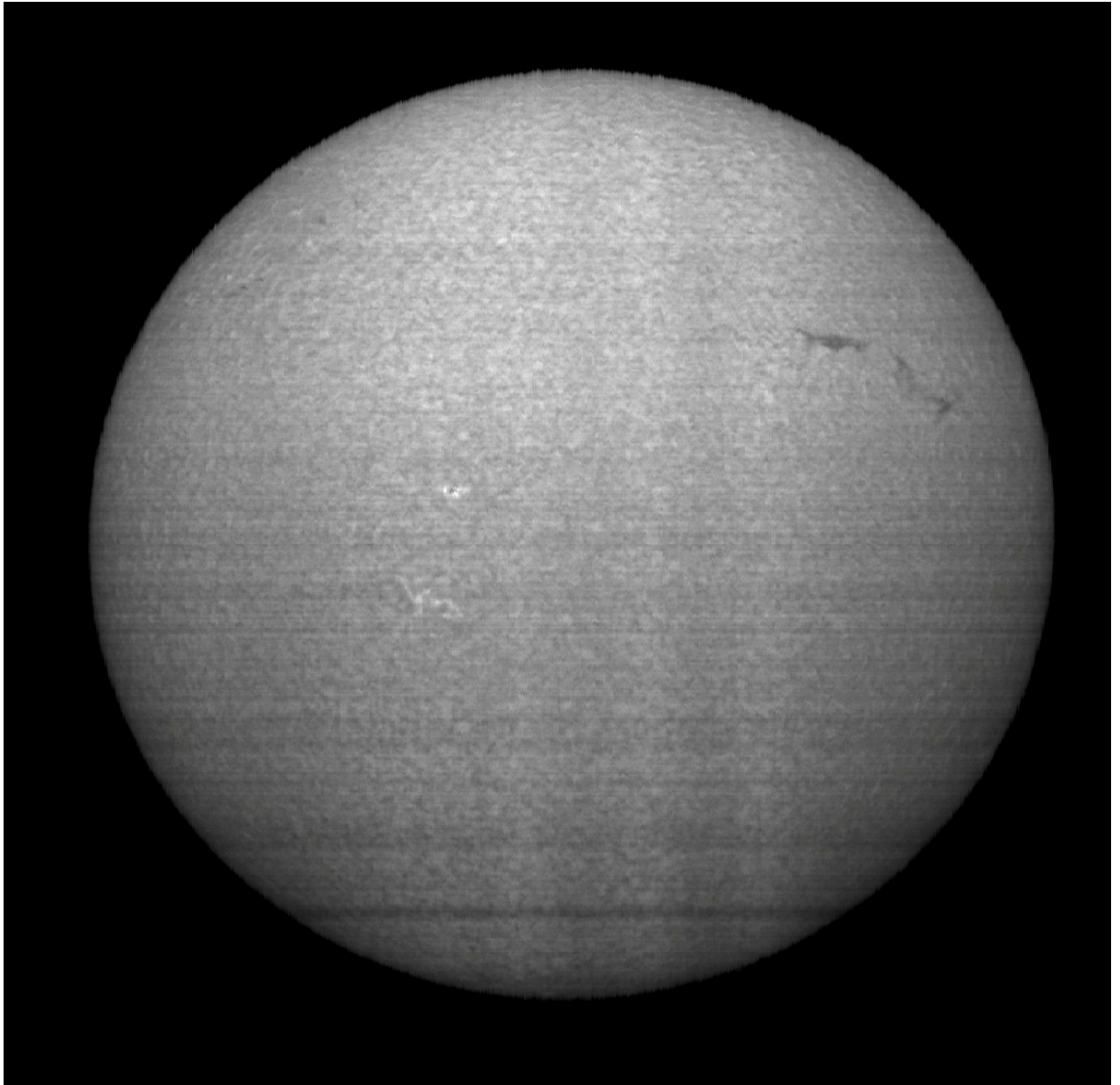
Then take the one corresponding to the center of the line, say 21, and multiply by the one at the end towards the blue, the 1, using the appropriate menu "Image> Calculations" of Photoshop, the multiplication can also be done for both extreme images of the two wings, but the result is not always convincing. Once this is done and the levels are adjusted, a low pass filter (Blur) and a blurry mask (Unsharp Mask) can be applied.

Let see now an example of the procedure on an H alpha image by VHIRSS:



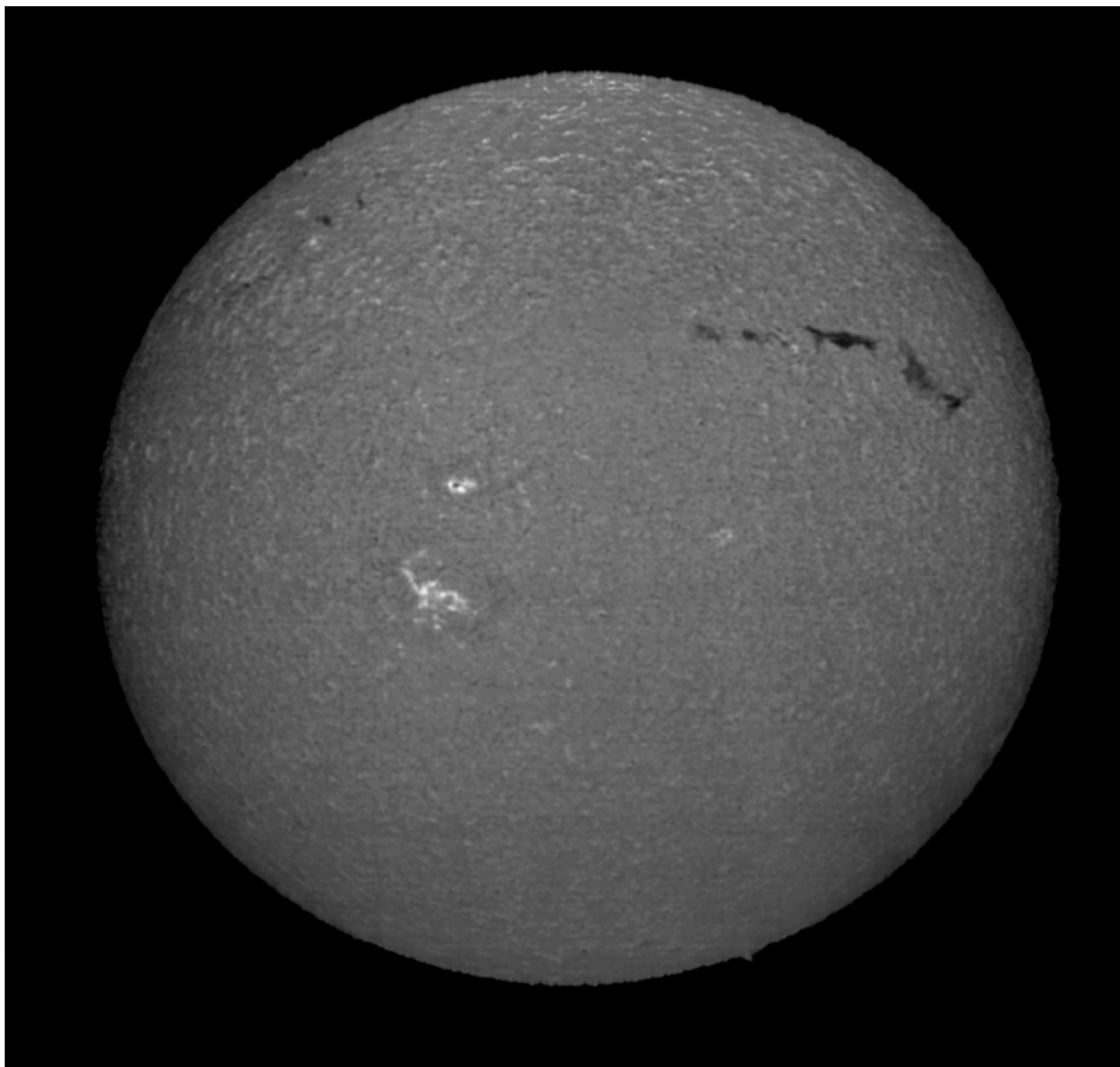
The image of the series at the very center of the line





Last image toward the blue wing

The following image is the one obtained by the multiplication and finishing process mentioned above and by the application of a synthetic flat. The improvement in visibility of details is obvious.

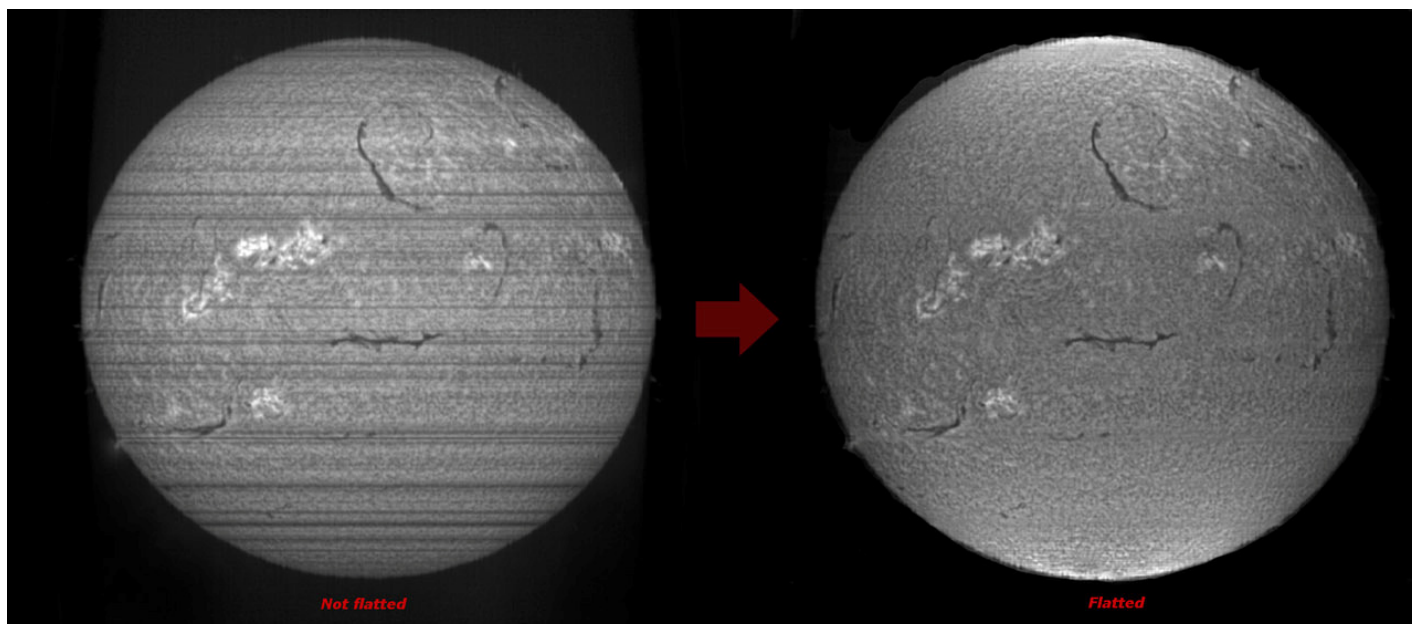


## 2 - The synthetic flat

As we said, the only way to eliminate or minimize the transversalium, the horizontal lines due to the slit, consists in operating a synthetic flat, since the ordinary flat is not possible with sunlight. Some programs, such as BASS, already provide a routine to make the flat of the spectral images, others like Spectral Line Merge, indicate the procedure to carry it out. In any case, these are operations of a certain complexity, so I posed the problem of finding a simpler and quicker way for this task. I knew that Astroart software allows, in all its versions, from 3 onwards, a binning operation on the images, which consists in "stretching" the image in the direction of the X side of the pixels or on that Y (image> binning> X average or Y average). I therefore thought to carry out this simple procedure:

- 1- Load and duplicate the image on AA3
- 2- On the duplicate, perform the binning X average operation
- 3- Subtract this binning image from the main one (aritmetic> subtract)
- 4- To make it readable, operate an "add offset" (aritmetic> add offset) between 60 and 80.

It may seem strange to make a flat by subtraction rather than by division, but the fact is that by doing the division the image is often "burned" in the north and south in some cases, while in another it works properly, as in the example below, so the correct procedure must be established on case by case basis considering that the flat applied with the division seems to provide better results than that with subtraction when the transverse lines are many and marked, while the subtraction provides a good result with little evident lines.

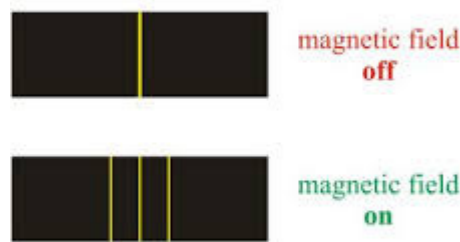


## **Not just imaging**

After this overview on the possibilities offered by the digital spectroheliographs, in my opinion of extreme interest for both the advanced amateur astronomer and the beginner eager to learn, we can ask if the instrumentation dedicated to it that has been discussed before has exhausted its possibilities. The answer is negative, because the same instrumentation (in some cases with small changes) will allow us an even more exciting challenge: the measurement of the magnetic fields of the active regions and sunspots through the Zeeman effect, an activity so far exclusive of professional instruments costing millions of euros or dollars. But let's go in order:

### **A brief reference to the Zeeman effect**

The Zeeman effect consists of enlarging or splitting in several parts of a spectral line by the effect of a magnetic field. More specifically, the Zeeman effect can be defined as the physical phenomenon connected to the decomposition of the atomic energy levels or the spectral lines due to the action of an external magnetic field. Peter Zeeman, the Dutch physicist who won the Nobel Prize in 1902 for the discovery of this effect which took the name from him, realized experimentally that, in the presence of a perpendicularly oriented magnetic field, some spectral lines were broken up into three different lines (orthogonal Zeeman effect) while with a magnetic field oriented parallel to the object the lines of the decomposition were two, and the central one disappeared (longitudinal Zeeman effect). Subsequently we realized that the decomposition was much more complex than first appeared and, in relation to the spin of the electron, we talked about anomalous or normal Zeeman effect. In astrophysics, the American astronomer George Ellery Hale was the first to observe and report officially in his article of 1908 such effect on the magnetic field of sunspots even if other astronomers, including the Italian Lorenzo Respighi many years before had observed the same phenomenon. Today, the same effect is used to obtain magnetograms of the solar surface with highly sophisticated instruments such as the SDO HMI.



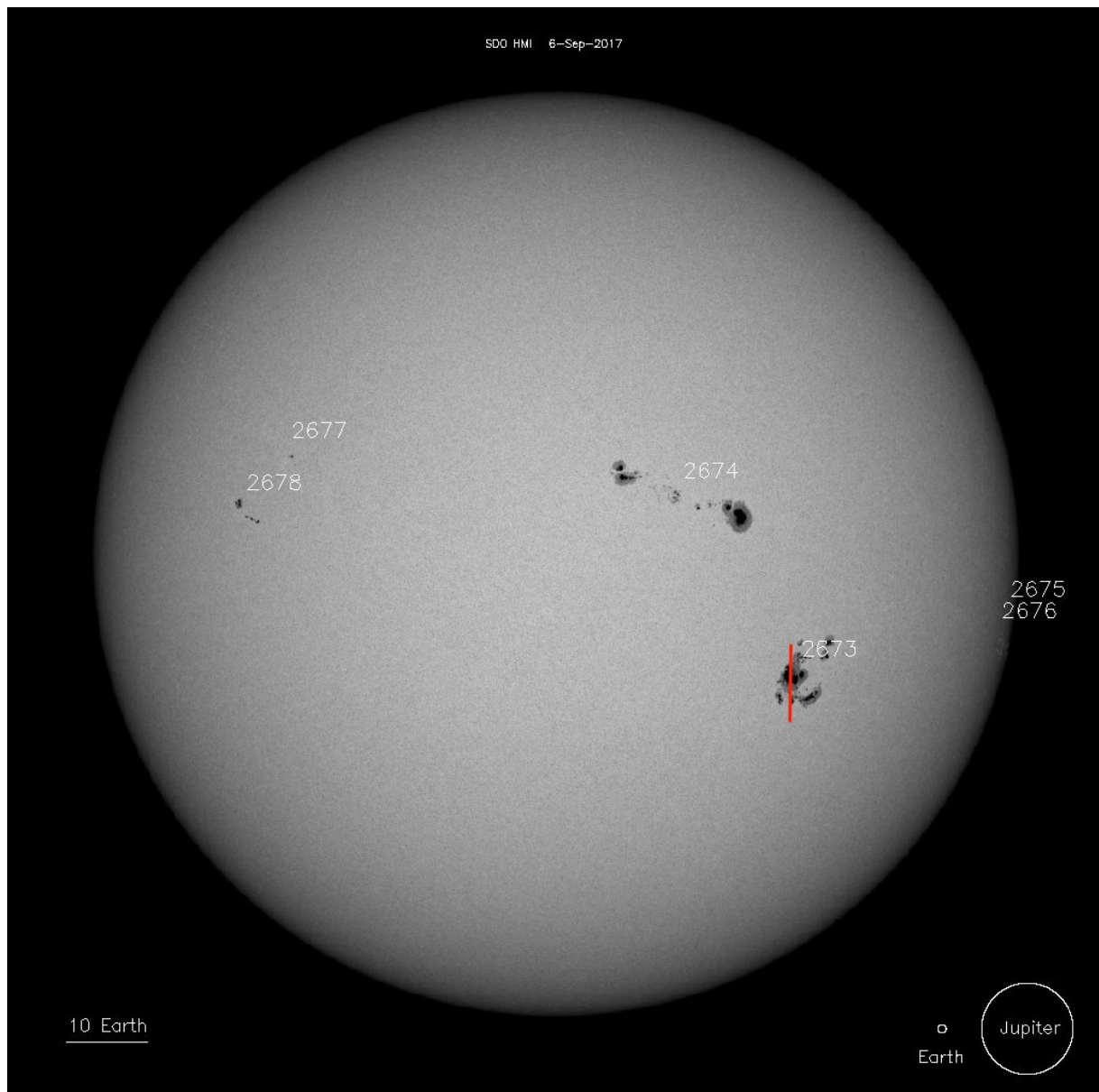
If the line is in emission we speak of direct Zeeman effect, while if it is in absorption, of inverse Zeeman effect. From the point of view of amateur astronomy, the phenomenon in question is very difficult to observe due to the simple fact that it requires very high spectral resolution powers (in my opinion > 60,000) and a certain familiarity with the solar spectrum lines for the individuation of the iron lines affected by the phenomenon, among which first those FeI at 6173 and at 6302 Å. The recording of the Zeeman effect on the solar spectrum lines in the presence of strong magnetic fields of sunspots is therefore a real challenge for the amateur who deals with spectroscopy and its instrumentation.

In my case the instrumentation was already ready and tested: the Hires Solarscan spectroheliograph and a DMK 41 camera, with a 1280 x 1024 Sony sensor on a Losmandy G mount 11. That is to say. This instrument, built with professional criteria, was excellent under all the aspects, however, for such a difficult task it was necessary to strengthen even more its features and potentialities. A decisive increase of the performances could be obtained, all other conditions being equal, only by acting on the slit: therefore I decided (not without regrets) to replace the original motorized adjustable slit with a sophisticated and complex spring system, with a fixed 5 micron slit, purchased by Edmund Optics, whose edges were cut to precision lasers and therefore with very tight tolerances, difficult to obtain with a closing system made with ordinary machined steel blades, no matter how well built. This choice proved to be a winning weapon, as it gave me a considerable gain in spectral resolution, which exceeded  $R = 100000$  with the application of a light wavelet filter to the spectrum. From an instrument of such size and weight, one could not expect more.

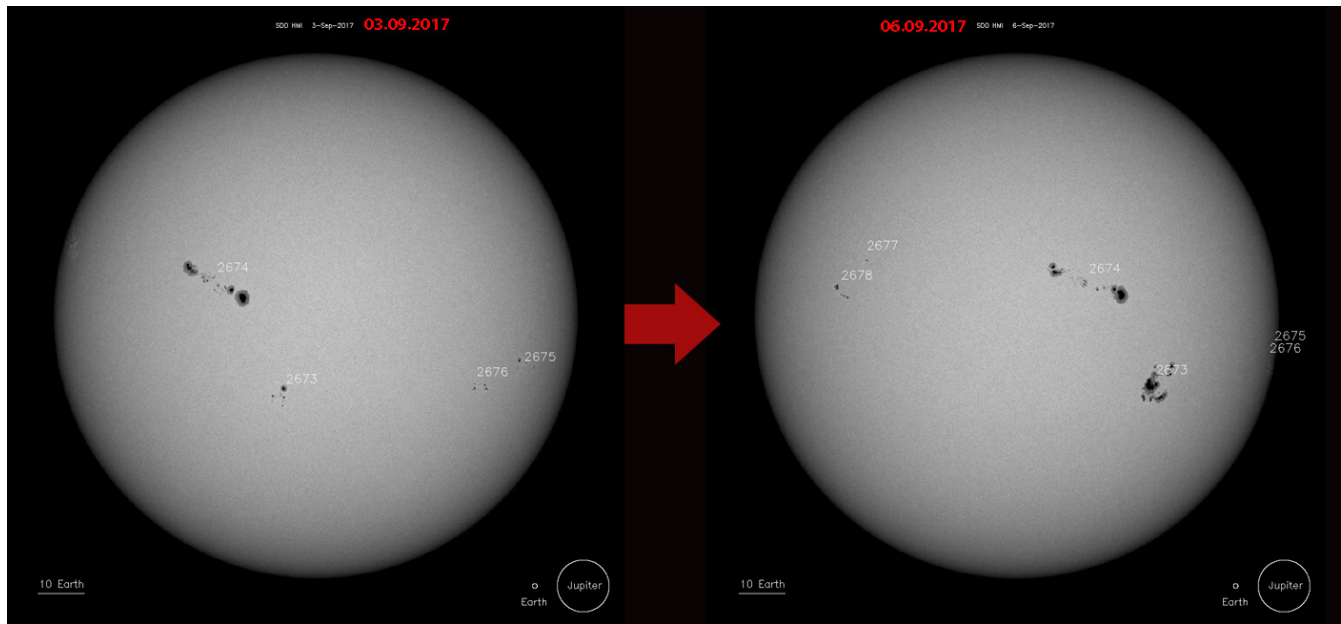
This choice of Solarscan was not dictated only by the quality of the instrument and its components, but also by the awareness of its reliability and stability over time in the observations of the phenomenon in question.



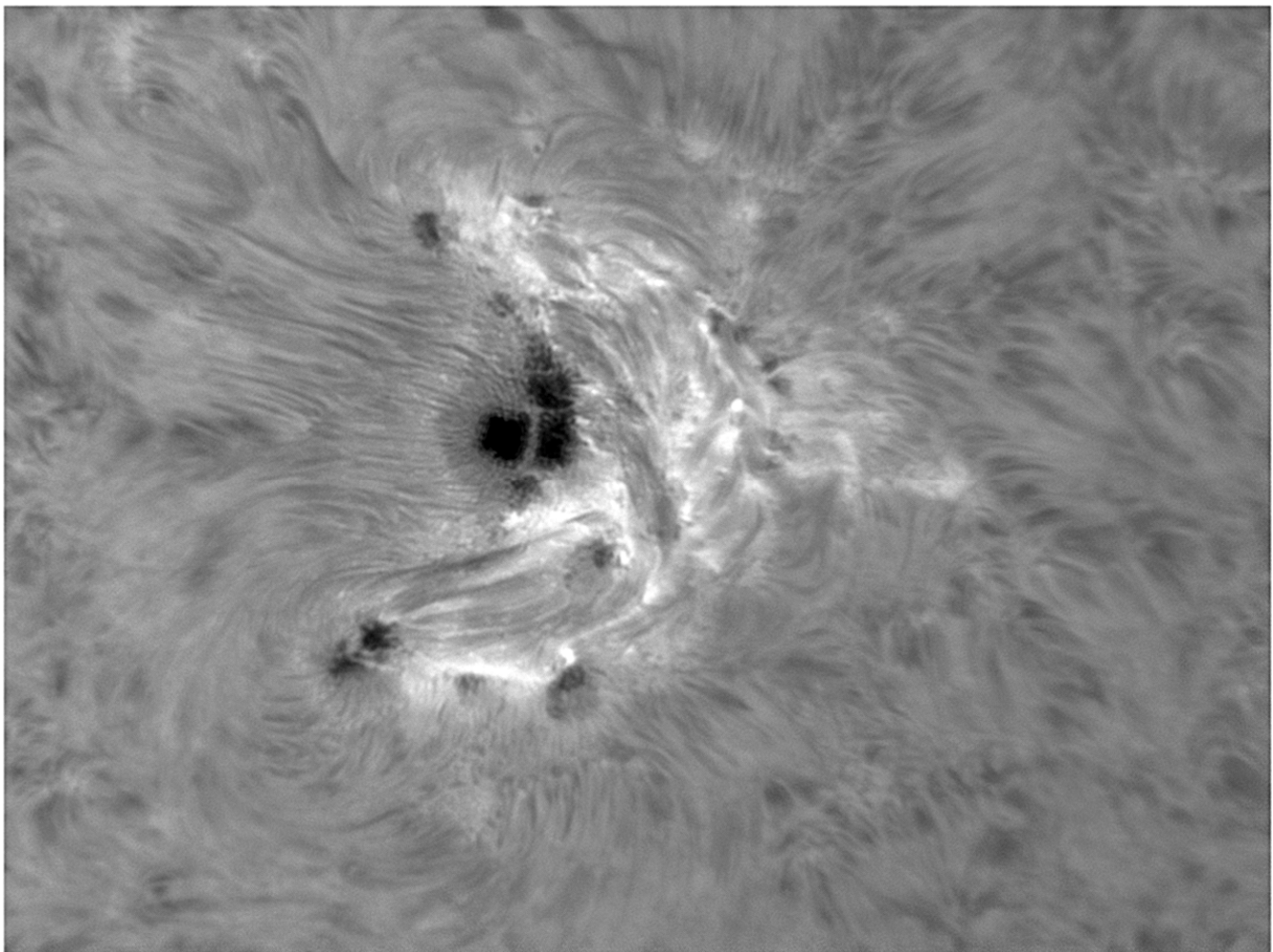
The case of the most intense sunspot in 2017, the AR 2673, was an example, the observation of which was carried out on September 6 2017. This sunspot was part of a rather complex active region as seen in the figure below ( source SDO-HMI) which also shows the position of the slit during the observation.



The feature of this sunspot was to present in only three days a truly marked increase in its extension and magnetic strenght, as we can see in the following image (source SDO-HMI).



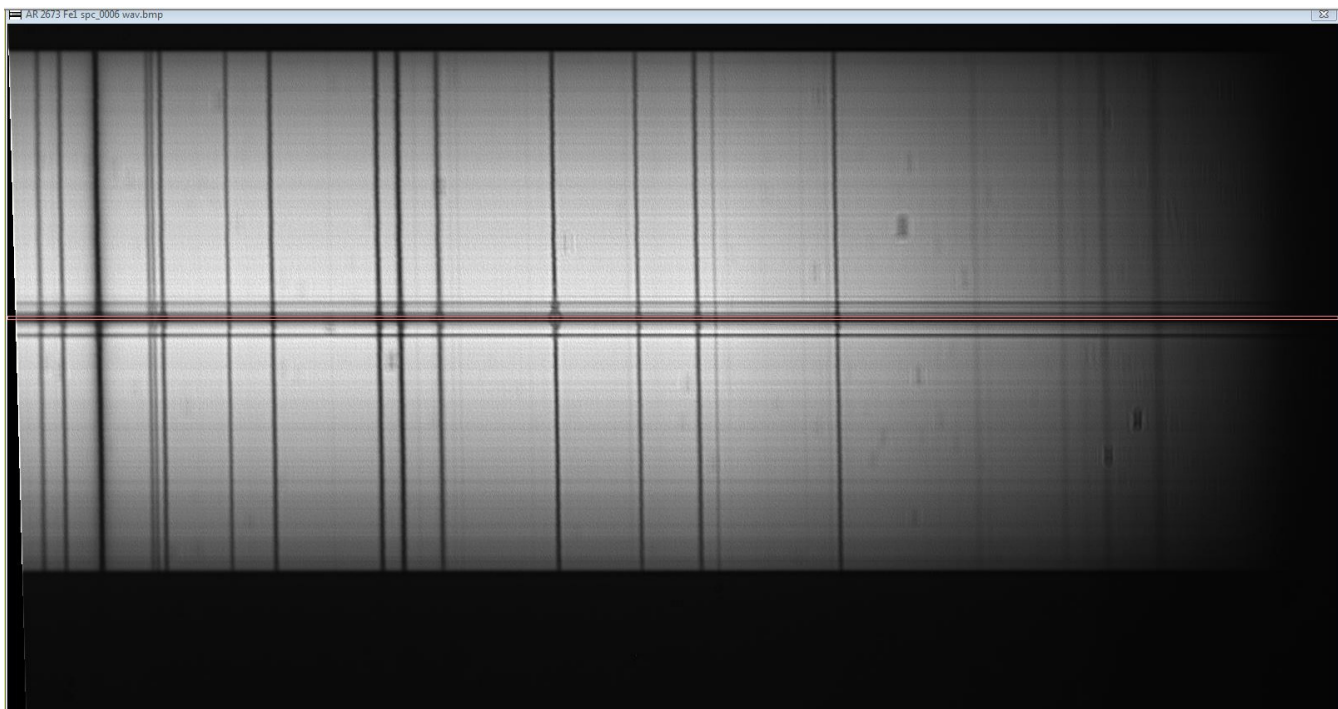
Evolution of AR 2673 in only three days, from September 3, to September 6, 2017.



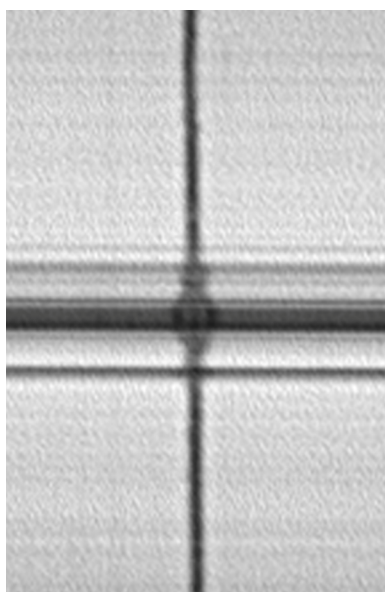
The complex activity around the sunspot AR 2673: photo of the author in H alpha light with a modified (with a 70 mm ERF in the optical path) achromatic refractor 150 mm aperture and 900 mm focal length, and a H alpha Daystar Quark cromosphere filter.

This development was a symptom of complex magnetic activity, as has been observed by the numerous microflares and flares (the largest one in M8.1 class): the sunspot was therefore the ideal candidate for a sufficiently precise measurement of its magnetic field in non-polarized light.

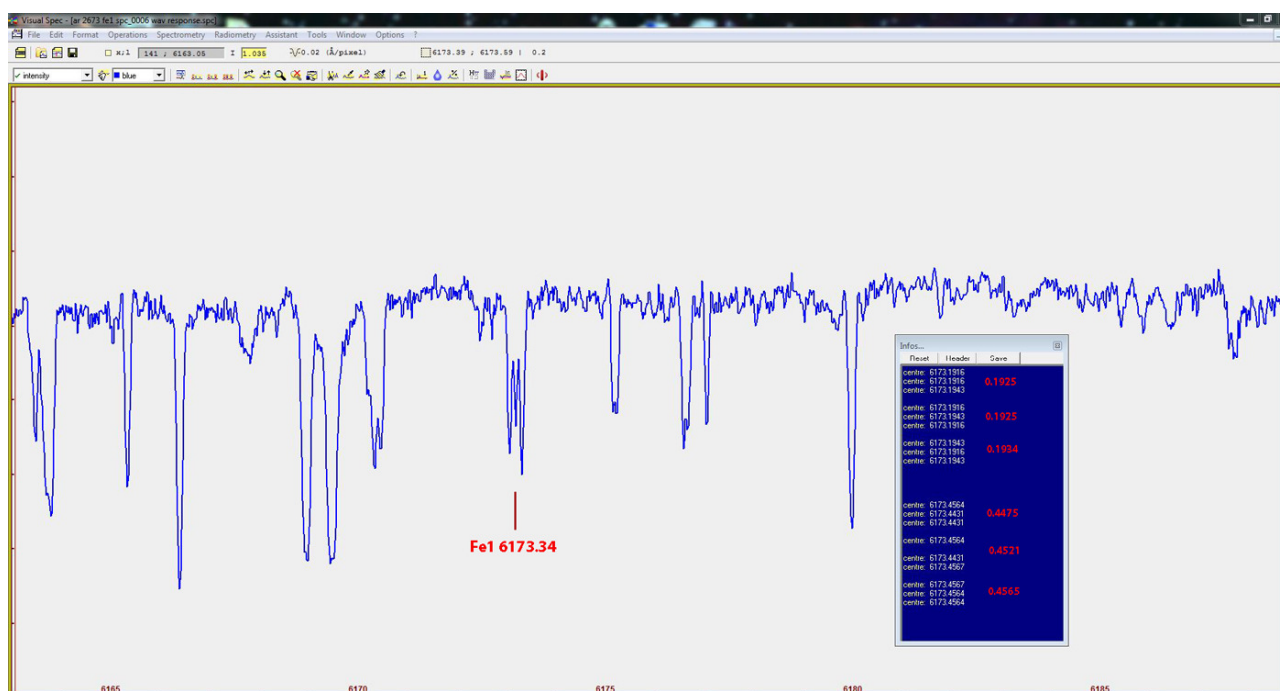
The chosen spectral line was that of the Fe I at 6173 Å. For the acquisition of the videos, an Imaging Source DMK 41 camera was used, with 1280 x 1024 pixels, and the dispersion was 0.02 Å / pixel. The spectrum on the line was as follows: the most intense central transverse line is the appearance of the central major sunspot on the spectrum, while the finer lines were the other smaller sunspots of the group: The double orange-colored line indicates the position of the binning, that is the area of the spectrum on which the measurement of the magnetic field has been made.



The software used was Visual Spec, a free software I usually use together with BASS for stellar and deep sky object spectroscopy.



An enlarged detail of the previous image, in which the Zeeman splitting is very well observable in three distinct parts on the central sunspot (larger transverse line), and also with lower intensity, in the other sunspots of the same group (smaller transverse lines). Below the spectral profile of Visual Spec used for the calculation of the magnetic field, in which the three cusps of the orthogonal zeeman splitting of the line appear even more clearly. The difference in wavelength between the two external cusps divided by two gives the  $\Delta\lambda$  value for the calculation of magnetic field in Gauss B.



The theoretical formula applied was the following:

La relazione tra  $\Delta\lambda$  ed il campo magnetico  $B$  è:  
*the relation between  $\Delta\lambda$  and the magnetic field  $B$  is :*

$$(1) \quad \Delta\lambda = \frac{\pi \cdot e}{m_e} \cdot \frac{\lambda^2}{c} \cdot g \cdot B$$

$$(2) \quad \Delta\lambda = 4.67 \cdot 10^{-13} \cdot \lambda^2 \cdot g \cdot B$$

dove:

$B$  è il campo magnetico in Gauss  
*is the magnetic field in Gauss*

$\lambda$  è la lunghezza d'onda della riga;  
*is the wavelenght of the line*

$e$  è la carica dell'elettrone;  
*is the charge of electron*

$m_e$  è la massa dell'elettrone  
*is the mass of electron*

$c$  è la velocità della luce  
*is the speedy of light*

$g$  il fattore di Landè della riga  
*is the Landè factor of the line*

dalla precedente (2) si ottiene:  
*from the (2) we obtain:*

$$(3) \quad B = \frac{\Delta\lambda}{4.67 \cdot 10^{-13} \cdot \lambda^2 \cdot g}$$

Ultimately, for the Fe I line at 6173.34 Å with a Landè factor value of 2.5 (values rounded to 1/100) the generic formula was:



$$B = \frac{\Delta\lambda}{\frac{4.67 \cdot 38110127 \cdot 2.5}{10^{13}}} = \frac{\Delta\lambda \cdot 10^{13}}{444935733}$$

in this case, being  $\Delta\lambda = 0.1296$  was

$$B = \frac{0.1296 \times 10^{13}}{444935733} = \mathbf{2913 \text{ Gauss}}$$

And the statistic error

$$\frac{0.002 \times 10^{13}}{444935733} = \mathbf{45 \text{ Gauss}}$$

Then, definitely the magnetic field of the umbra of the main sunspot of the group AR 2673 was **2913 +- 45 Gauss \***

And here's how an instrument essentially conceived for spectroheliography can be destined to a task in some ways much more challenging and difficult, once prerogative of some solar towers, like the one of the Rome Observatory, where this task of measuring magnetic fields of sunspots had carried out in the 1970s in a collaborative work with that of Mount Wilson, in USA.

This is a further demonstration of the versatility of a high-resolution Littrow spectroscope in solar observation.

#### Note

\*) For details on the working methods of the measurement work see also my article on the lightfrominfinity.org website at the link:

<http://www.lightfrominfinity.org/Osservazioni%20Zeeman%20del%202017/Le%20osservazioni%20Zeeman%20del%202017.pdf>

See also the article on the number **222/2018** of the online italian magazine **Coelum**

## Conclusions

We have come to the end of this overview on a theme that is certainly not popular, but I think it is interesting for most amateur astronomers, the study about the digital spectroheliography and the construction of necessary instruments. We have seen the unexpected and surprising possibilities of instruments built with not very sophisticated means, but with a great desire to succeed and enthusiasm.

In a word, from a small balcony, like that of the figure, we can imagine, without going too far from reality, having installed a solar tower of 20 or 30 meters from which the Sun, our star, is observed and examined minutely in all its most hidden aspects with a common camera costing a few tens of euros or dollars.

It is a further demonstration of how the progress of information technology has been able to overturn our lives, making possible the unimaginable of a few decades ago.

I would like to conclude by greeting all the amateur astronomers of all the countries that have begun, and continue to feel the passion of the spectroheliography, and wishing for all those living in Italy or all over the World to carry on by putting their skills at the service of this branch of Astronomy.

Rome, February, 20, 2019





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<https://sdo.gsfc.nasa.gov/>

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Phil Rousselle - Observing the sun with a Spectroheliograph-

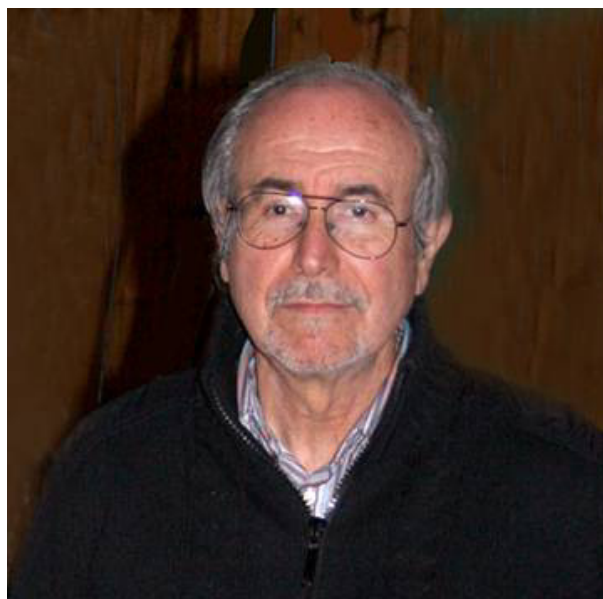
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### **The author**



Fulvio Mete, graduate in economics with a mathematical background, has devoted much of his life to the passion for astronomy, integrating his studies in astronomy with those of physics, computer science, mechanics. He has been dealing with astronomical spectroscopy for 20 years, and directed, for about six years, the research Sector of spectroscopy of the UAI (Italian Amateur astronomers Union). Actually he deals with spectroscopy of supernovae, high resolution solar spectroscopy, CCD imaging in the near IR. He organized some events at national level, such as the Asiago Observatory Spectroscopy Seminar, that of Solar Observation and Spectroscopy at Arcetri Observatory, and numerous initiatives at local level. He has published numerous articles in Italian magazines of astronomical divulgation (Coelum, Nuovo Orione, Astronomia UAI), as well as articles in English and French on foreign publications. He has designed, built and still builds self-made instruments for spectroscopy of the sun and of the deep sky objects.

### **Websites of the author**

<http://www.lightfrominfinity.org/>

<http://www.pno-astronomy.com/>

<http://www.amateur-astronomy-researchers.com/>



