

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.

Introduction

The Sun, the closest star to us, is a gigantic laboratory where we can study physical phenomena which, due to their scale, are not accessible to terrestrial experimentation and cannot be studied in the more distant stars. For this reason the study of the Sun has contributed in remarkable way to the general progress of astrophysics. This concept is equally valid for spectroscopy and spectroheliography, 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 for other amateur astronomers, with an eye to simplicity. It is therefore not an exclusive book. However, to repeat the experiences I discuss and demonstrate, one need a sufficient knowledge of spectroscopy, techniques, and a certain degree of 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 this specific theme, and the second on a planetary level after that, very well done, by my friend Ken Harrison. Unlike his book, in which are reported the experiences of a certain number of amateur astronomers (myself included), I have tried here 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 exception, I hope you enjoy reading.

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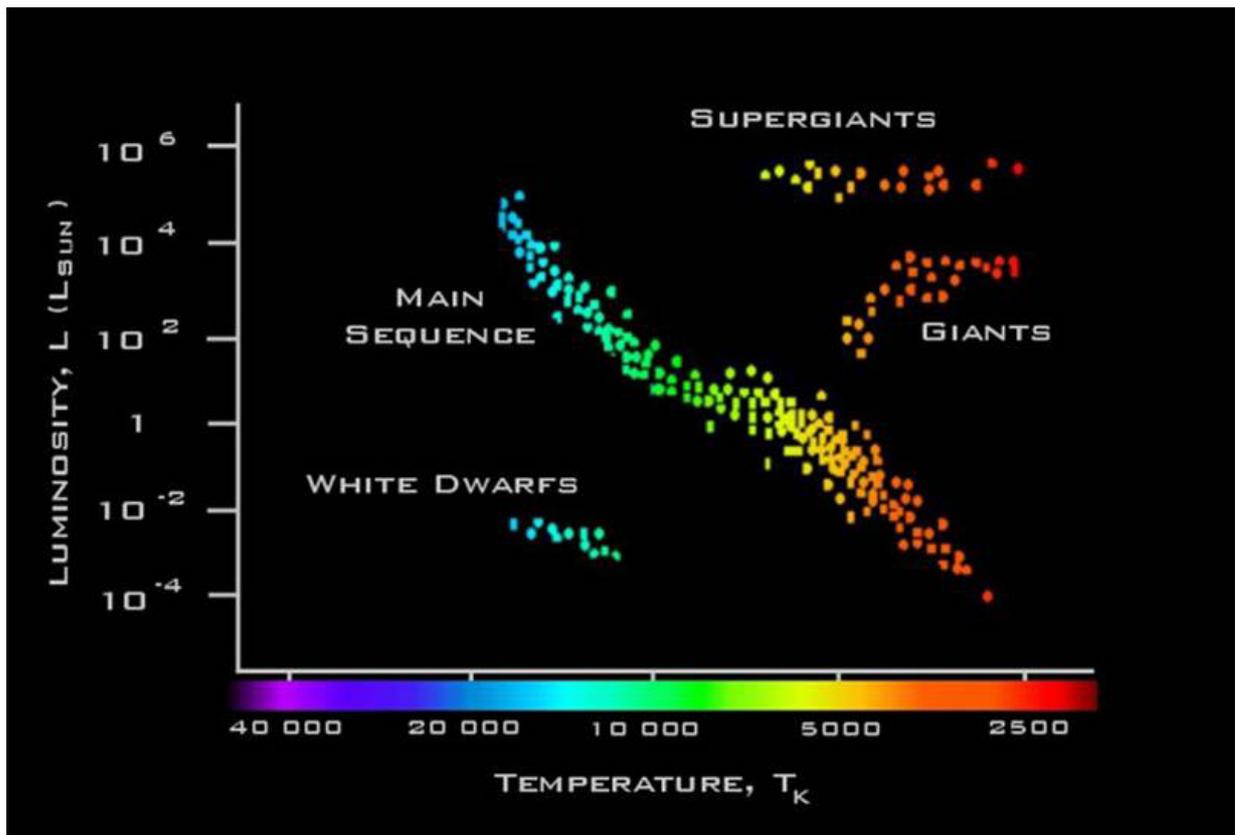
Before talking about spectroheliography it is good to provide some information on the object of interest, the Sun.

The Sun, the nearest star



Most of the visible light we observe 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 696,000km, averaging 149,597,000km from the earth (according to the last definition of astronomical unit defined by the IAU), with a mass of 333,400 times the earth and is made up mainly of hydrogen (about 73.46% of its own mass), and Helium (about 24.85%), to which heavier elements, (metals, 1.69%) are added. (Rif Bianucci "Il Sole" - Giunti Ed.) It is classified as a yellow dwarf of spectral type G2V. G2 indicates that the star has a photosphere surface temperature of 5776K (The temperature is commonly measured with the Kelvin scale (K), called "absolute scale", where zero degree = -273°C . Then $5776\text{K} = 5776 - 273 = 5503^{\circ}\text{C}$), characteristic this 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 converts, in its nucleus, the hydrogen into helium. The enormous amount of energy generated 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.

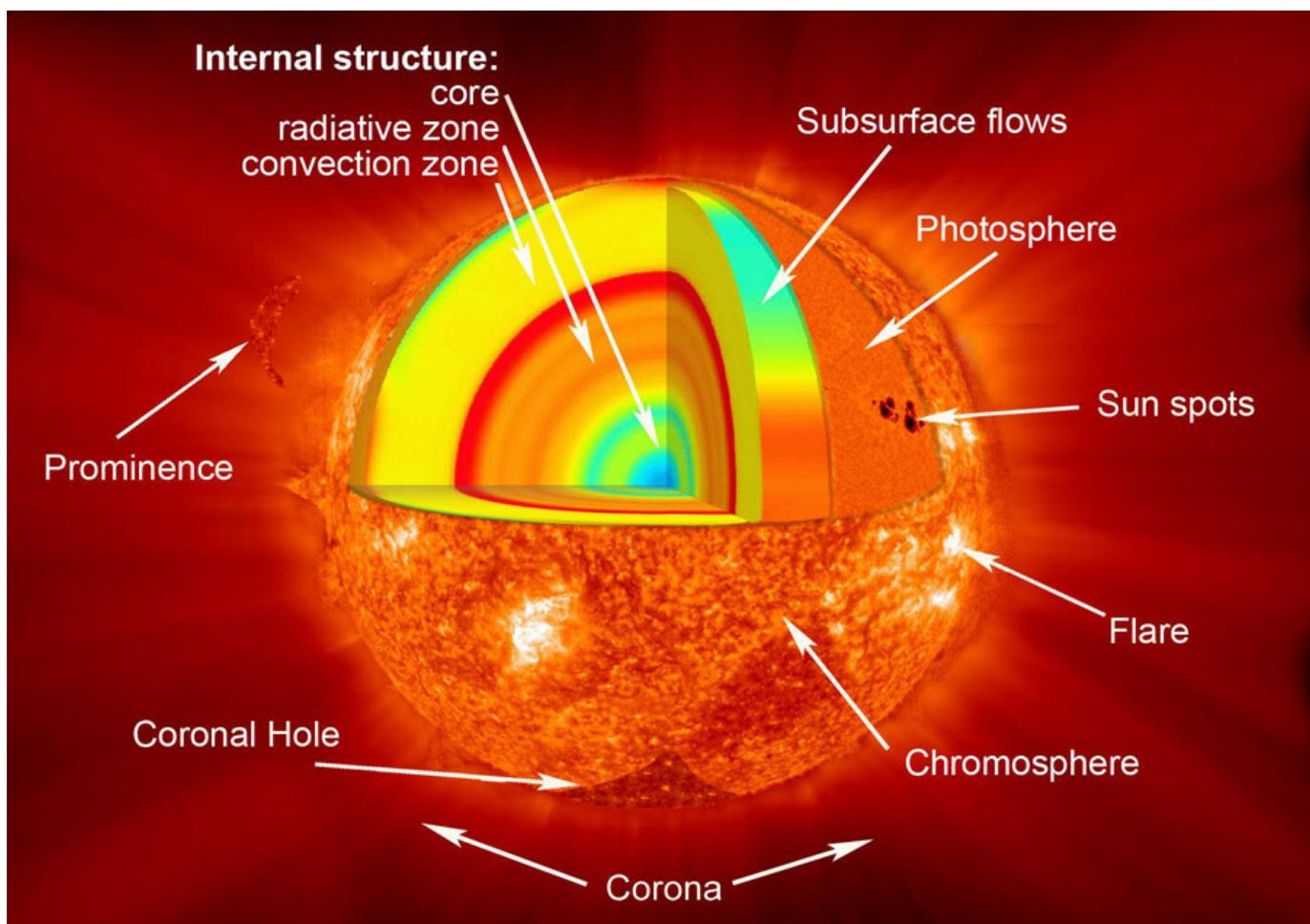
This process of nuclear fusion generates a large quantity of energy every second (equivalent to 3.83×10^{26} Joule per second), thrown into the space in the form of electromagnetic radiation (solar radiation), in the flow of particles (solar wind) and neutrinos. Solar radiation, emitted basically as visible and infrared light, allows life to exist 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, i.e. 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). A G2 class star such as the Sun, considering the value of its mass, takes 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 cannot be used in new thermonuclear cycles due to the small mass of the star, will accumulate inert in the nucleus; meanwhile, failing against 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. Incineration 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 really one zone, given that temperature and density vary in it almost continuously), and the 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

This represents, in volume, 10% of the star and in mass over the 40%. Here the reactions of nuclear fusion take place, the principal source of solar energy. With the nuclear fusion of 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 are the neutrinos), whose mass is lower than the four initial hydrogen nuclei; the difference is converted into energy on the basis of the famous Einstein equation $E = mc^2$. Astrophysicists believe that the solar core has dimensions close to 0.25 solar radius (174,000km), with a density higher than $150,000 \text{ kg/m}^3$ (150 times that of water), a temperature that reaches 15,600,000K 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 ray 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

This is located outside the core, extending from about 0.25 up to 0.7 solar radius (about 490,000km); 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 zone, and called the tachocline, extending, 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 it would intervene in the function of the solar dynamo (mechanism by which the magnetic field of our star originates) reinforcing the weak polar fields to create a more intense one of toroidal form.

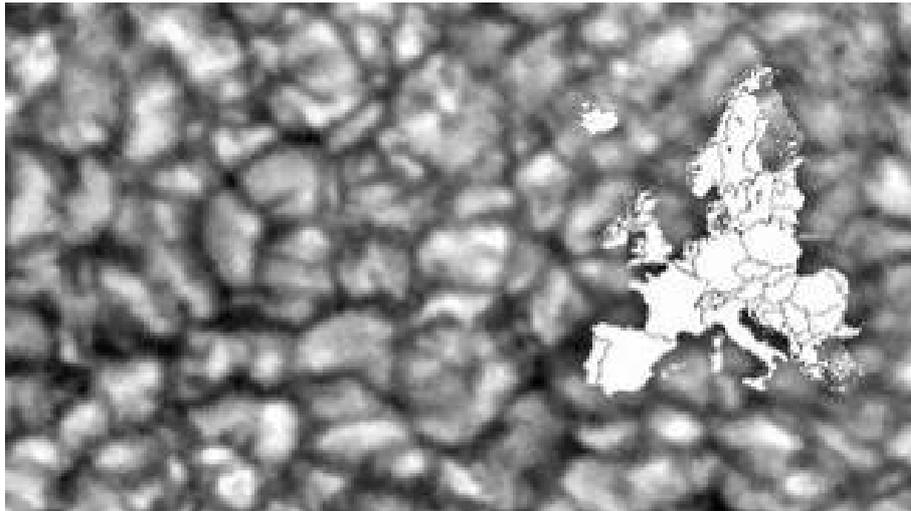
The convective zone

It has a thickness of about 200,000km 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 cannot 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.

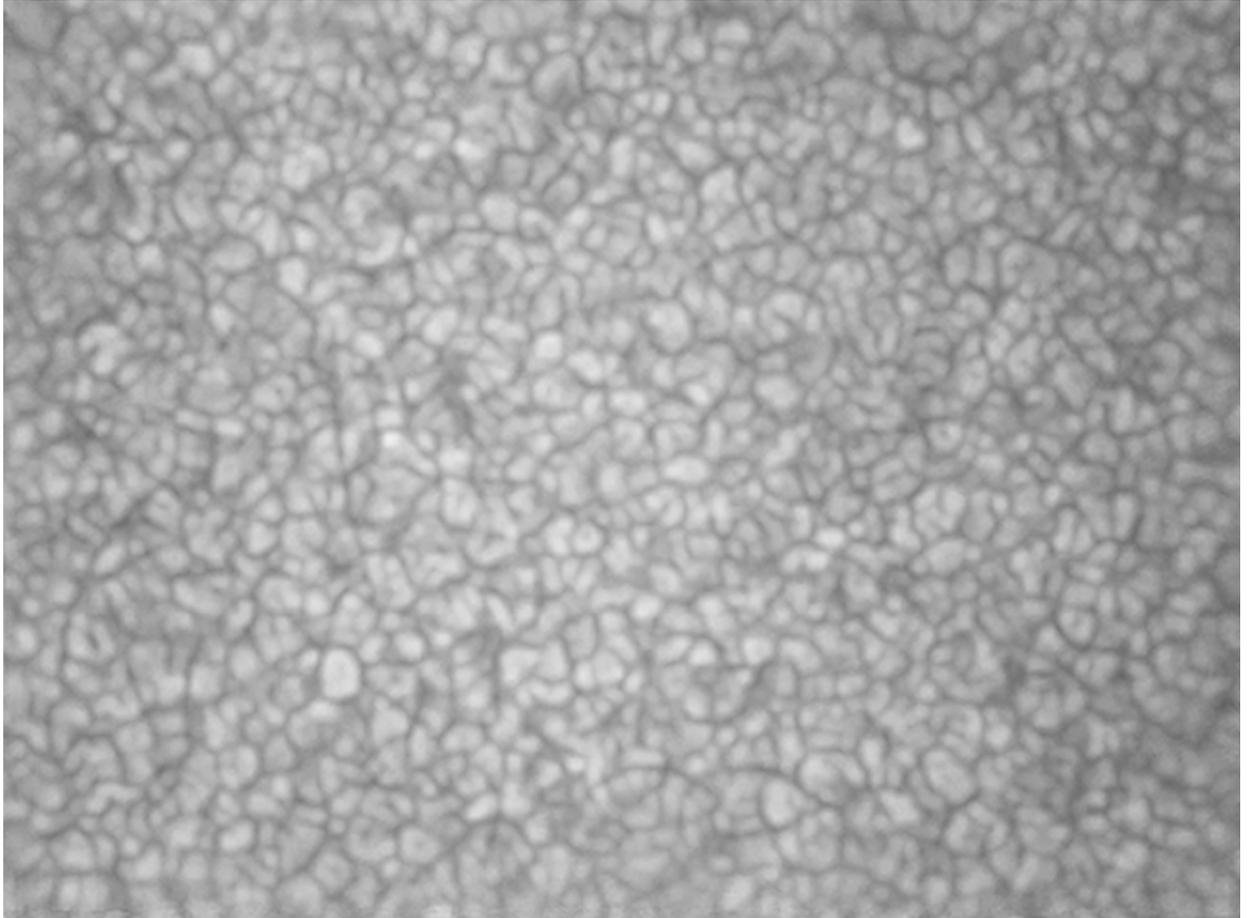
The photosphere

is the surface layer of the Sun, thickness on average 500km (its thickness depends on the solar 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 5776K, 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 800-1300km, an average angular size of 0.8-1.8arcsec and last from 4 to 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 center. The darker intergranular space subtends about 0.4-0.5arcsec. In the figure (Source: NST-BBSO) a zone of photospheric granulation is compared to the map of Europe.

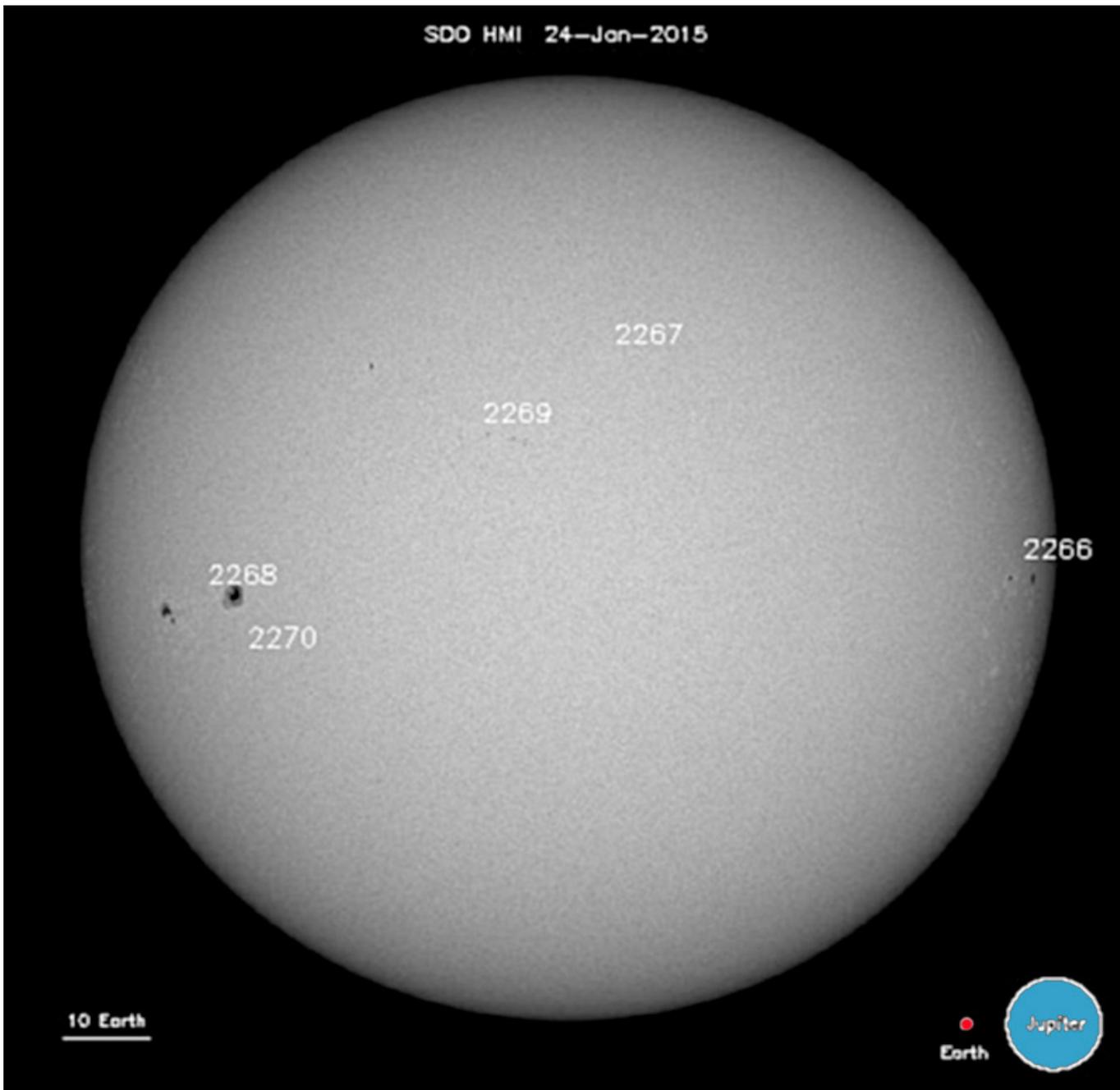


In the following image an excellent amateur photo of the photospheric granulation captured by the amateur astronomer Salvatore Lo Vecchio with an apochromatic refractor of 150mm at 9.6 meters equivalent focal length and a DMK 21 camera. As we observe the granule sizes are varied, as well as their shape,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

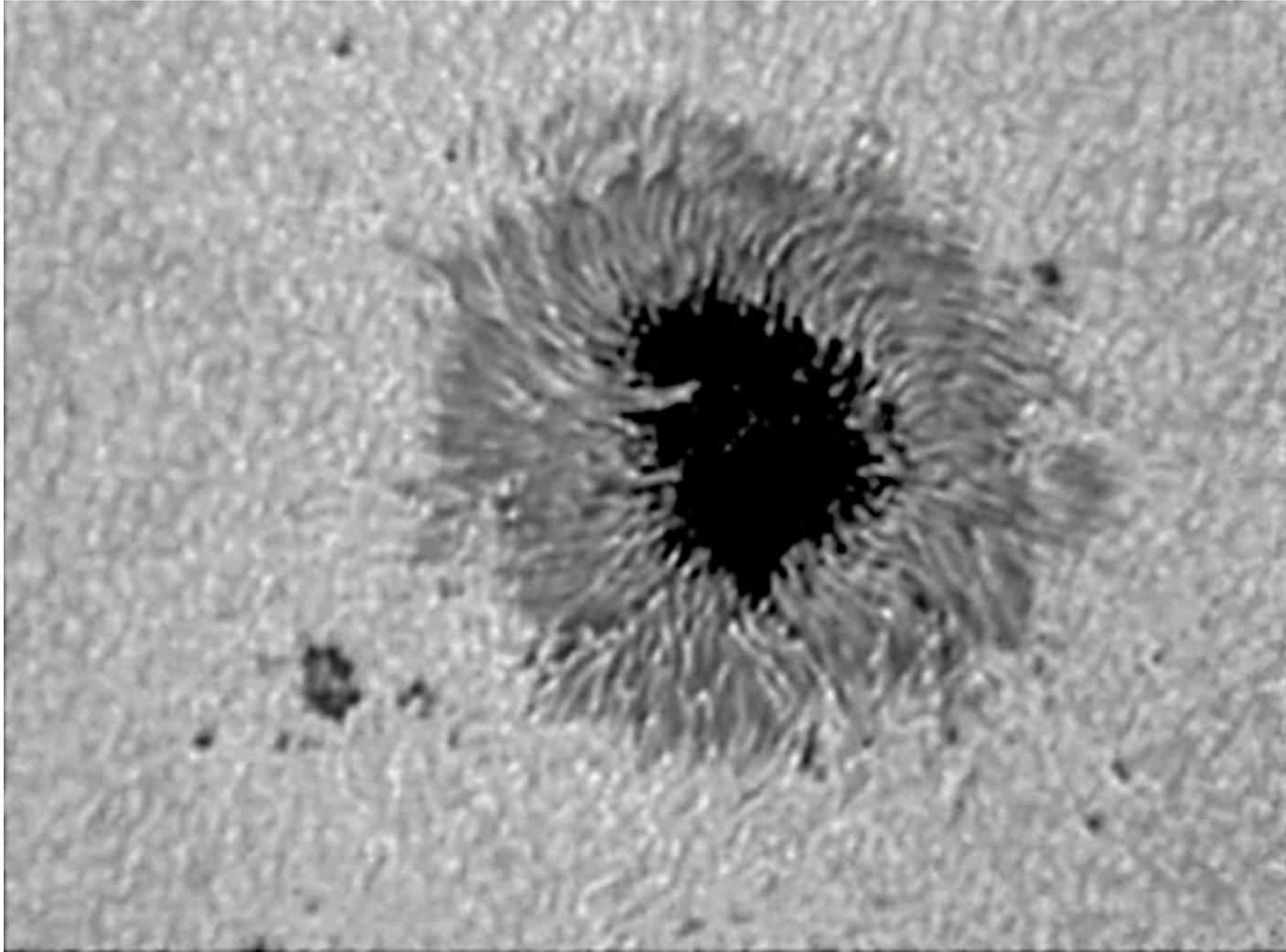


Sunspots are areas of the Sun distinct from the rest of the photosphere surface for the lower temperature and a strong magnetic activity. Despite being very hot (between 3000 and 4500K) they appear dark by contrast with the remaining solar surface at 5776K. They normally appear in pairs having opposite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

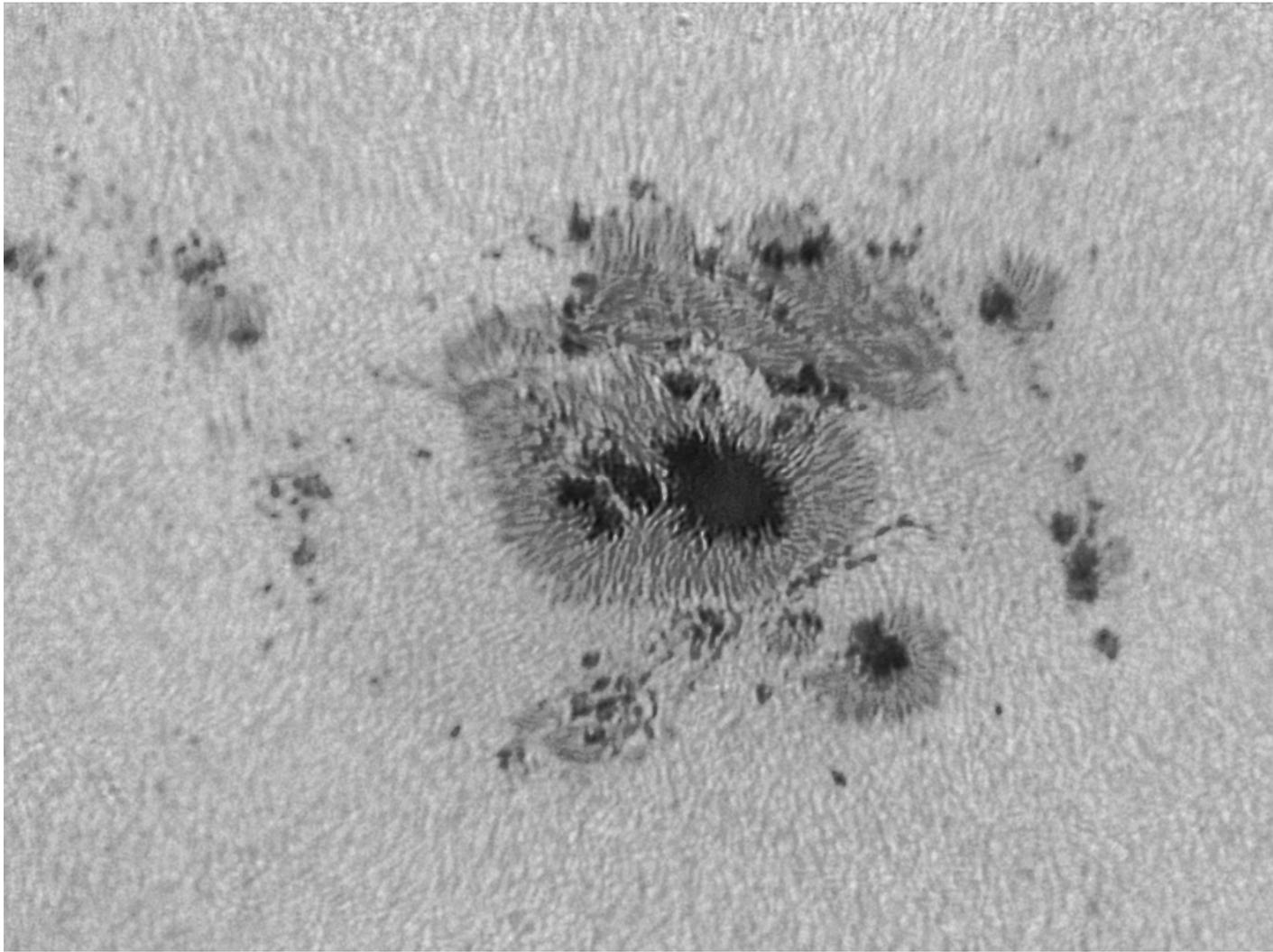
In the following image the solar disk with some sunspots (Source: SOHO -SDO)



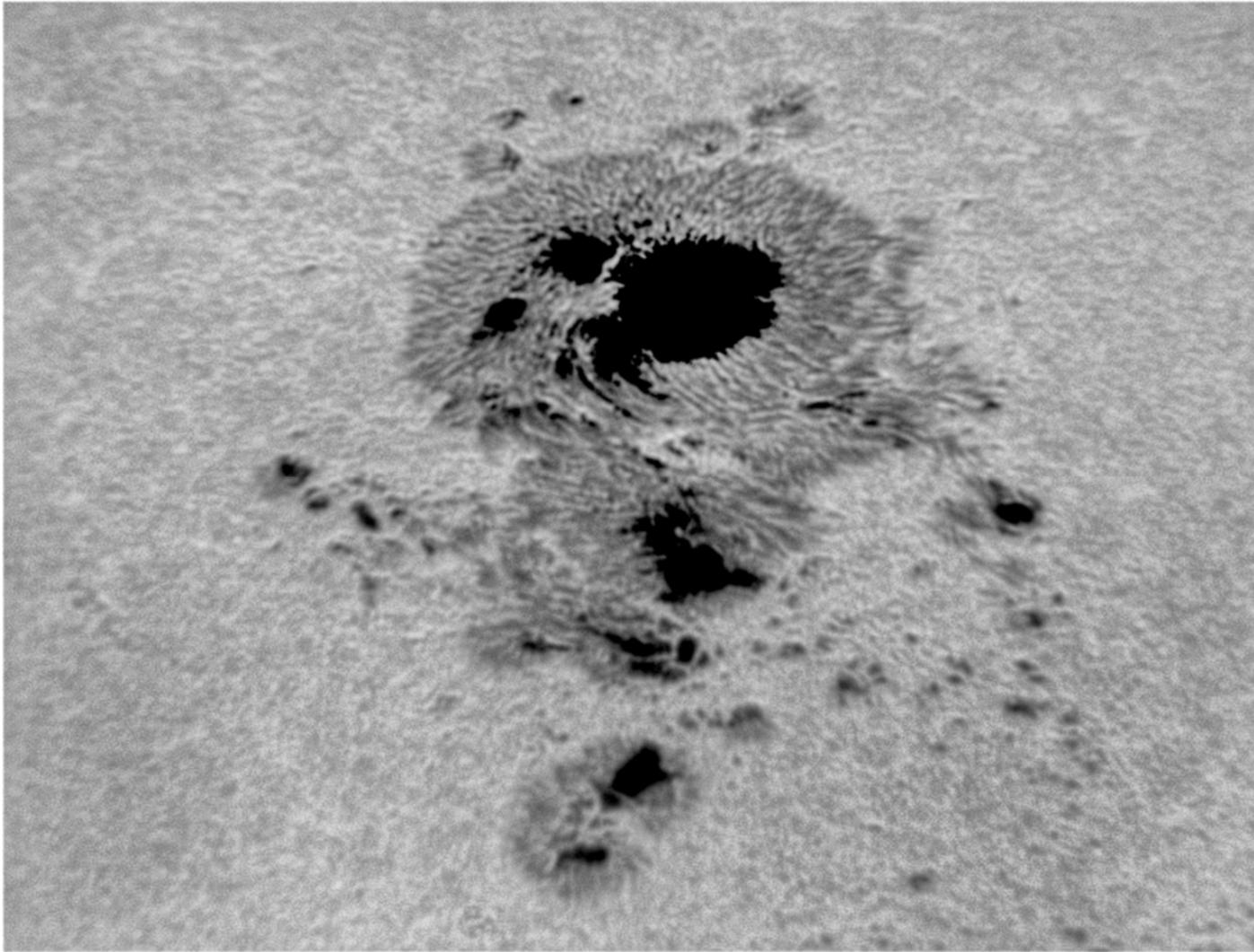
The following are the author's photos of high-resolution sunspots in white light, obtained the first with a Newtonian solar reflector with a non-aluminized mirror of 200mm and the other two with a 115mm apochromatic refractor at an EFL of 4000mm. Note the granulation and the filaments of the penumbral zone, of about 1arcsec 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, where plasma temperatures are higher than the background. It can sometimes be a symptom of an increase in activity in the chromosphere.

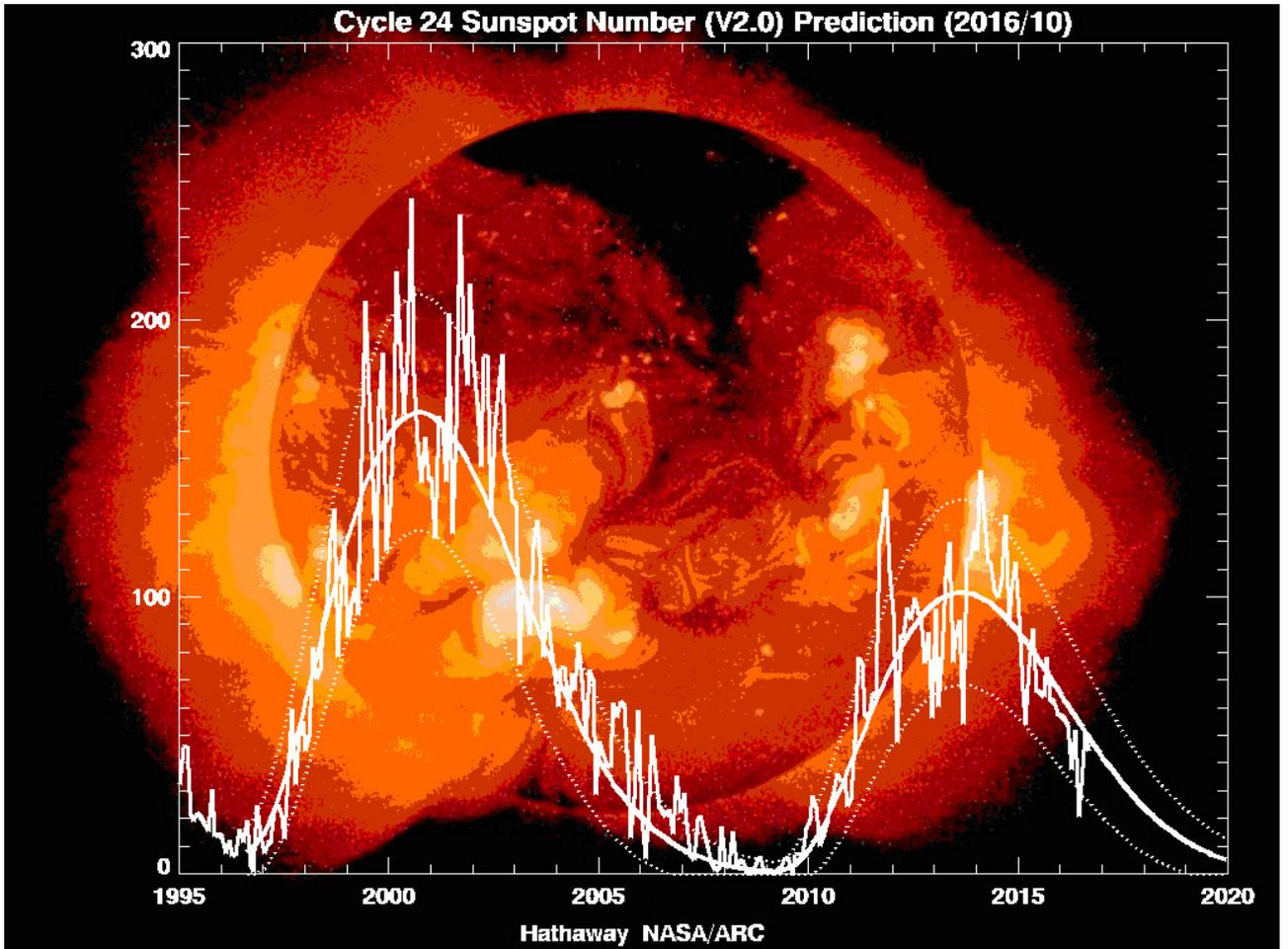


The image below was obtained by applying a 720nm IR-Pass filter (it may seem a contradiction) after a Herschel prism, at the focus of an apochromatic refractor TMB LZO 115/800 at 4000mm EFL using a 5X barlow. Note the relief of the macular area compared to the quiet sun.



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.

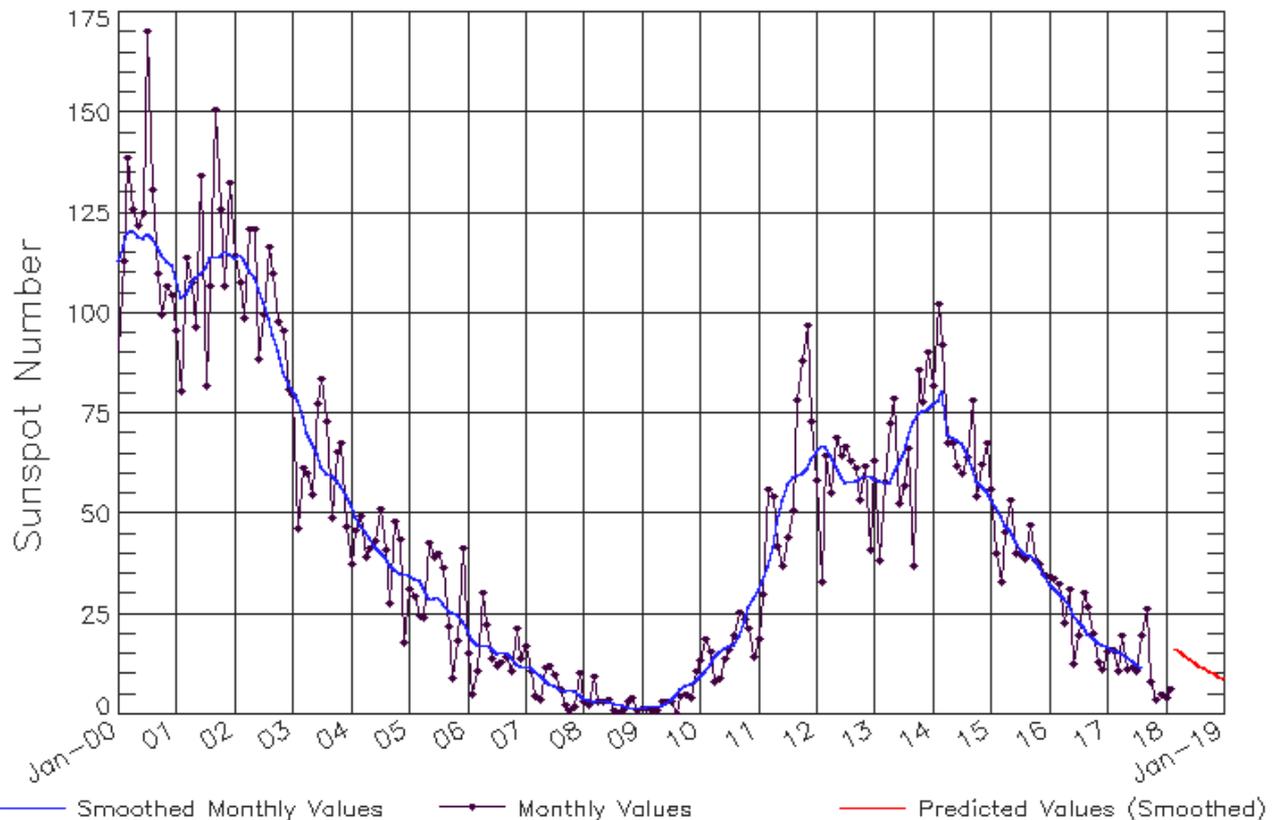
In the following image (Source: NASA / ARC) the solar cycle forecast from 1995 to 2020, with the actual data up to October 2016 and the projections for the next period. As you can see it seems that the number of spots (Wolf number) and therefore the solar activity is decreasing in recent years. However,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



Below is shown the real data of the Wolf number 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



Updated 2018 Mar 5

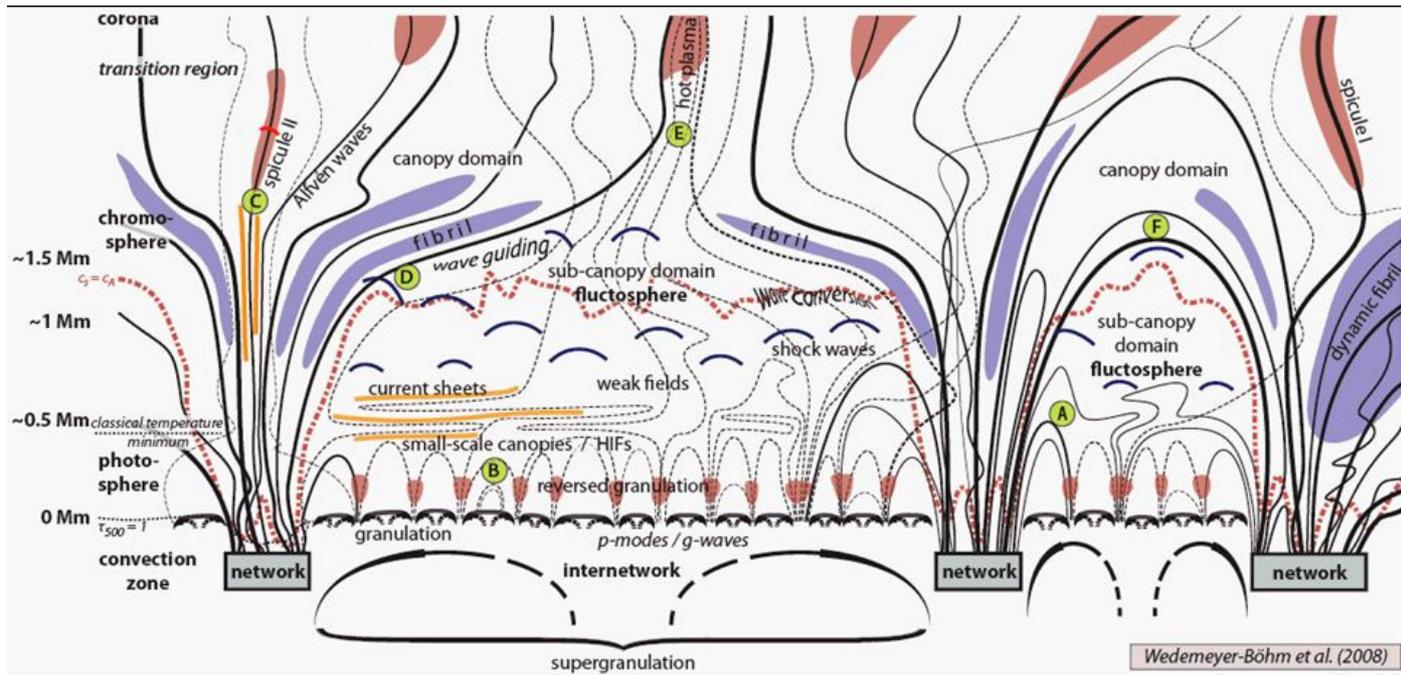
NOAA/SWPC Boulder, CO USA

The chromosphere

The chromosphere is a thin band about 2300km 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 ionized hydrogen ($H\alpha$) at the wavelength of 6563\AA (deep red). The low pressure of the chromosphere allowing it to emit radiation of this color. Its temperature, on average is between 10,000 and 20,000K, more precisely it is about 6000K at the border with the photosphere, begins to decrease immediately after down to 3800K, then increase again up to 10,000K and then 20,000K in its highest layers, reaching even 30,000K and beyond in 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)

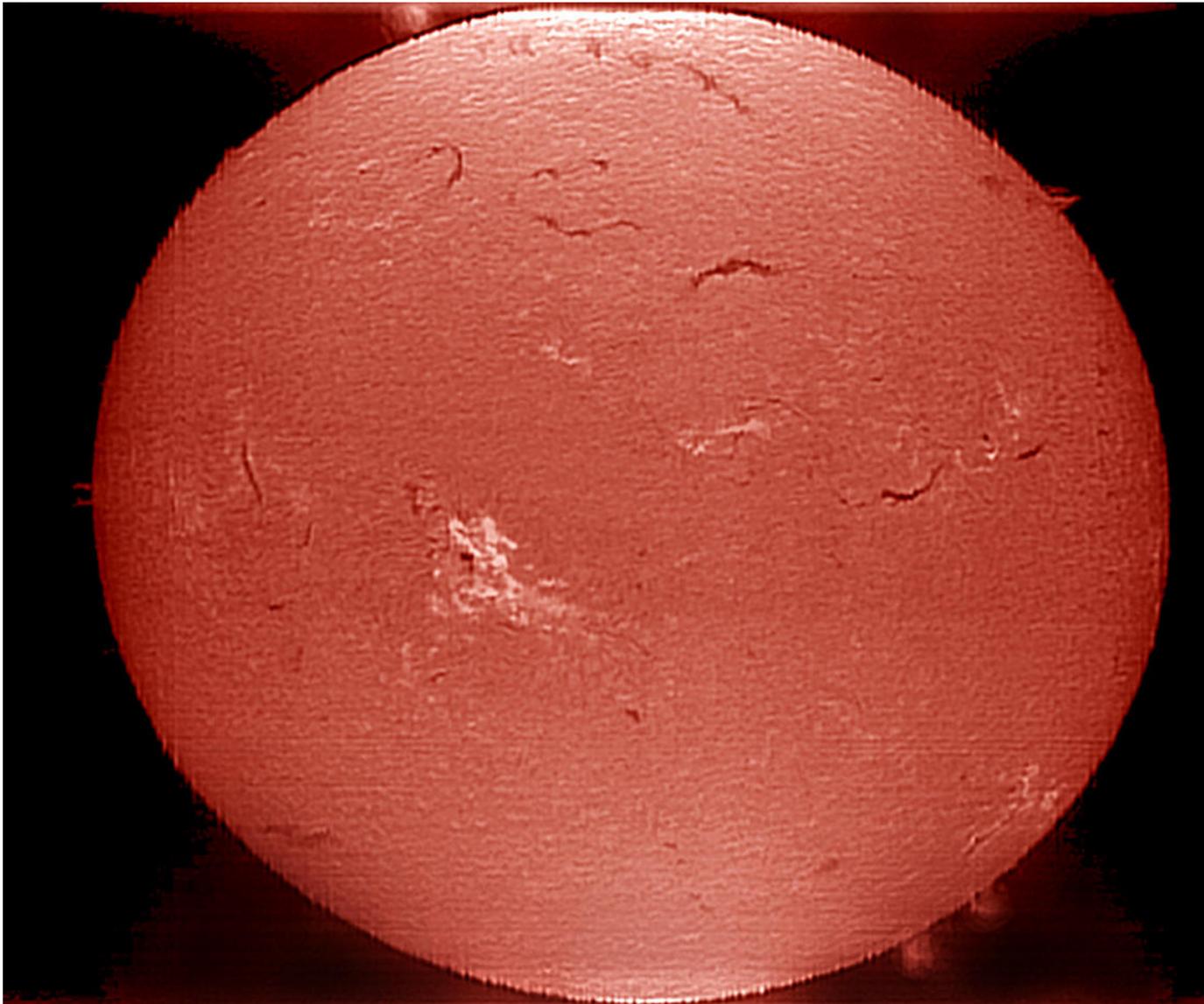
Wedemeyer-Bohm 2004

The figure above (Source: NASA- The chromosphere- Wedemeyer - Bohm 2004) shows in detail the structure of the solar atmosphere. Note the magnetic loops of the granulation between the photosphere and the convection zone and the different height of spicules and fibrils.

These are particularly popular objects for solar observers of the chromosphere using narrow bandwidth filters (between 0.3 and 1Å) in H α light at 6563Å.

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 prominences, as observed in this beautiful image from Danilo Pivato, an Italian amateur astronomer, in which is visible both the chromosphere (thin red strip surrounding the solar disk), and the prominences, both (in part) the corona.

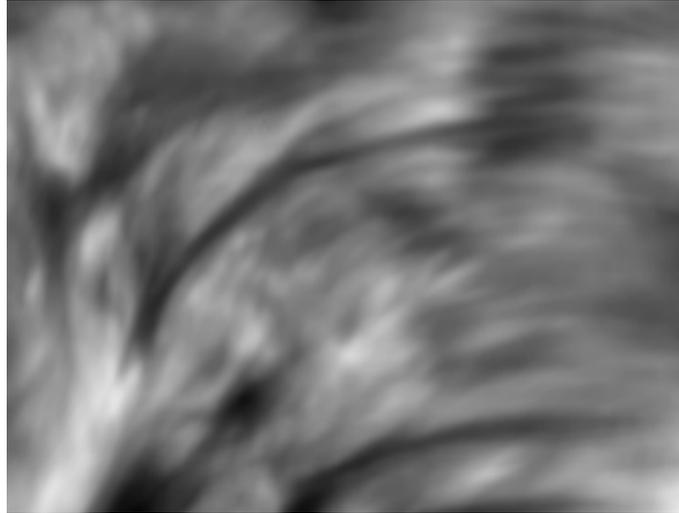
In the images taken with chromosphere filters centered on the $H\alpha$ line of the Hydrogen or with telescopes or spectroheliographs (SHG), the chromosphere shows all its features, as in the following picture, by the author using a DIY SHG.



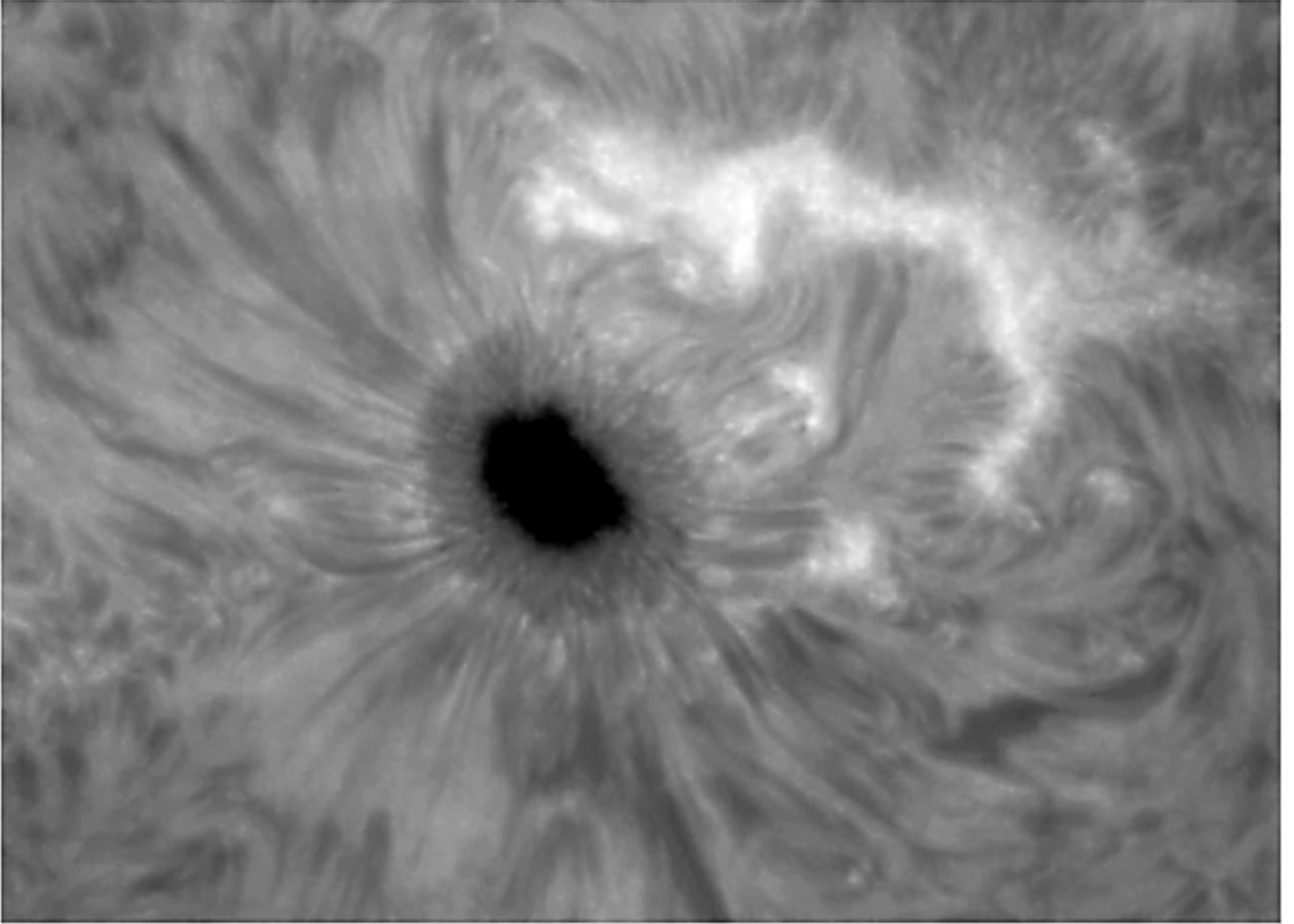
The most important features of the Chromosphere are the following:

The so called "*Chromospheric Network*" that shows supergranulation, better visible in $H\alpha$ and ionized calcium light, with supergranules of diameter of about 30,000Km., therefore much larger than the photospheric granules.

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



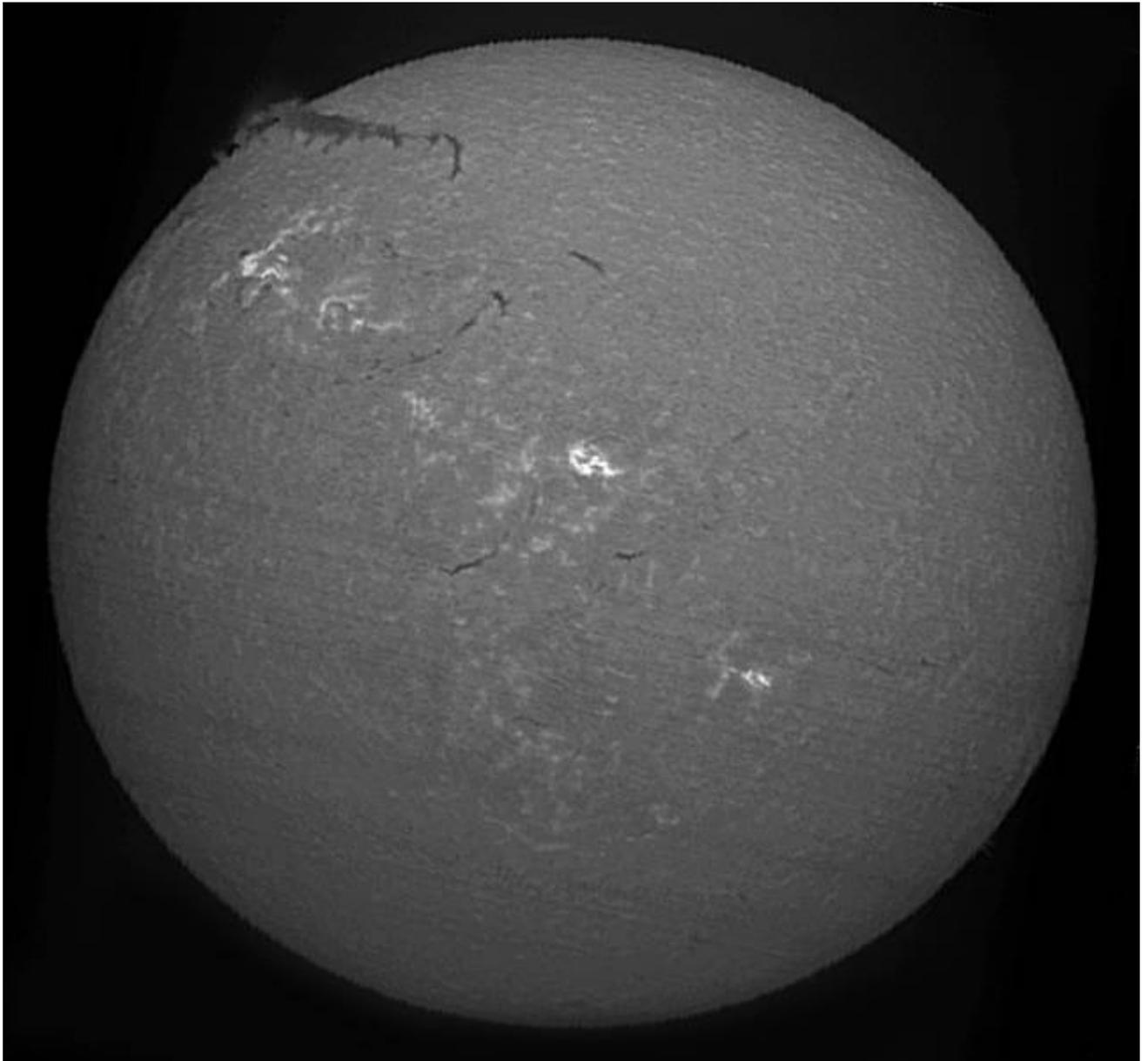
Chromospheric sunspots, plage and fibrils in H α light. Image by the author.



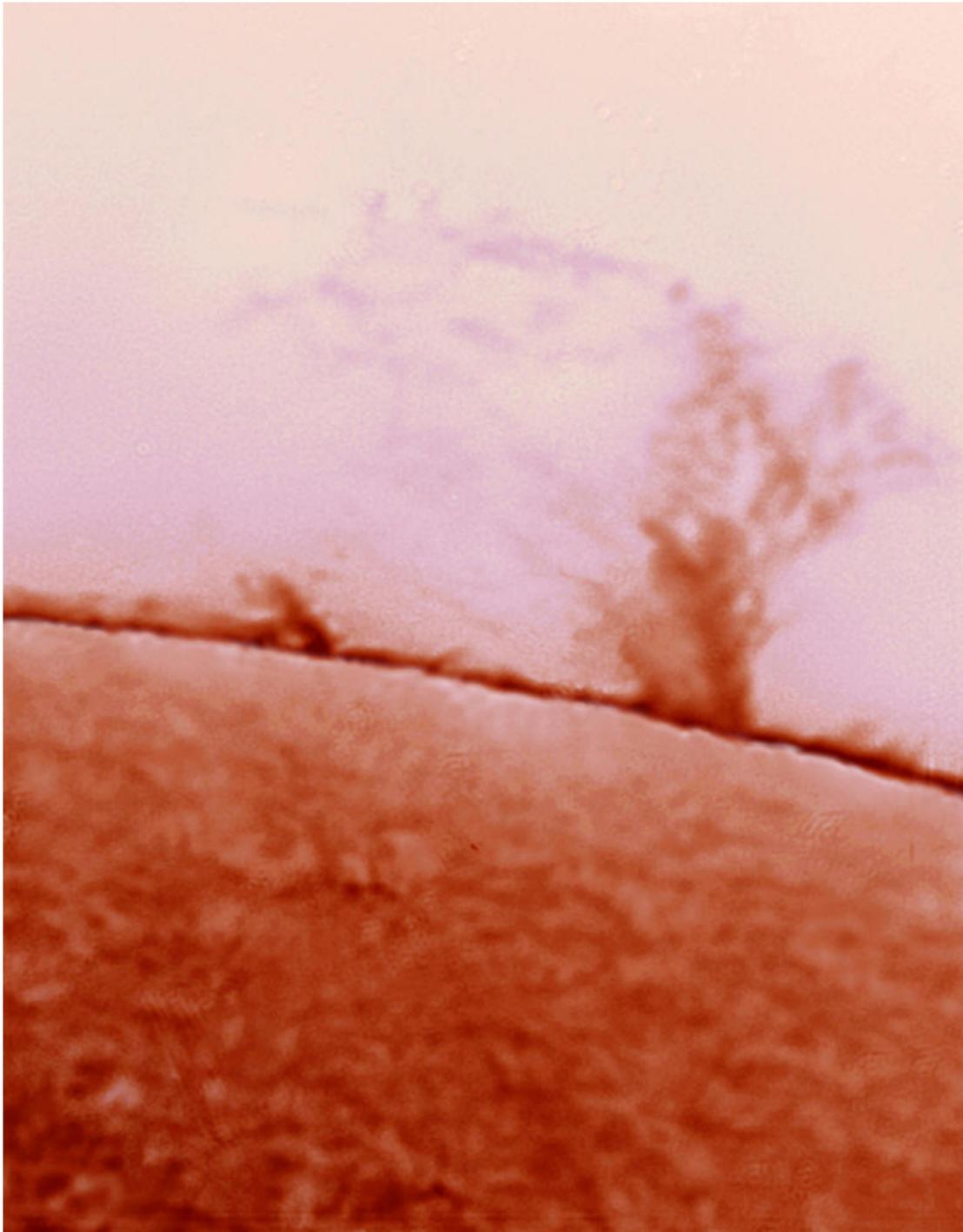
The *mottles* constitute the elements of chromospheric supergranulation, and appear dark or light in light H α (absorption) and bright in light CaII K and H (emission).

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, where they appear dark by contrast, as we can see in the following image (photo by the author with VHIRSS) in which there is a large prominence 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 by the author with a modified Coronado PST).

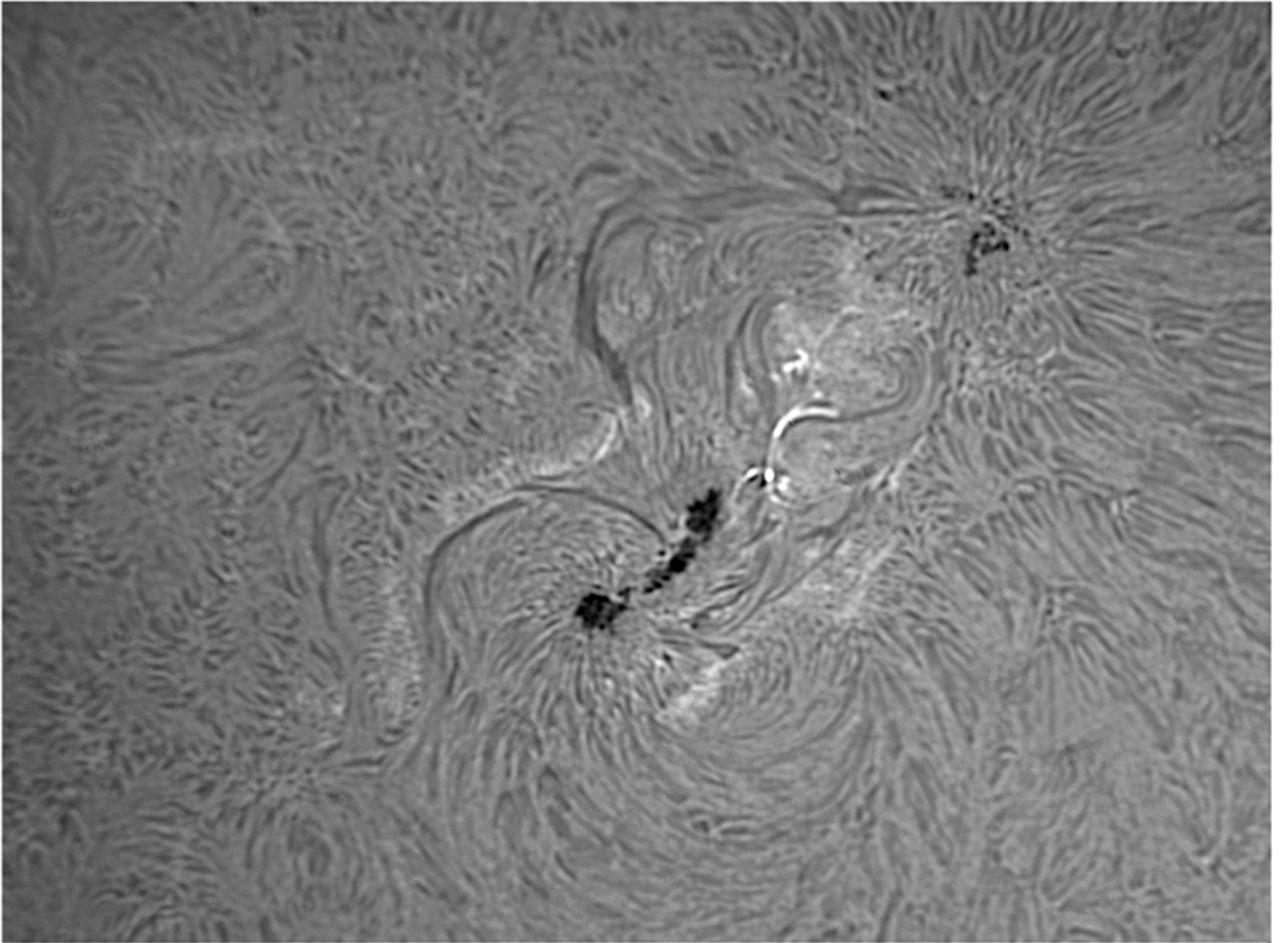


Other phenomena occurring in the chromosphere:

Flares

Under some conditions, in the chromosphere, near the active regions, a very bright eruption of particularly intense energy can develop, called flares, which reach up to the equivalent of 160 billion megaton! They are caused by the 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 million Kelvin.



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

Ellerman bomb

The "Ellerman Bomb" are small, short-lived (less than 5 minutes), brilliant structures, similar to flares but much smaller, associated with active regions, at the edges of the sunspots.

The bright emission appears as "moustaches" in the spectrum

The transition to the corona

This area is located above the chromosphere, and in it the temperature rises rapidly from about 100,000K 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 cannot 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, take 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 corona have a density of 10^{14} - 10^{16} particles per cubic meter (the Earth's atmosphere at sea level has a density of 2×10^{25} particles per cubic meter) and is home to numerous magnetic phenomena, 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.

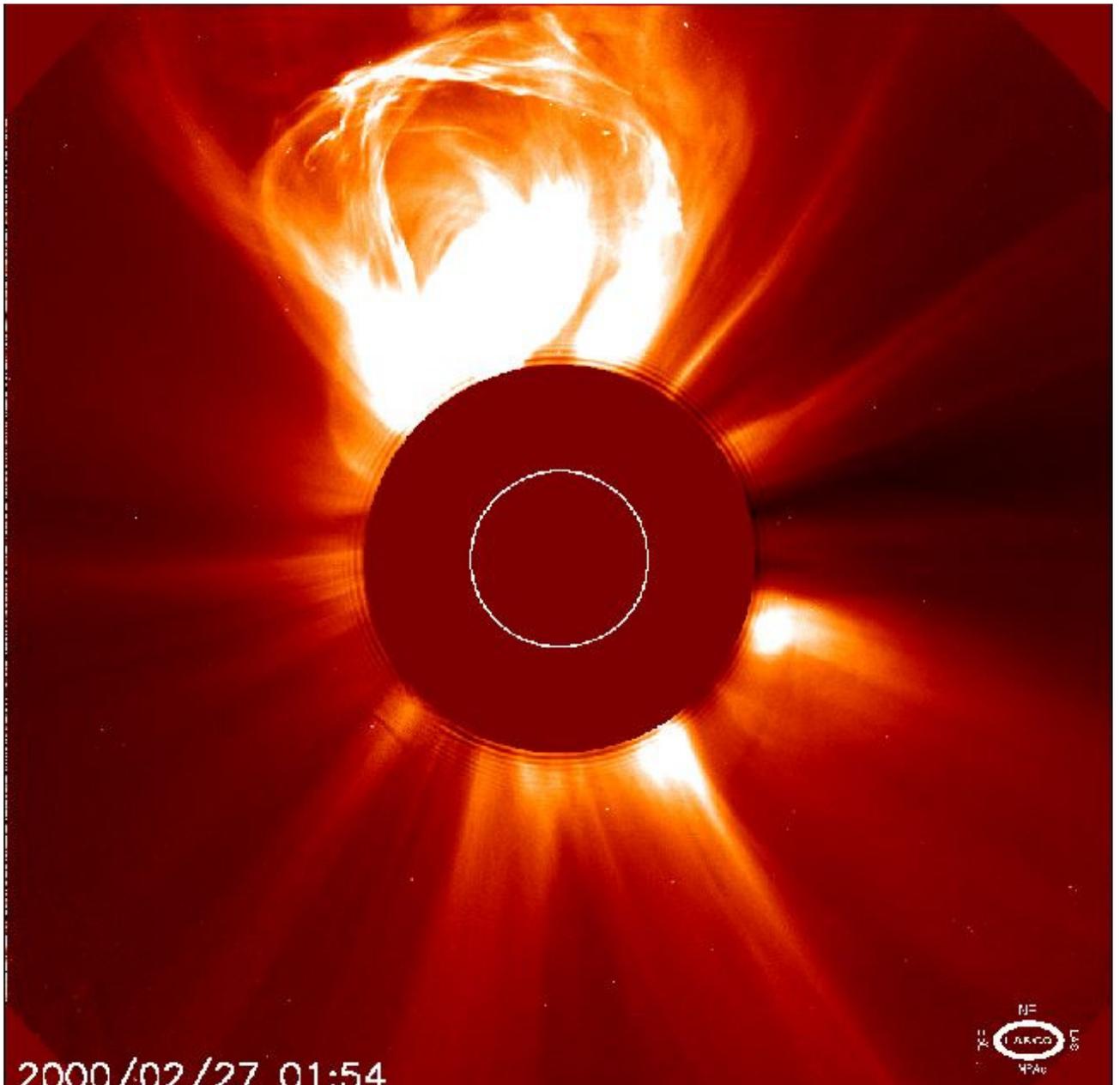
The corona is not normally visible, but it is on the occasion of the total eclipses of the sun, or with a special instrument called coronagraph, which simulates an eclipse by concealing the solar disk.

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

Total Solar Eclipse of 2017 August 21 - 11h 41m 26s - Hiland - Wyoming U.S.A.
Telescope: Nikon 300mm f/4 + Teleconverter Nikon TC-14E II - Foc. eq. = 700mm - Processing in HDR of 9 images from bracketing
Photo: Danilo Pirato
WebSite: www.danilopirato.com



It should be noted that during the minimum period the corona 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)

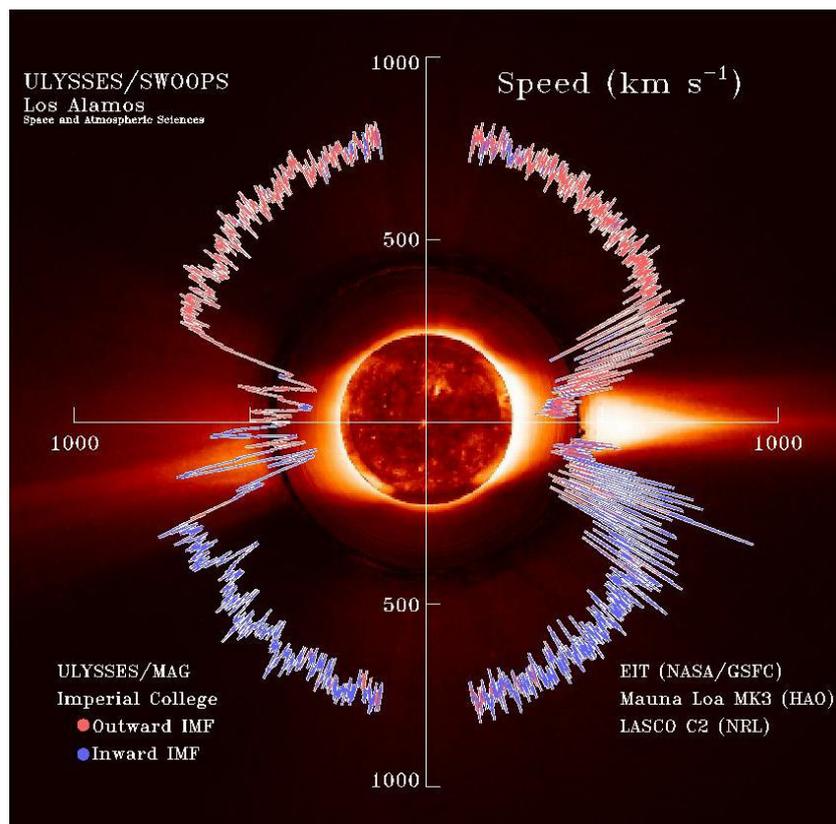
Summarizing: chromospheric and coronal activity has the following main explosive features:

- 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 450km/sec (slow solar wind) and from 450 to 900km/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 (161cm) (Arizona-USA)
- Big Bear Solar Observatory GST (160cm) (USA)
- Swedish solar telescope (100cm) 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 being replaced by the instrumentation on satellites, consists of a structure of a certain height (20-50 meters) on top of which there is a cœlost, 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. The image of the sun is then focused through another system of mirrors on the instrumentation at the base of the tower, generally a spectroheliograph (SHG), i.e. a high resolution spectroscope from which images of the Sun are obtained in the various wavelengths.

Among the main operative solar towers we mention:

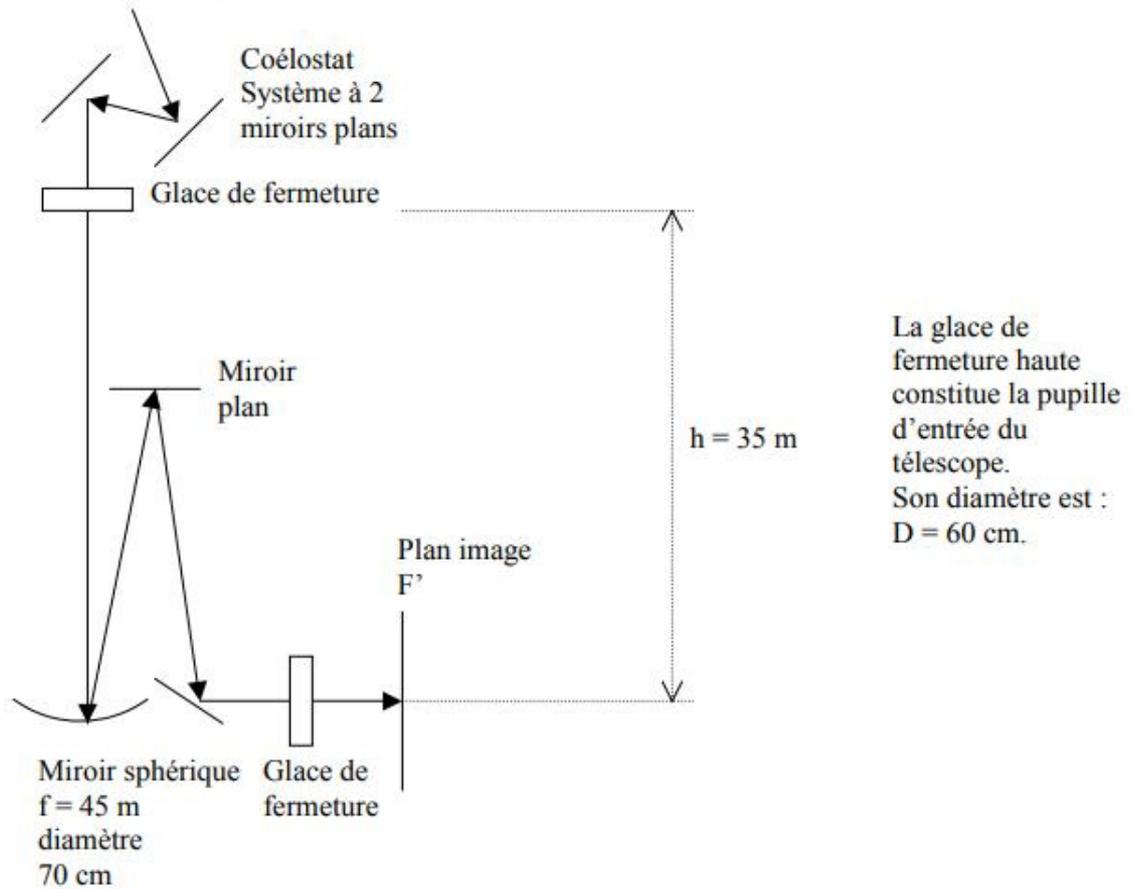
- The 150-foot (45-meter) tower of Mount Wilson (USA)
 - The solar tower of the Meudon Observatory, in Paris
- The beautiful solar tower of the Rome Observatory (34 meters) and that of Arcetri are now intended for educational needs.



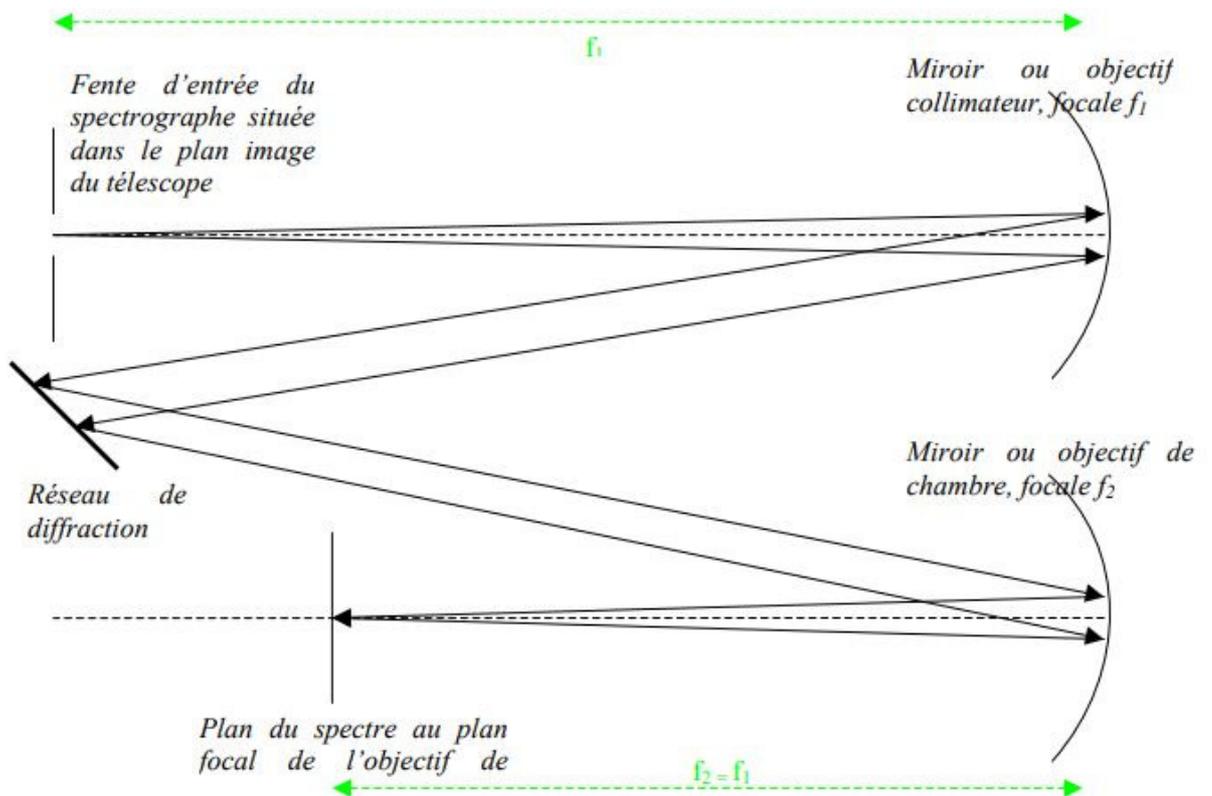
The solar tower of Rome Observatory, on the hill of Monte Mario
(Source: INAF, Observatorio di Roma)

The images that follow show 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). This principle is 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.

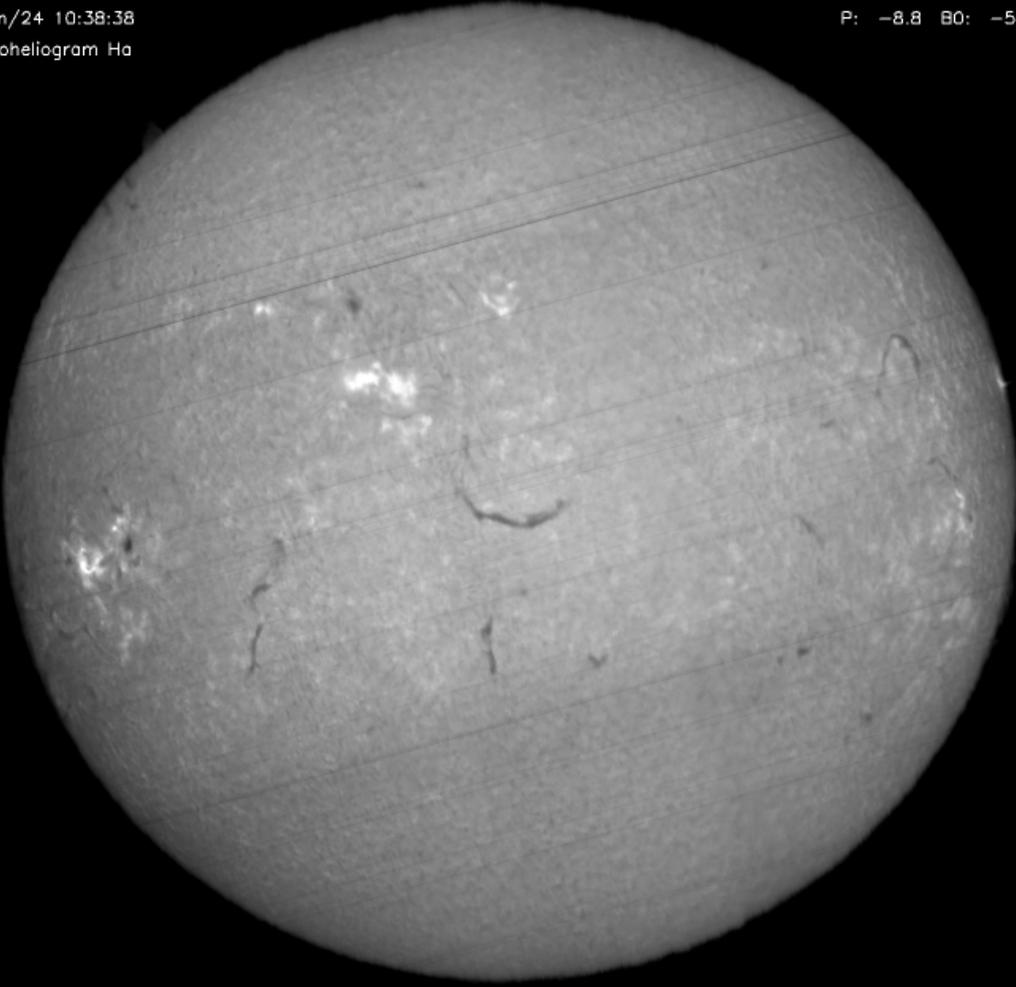


Layout of the spectrograph of Meudon solar Tower

A solar image in $H\alpha$ light at 6563\AA obtained with the SHG of Paris-Meudon Observatory (Source: BASS 2000).

Observatoire de Paris–Meudon
15/Jan/24 10:38:38
Spectrohéliogram H α

ROT: 2159 Lc:103.2
P: -8.8 B0: -5.4



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

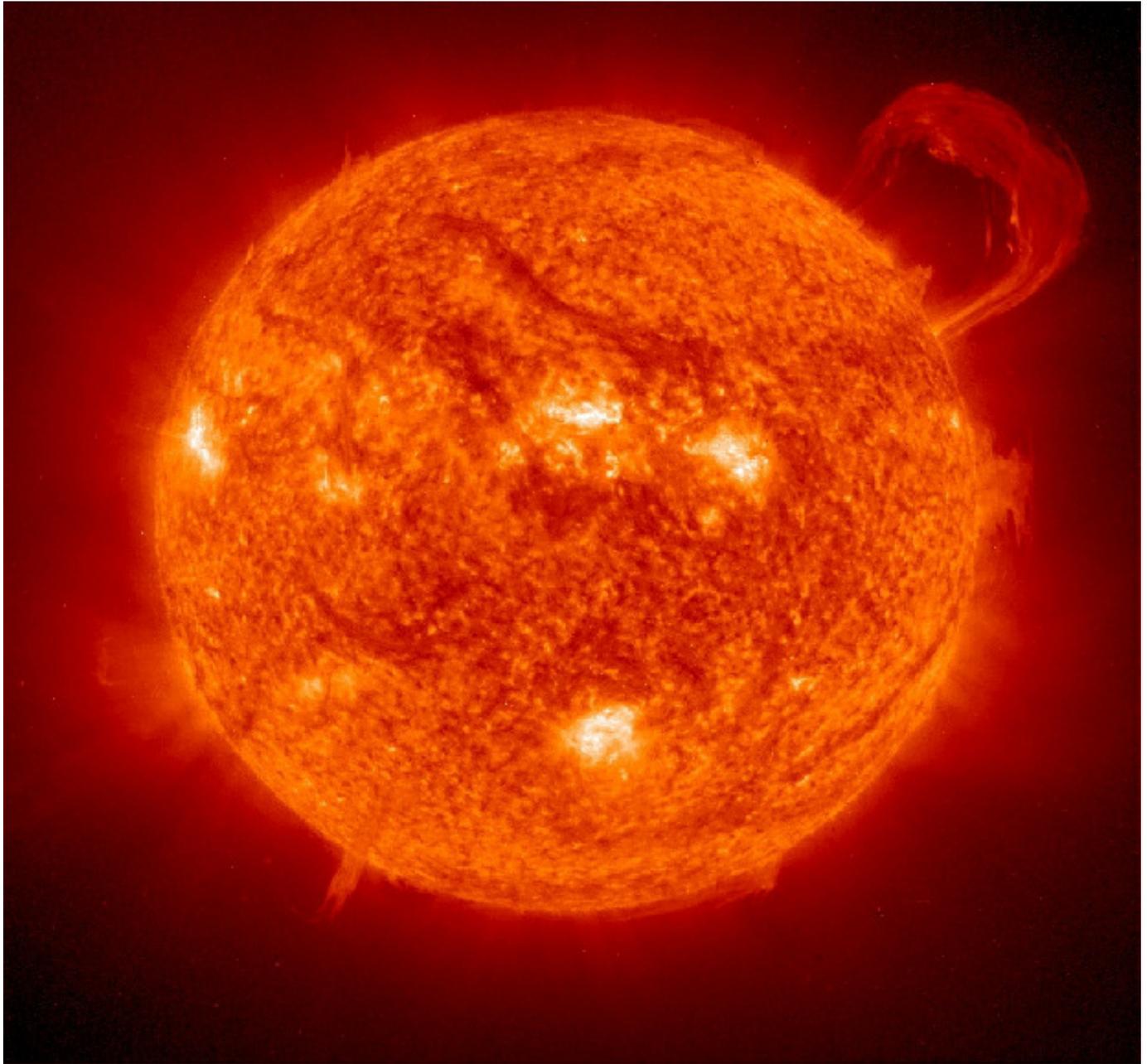
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1- SOHO (Solar and Heliospheric Observatory)

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 instruments. NASA was responsible for launching and monitoring the mission. SOHO has provided unprecedented and provides 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 171Å, which correspond, in order, to ever higher layers of the solar atmosphere and temperatures ranging from 60,000 to 2 million Kelvin.



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

2-STEREO (Solar TERrestrial RELations Observatory)

STEREO is the second mission in recent years 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:

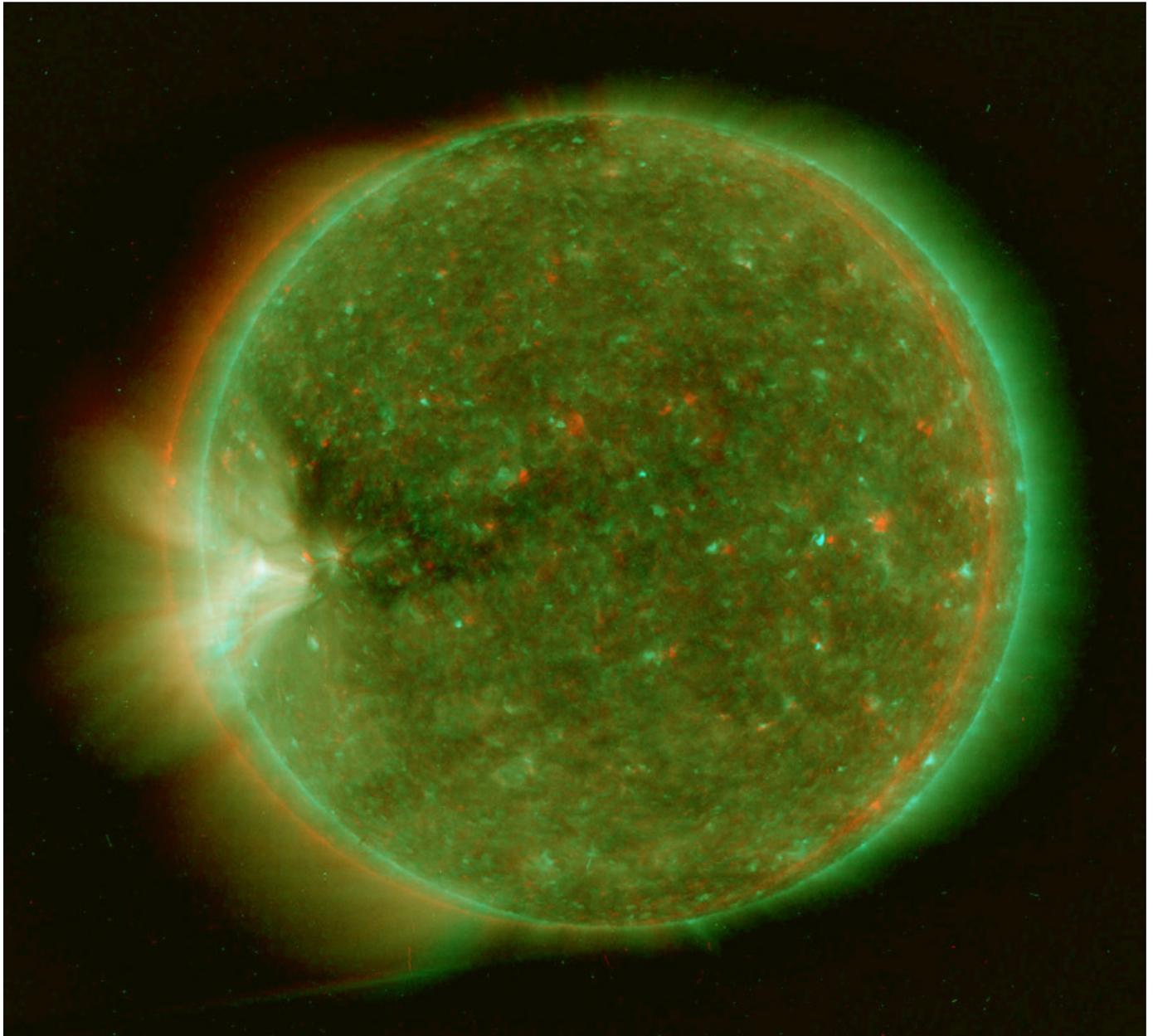
Understanding the causes of coronal mass ejection mechanisms (CME).
Characterize the propagation of the CME through the heliosphere.
Discover the mechanisms and sites of acceleration of energy particles in the lower corona and the interplanetary medium. Improve the knowledge of the solar wind structure.

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 corona 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 at 284Å

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.

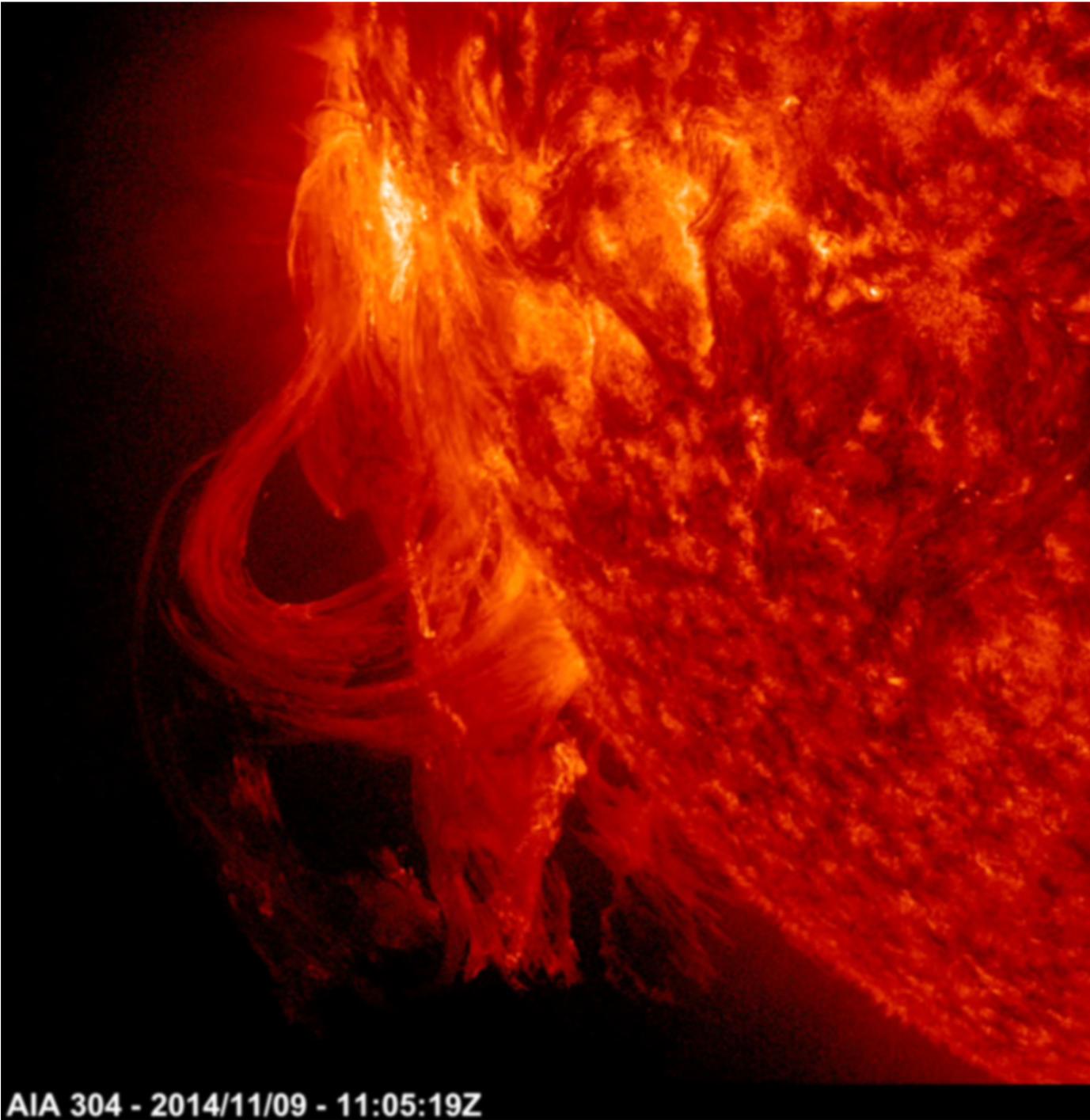
SDO uses three instruments to perform three main scientific experiments:

- 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. AIA (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 extreme ultraviolet (EUV) 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 304Å and many others can be consulted on the Helioviewer website:

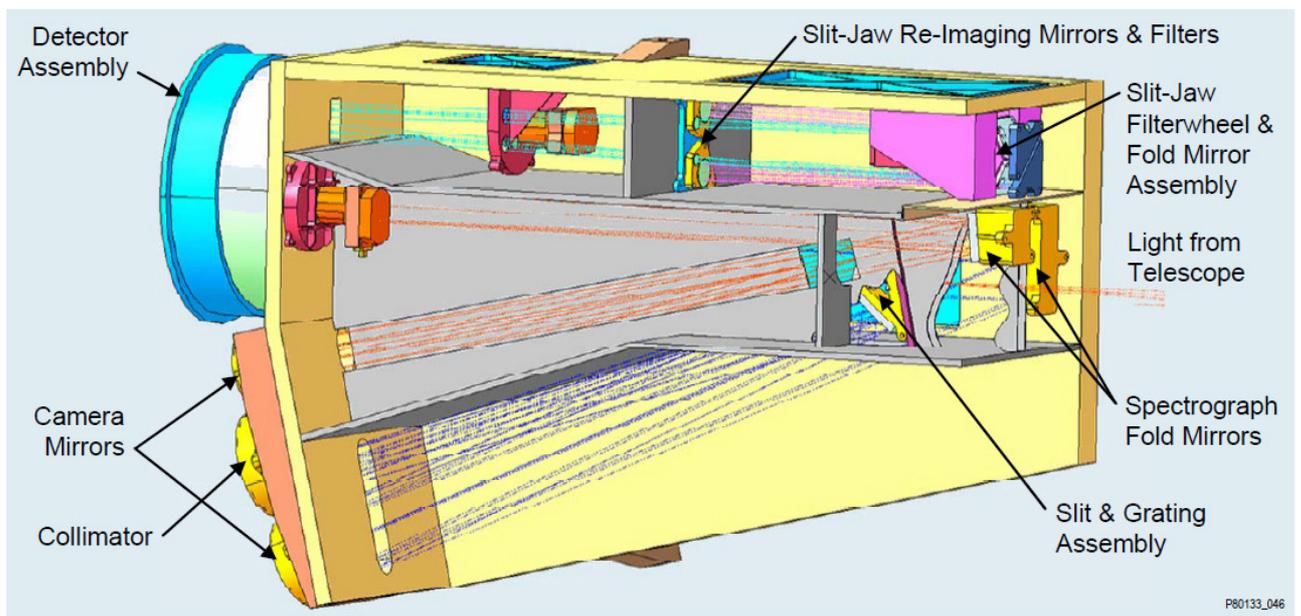
<https://www.helioviewer.org/>



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

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 or knowledge of 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-SHG which is shown the layout below (Source: NASA / LMSAL) able to record both images and spectra.

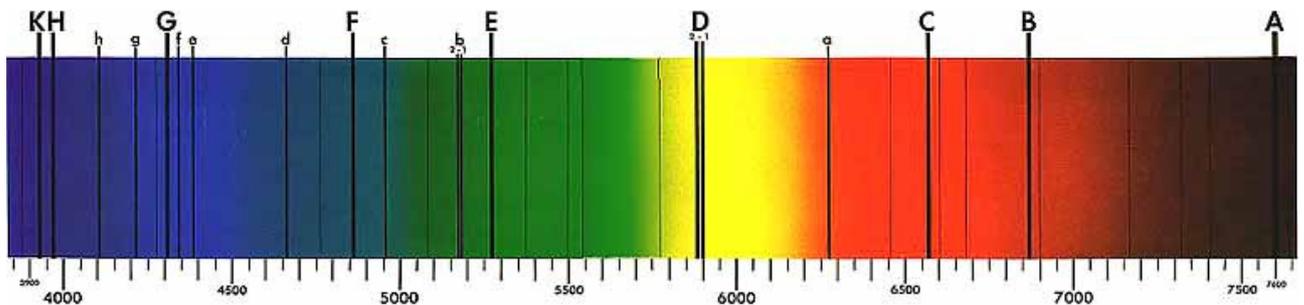


IRIS constitutes the state of the art and the most modern and advanced expression of spectroheliography, to which we will now turn our attention.

The solar spectrum

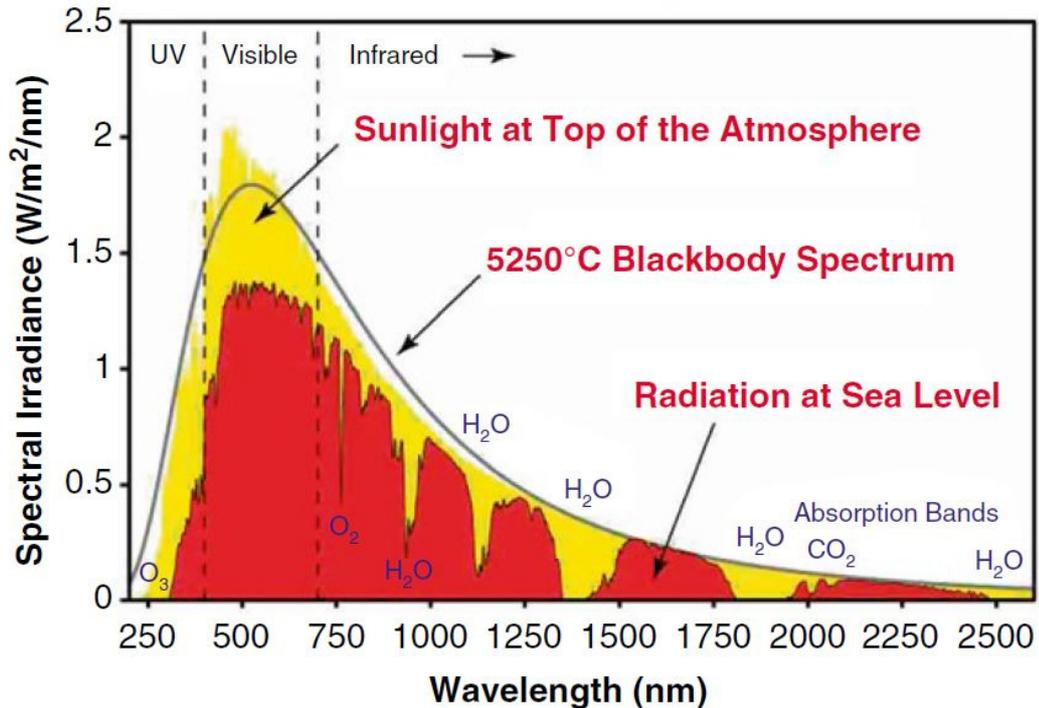
Of the solar spectrum I have already spoken in my spectroscopy text; however, it seems appropriate to recall here some aspects of the study of the solar spectrum, fundamental from the point of view of spectroscopy and spectroheliography.

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 left to Joseph Von Fraunhofer, a German physicist and astronomer, to observe and classify the major absorption lines for the first time, and which took their names from him. He cataloged 574 dark lines in the solar spectrum, assigning a letter to the most obvious (the famous H and K of Calcium and the C and F of Hydrogen).



Fraunhofer was unable to give an explanation of this phenomenon. Only in 1859 Gustav Kirchoff 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 500nm. It is therefore no coincidence that the sensors of digital cameras have a higher quantum efficiency (QE) in this area of the spectrum, in which, among other things, the human eye also has 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 eyesight. 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.

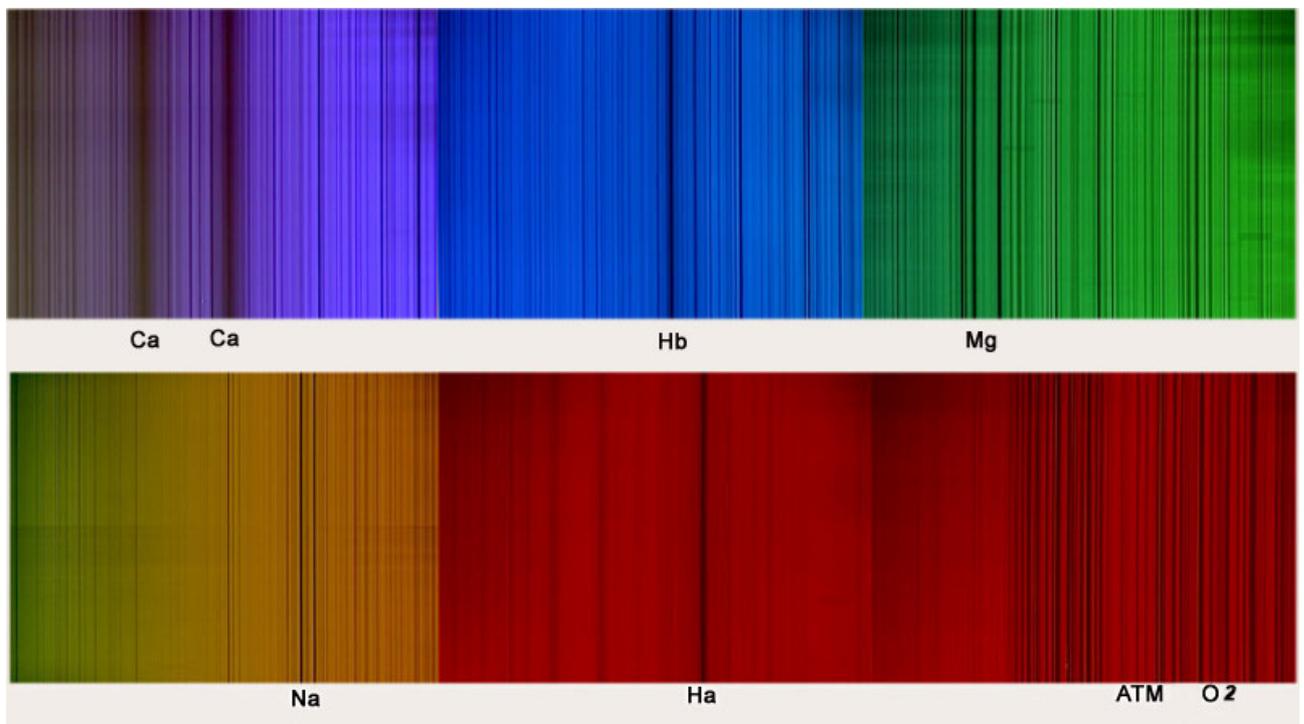
Moreover, in the solar spectrum there is a phenomenon of variation with the heliocentric angle. A spectrum obtained at the center of the Sun differs, even if not in a very pronounced way, from a spectrum obtained at the edge of solar disc.

The "standard" solar spectrum can be obtained in two ways: taking it at the center of the solar disk, taking care that there are no sunspots in the imaging field, or imaging a sun-like star, which is 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\AA , the so-called "Balmer jump" or Balmer discontinuity.

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 shown in the image below (TSA spectroscope), photo by the author.



But the observation of the lines and colors of the solar spectrum is not an end in itself. They provide us with precious 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.

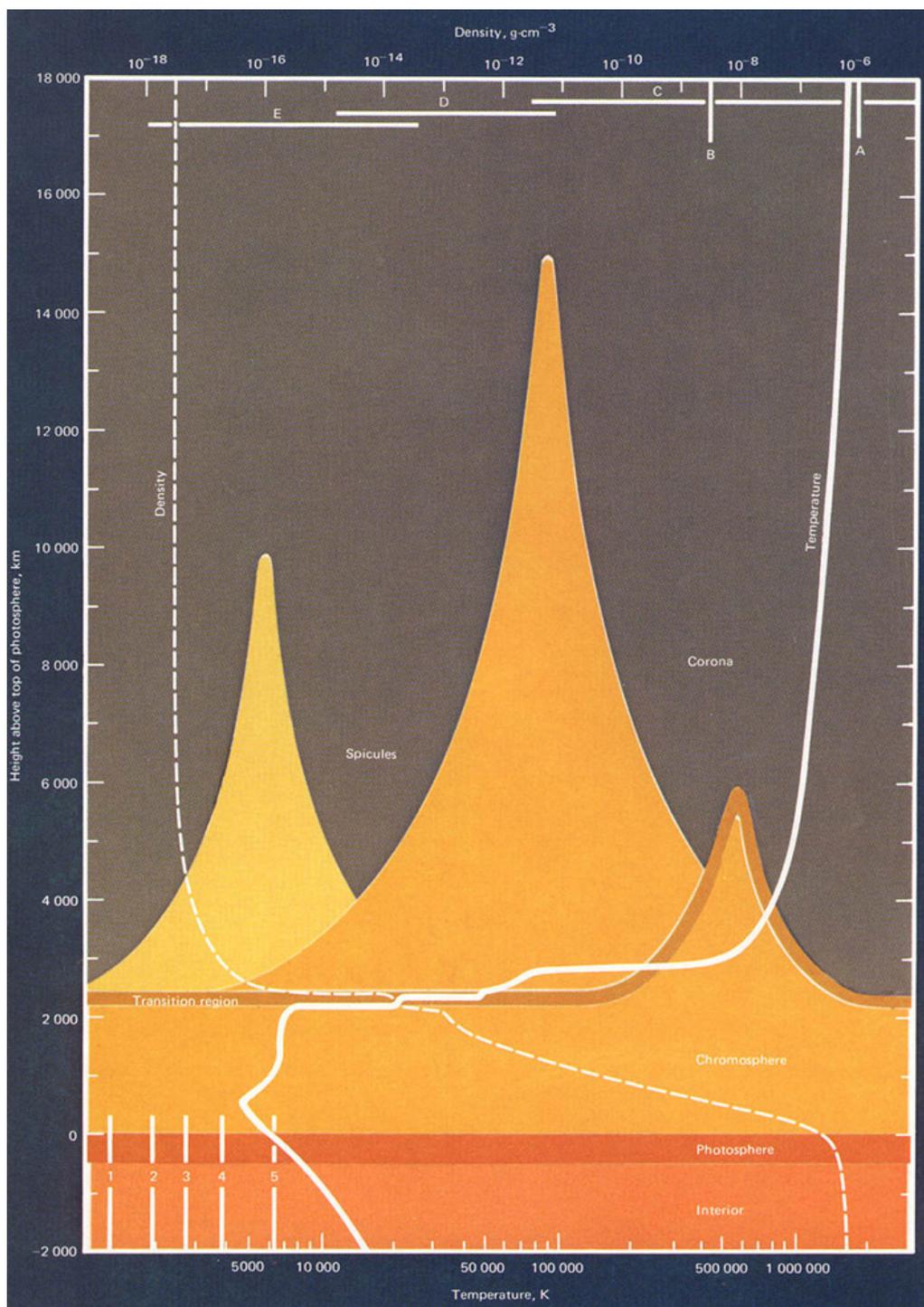
- 2-The atomic abundance of the element, deduced from the intensity of the lines.

- 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 (dividing into 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.

The following figure is a diagram of the photosphere, chromosphere, and solar corona according to height, temperature and density. From it we can estimate the point at which certain phenomena take place and the atomic populations of chemical elements. (Source: NASA-Skylab)

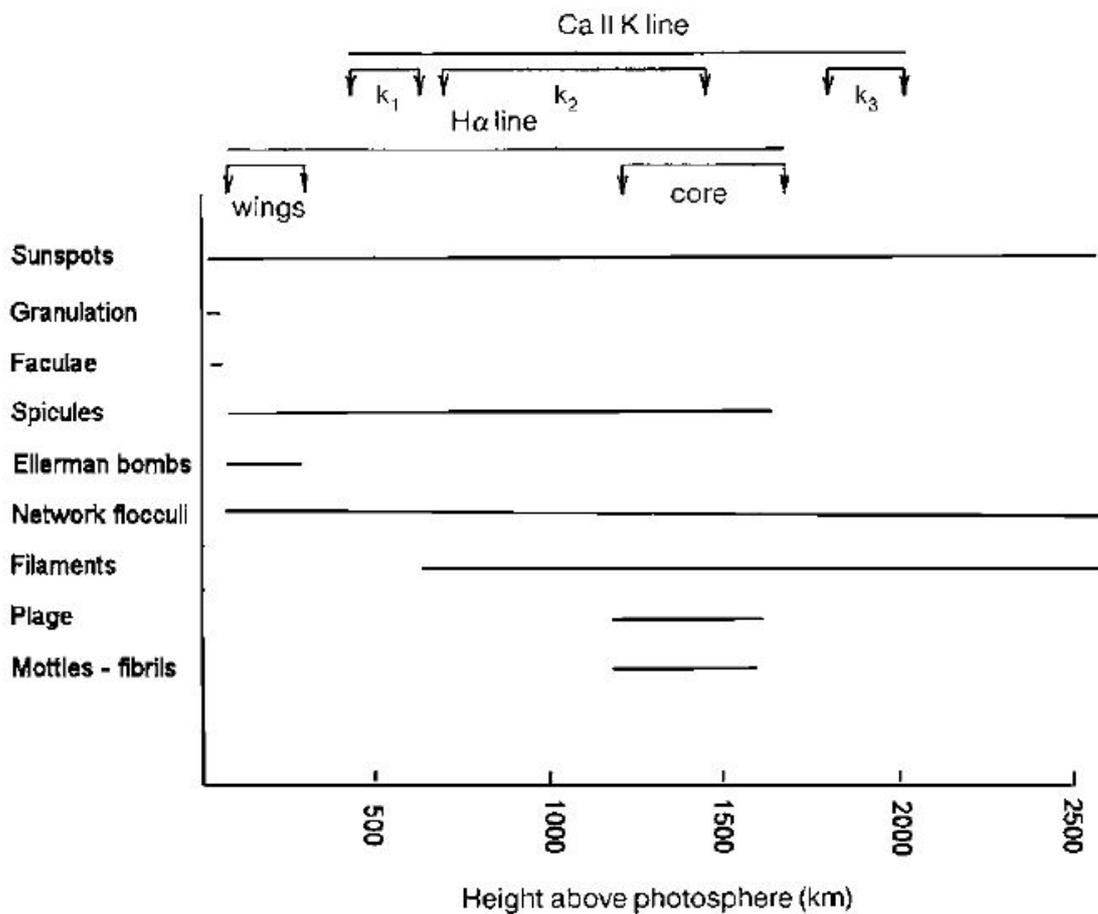


The table below (<https://solarnutcase.livejournal.com/9556.html>) gives information for the main spectral lines: Wavelength, the related element, the EW (Equivalent width) and their location within the solar atmosphere, with data on the height and the temperature.

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 (H α)	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)		

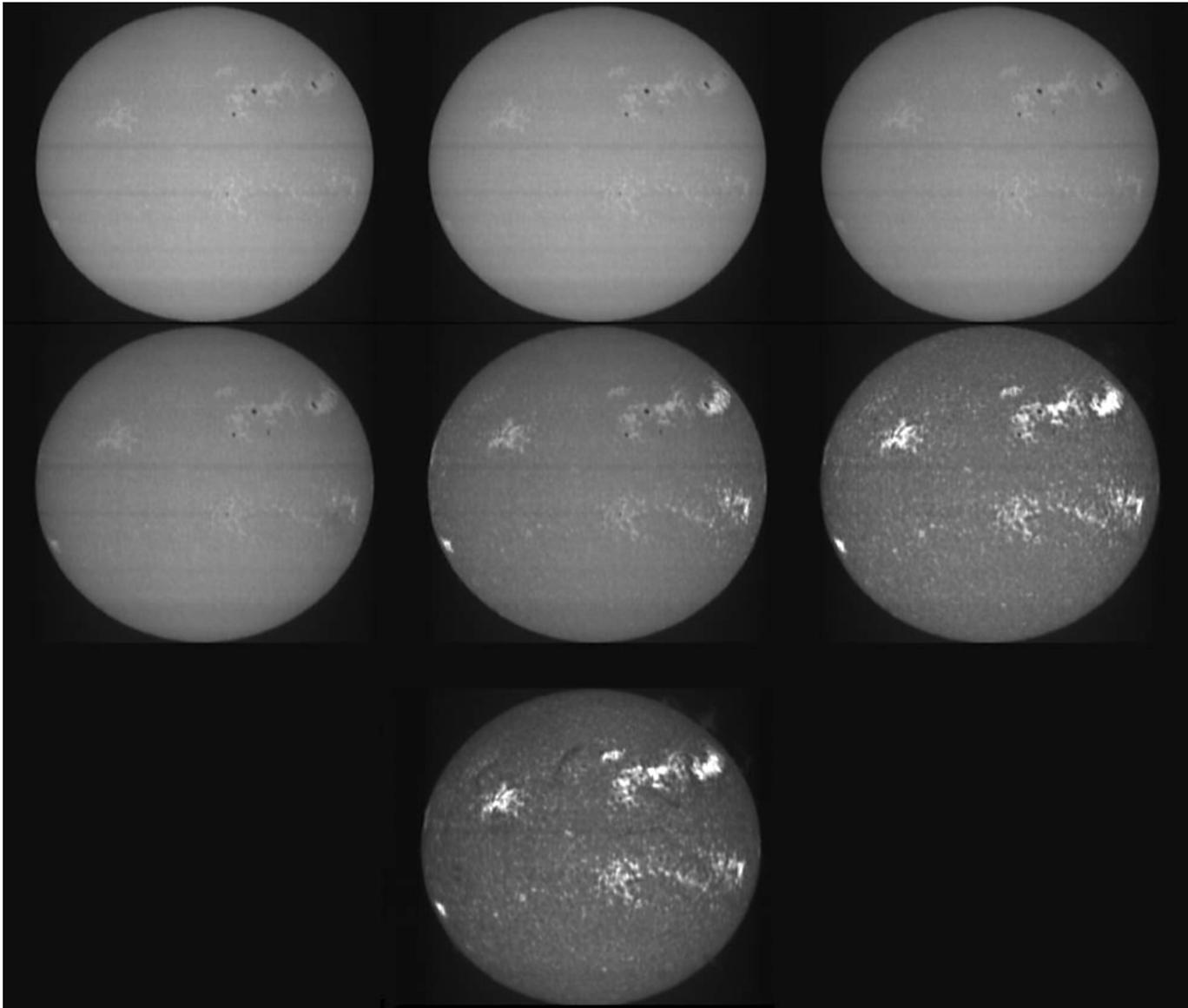
To further clarify the concept, the following diagram shows us how certain physical phenomena present on the sun (sunspots, faculae, filaments, plage, etc.) present a different aspect not only according to the element in whose light they are recorded or observed (for example H α or ionized Calcium) but also if the observation is carried out at the center of the line of the mentioned elements or in 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 2000km above 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 2000Km above the photosphere and passing from about 5500K to almost 10,000K in 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 CaII K_{2v} line at the borders of the continuum, up to the center (CaII K_3) of the same line. There is a dramatic intensify of the brilliance of the facula 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.

This sequence of images was obtained by the author with the VHIRSS DIY digital SHG.



While the "core" of the $H\alpha$ line at 6562.8\AA measures about $1.0\text{-}1.2\text{\AA}$, with wings it can extend up to 10\AA from the center, the CaII K at 3933.68\AA , whose center, including the stationary points ($K2_V$, $K2_R$) and the CaII K_3 covers about $2.2 - 2.4\text{\AA}$, with wings can reach 20\AA of extension.

As can be seen, therefore, the spectrum is not a simple substitute for narrow-band filters that are held in high esteem by the users, 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. Nowadays, there are thousands of documented solar lines, 24,000 of those are 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 duplicate and triple, or too weak to be recorded by amateur means. However, in the author's opinion, there are some 7-8000 with the potential to be explored with a very high resolution SHG. 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	H
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	H		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 ₂)
425.4346	0.0393	Cr I		589.5940	0.0564	Na I (D ₁)
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	H		630.2499	0.0083	Fe I
438.3557	0.1008	Fe I		656.2808	0.1020	H

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 SHG if they were readily available to the amateur (which currently they are not).

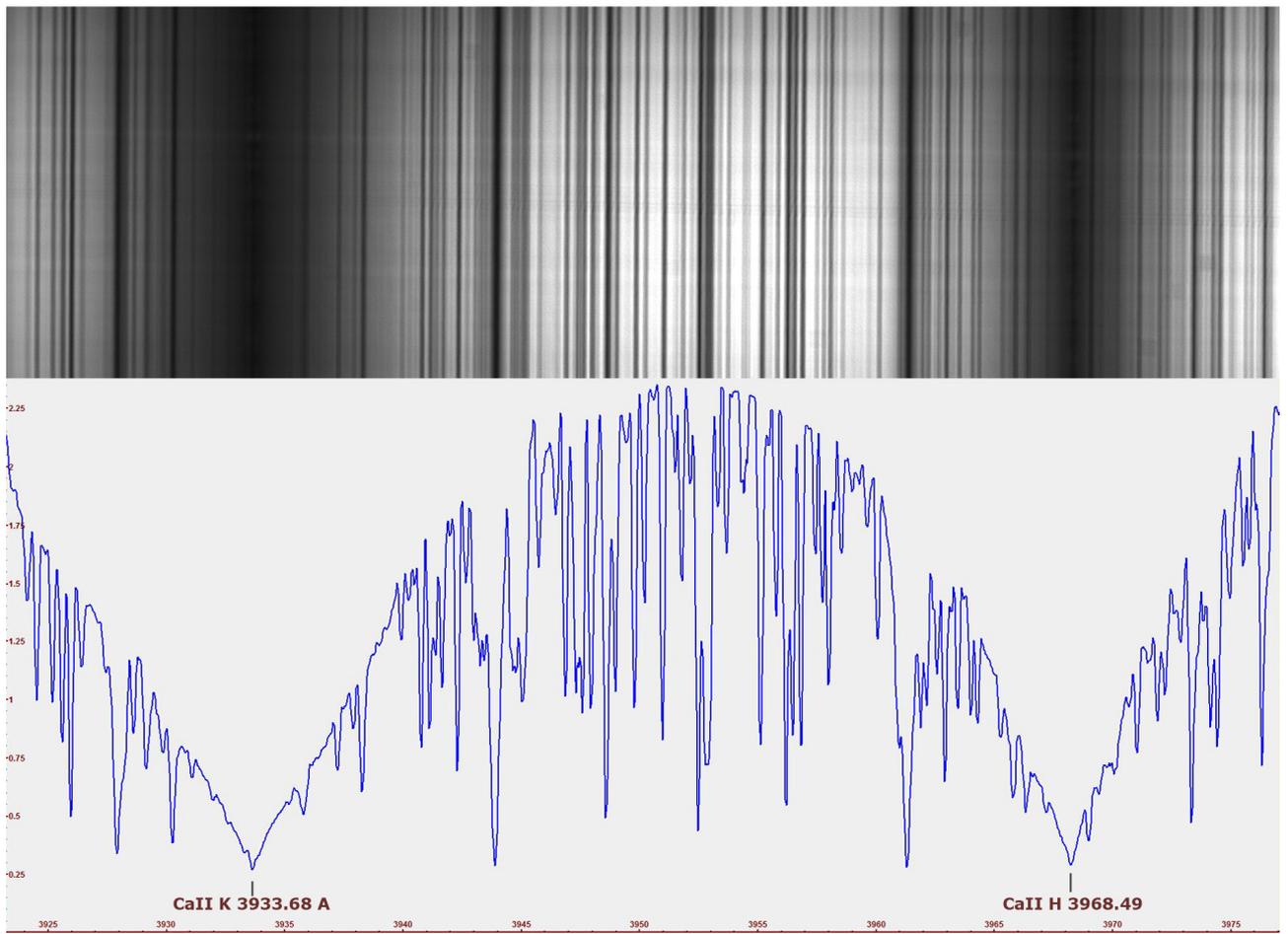
How much would it cost the amateur to invest in 50-100 very narrow band solar interference filters? Surely an amount ranging between 200,000 and 400,000€ (\$231,000 – \$462,000), not to mention that interference filters with so narrow a bandwidth to allow the selection of lines or parts of a line of 1/50th of Angstrom probably do not exist.

Here I will show how you can explore the secrets of our star with an outlay 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

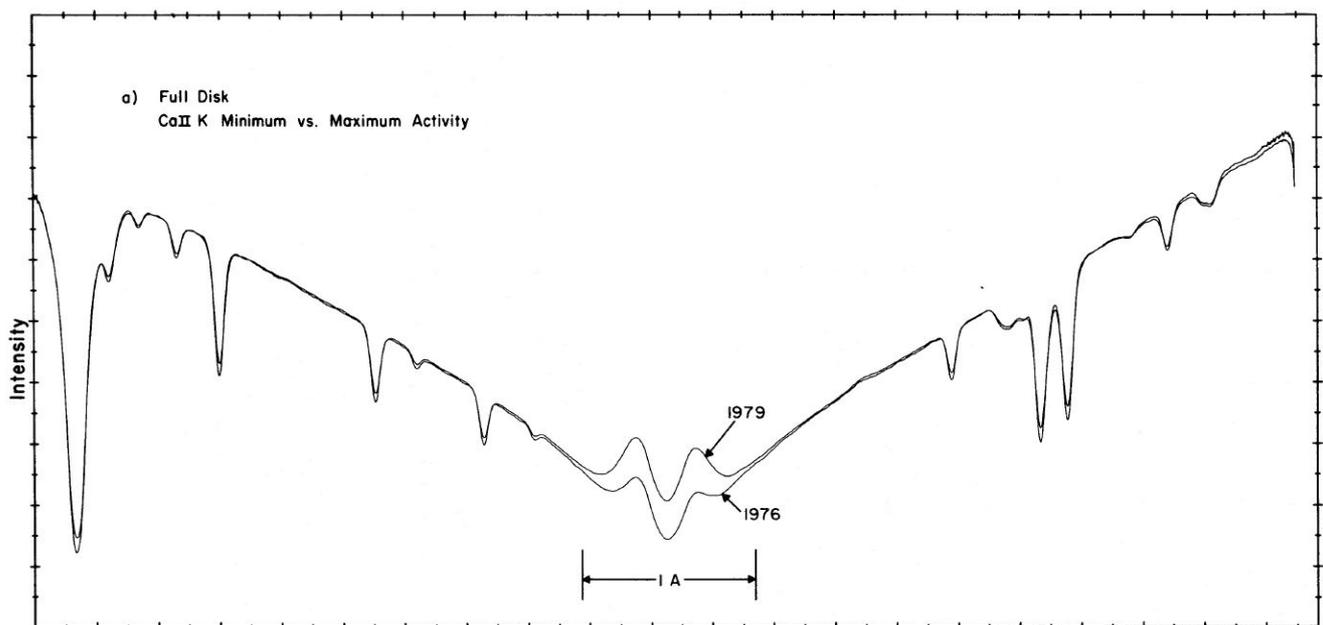
POSS2 CaII K & CaIIH lines



The lines CaII K at 3933.68Å and CaII H at 3968.49Å imaged with my DIY "POSS2" Hires spectrograph – SHG.

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 1Å centered on the line, and the core intensity values K_3 (0.15Å) 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 1100nm. The monitoring also extends to the CaII H line.

An example of the variation of core intensity of the central 1Å of the CaII K line ($k_{2V}-k_3-k_{2r}$) 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 8668Å (Calcium triplet), the most used by professionals, that at 8542Å, would however be rather difficult to reach for an amateur, not so much due to the spectroscope, which would require a grating optimized for IR, but to compensate for the lack of sensitivity of the amateur CCD or CMOS cameras at that wavelength.

The lines of Hydrogen observable on the Sun

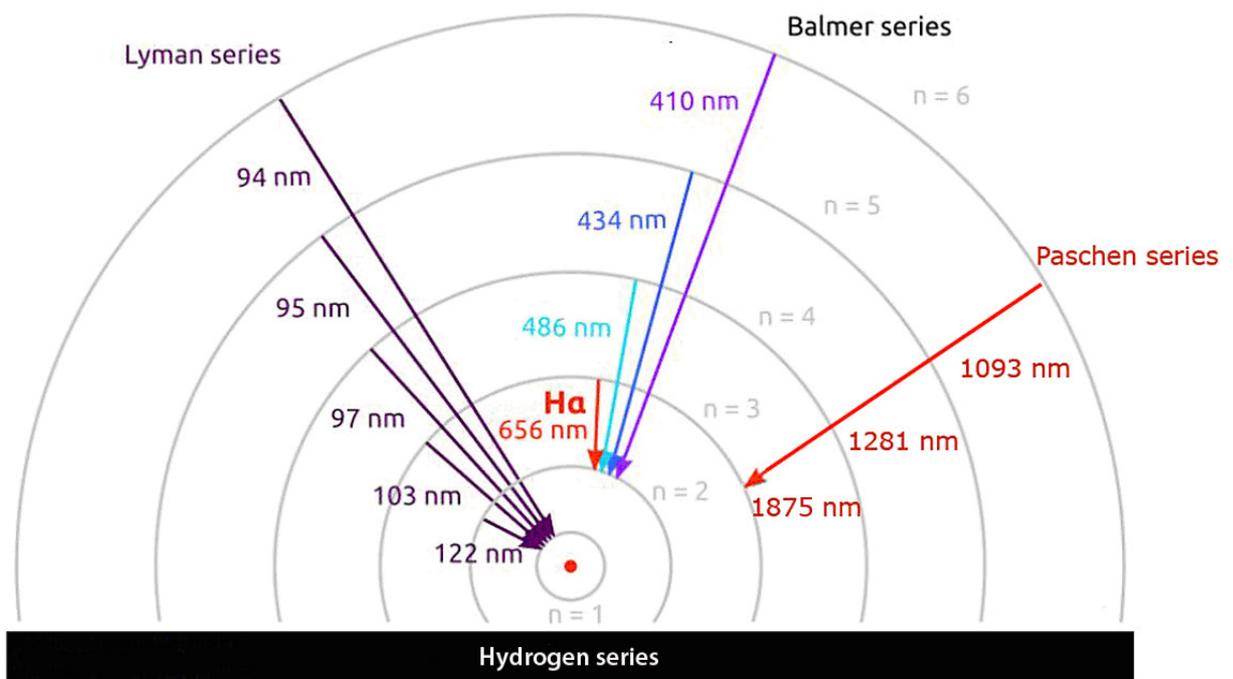
The spectrum of hydrogen is the simplest of the spectra since this element is made up of a nucleus containing a proton around which only one electron moves. The electrons move in orbits with quantized energy. The orbit, 1s, is the innermost one, a fundamental state, which corresponds to the minimum of 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 which is shown the layout below (Source: NASA / LMSAL), L_α , L_β , L_γ etc. 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 in 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_α , the second from 4 to 2 and is indicated with H_β while the third indicated with H_γ corresponds to the jump from orbit 5 to 2 and so on. The same sequence is repeated for the Paschen series whose lines correspond to the energy of the lines seen in 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 spectrum is undoubtedly the most interesting from our point of view, also because the ionized hydrogen H α at 6562.8Å 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:

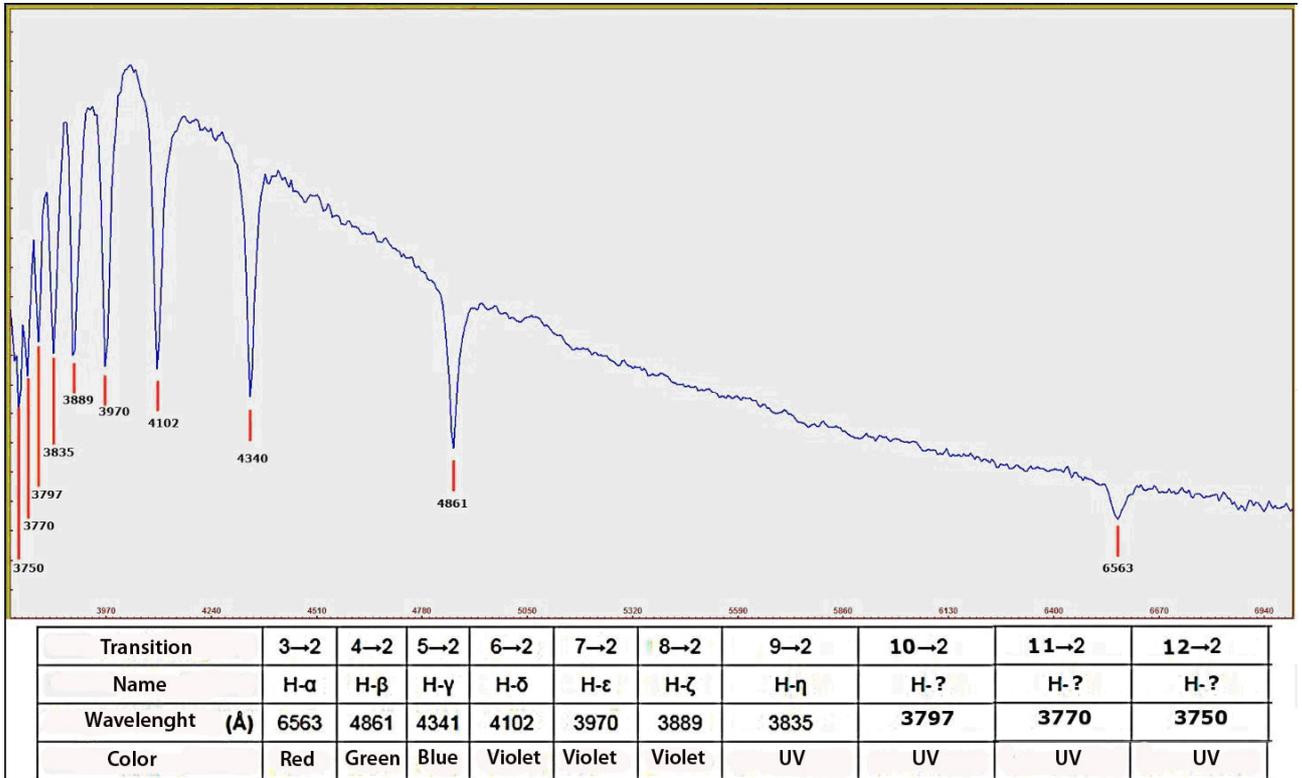
$$\lambda = B \left(\frac{n^2}{n^2 - 2^2} \right)$$

where B is the Balmer limit at 3646Å; n is any integer $n > 2$

Below, the absorption spectrum of the Hydrogen Balmer series I have calculated on the Vega star up to the 12 to 2 transition:

For example, for the transition 10 to 2 is:

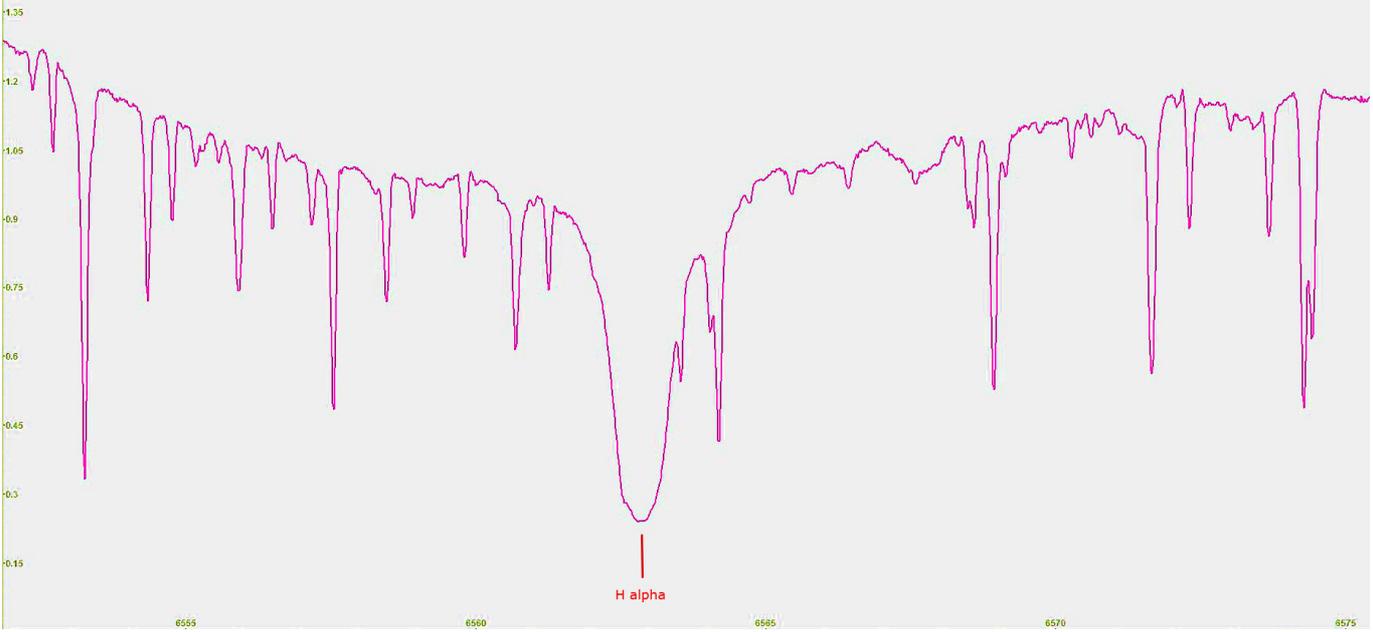
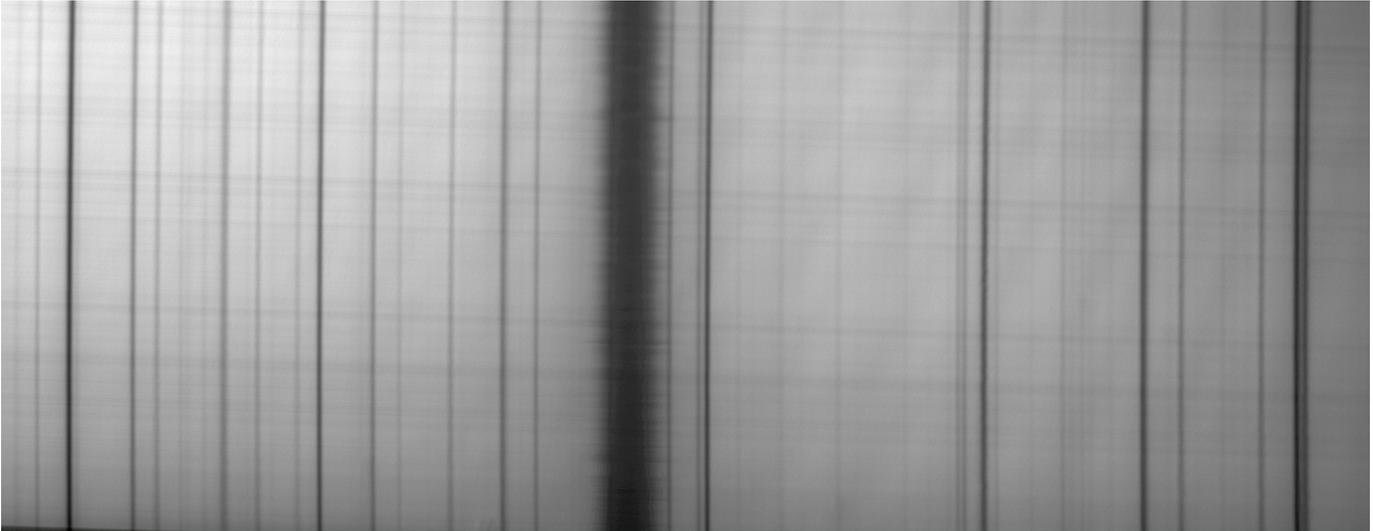
$$3646 \times (100/96) = 3797\text{Å}$$

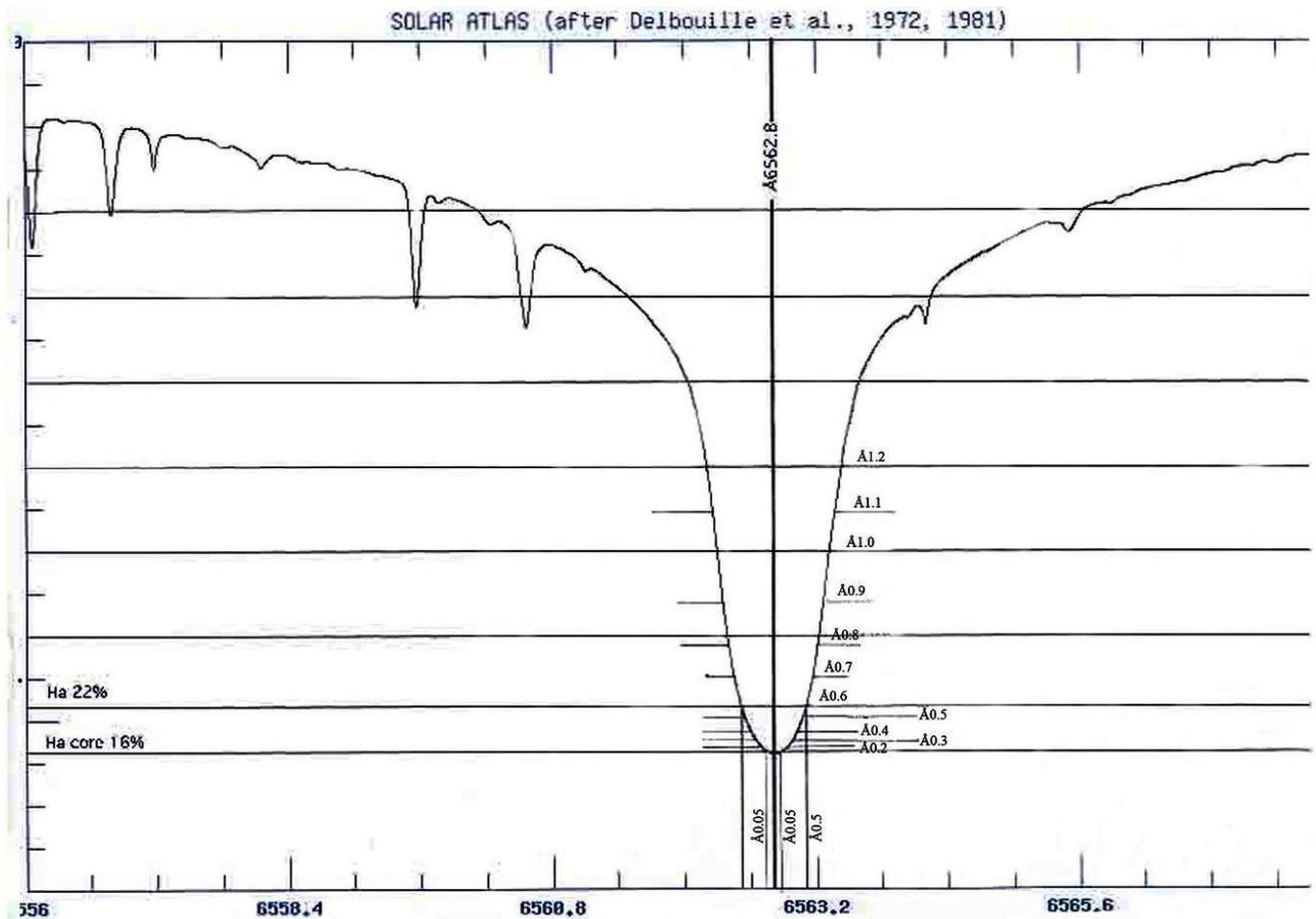


The H α line

As mentioned above, the hydrogen transition 3 to 2 at 6562.8Å (H α λ line) 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 refers to the high chromosphere, on average around 1500km, as shown in the figure on page 45.

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



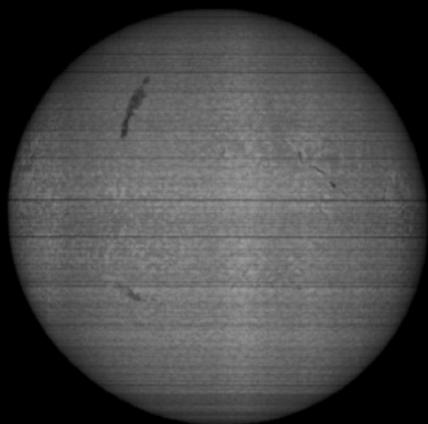


Profile of $H\alpha$ line in absorption with the extension in Angstrom of the core and the wings the FWHM is about $1-1.2\text{\AA}$. Source: Debouille-Solar Atlas – BASS 2000.

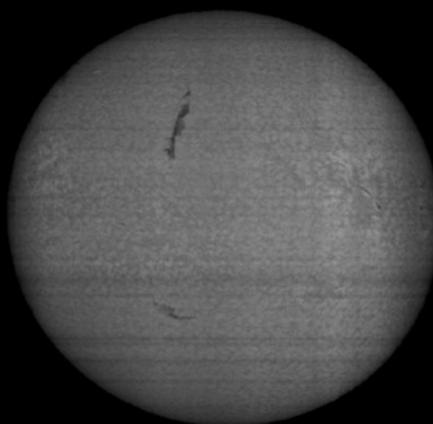
The $H\beta$ line

The $H\beta$ line at 4861.34\AA would seem at first glance less important for the study of the solar atmosphere, both for the smaller wing extensions with respect to the $H\alpha$ and for the attenuation of the same details, primarily plage and filaments. However, it is necessary to evaluate the good observability in the spectroheliograms in this line of solar flares. The author, participating in the survey "F-Croma" could verify this feature with a small flare observed on September 27, 2015 in the sequence of VHIRSS $H\beta$ images that follows made during the campaign.

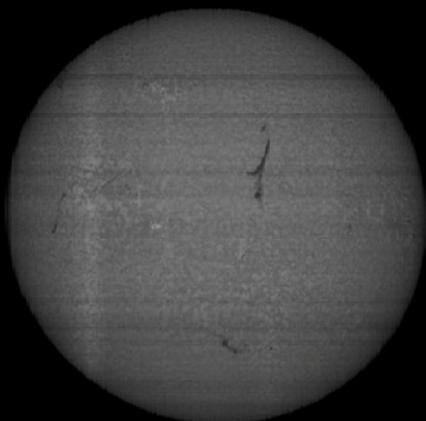
15-09-21



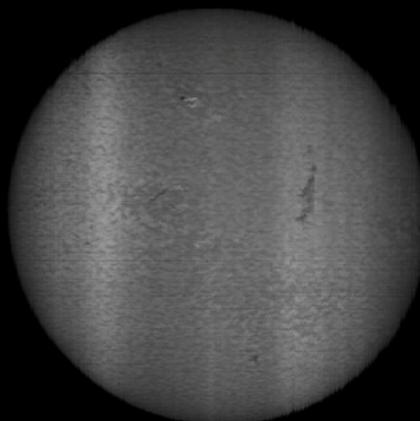
15-09-22



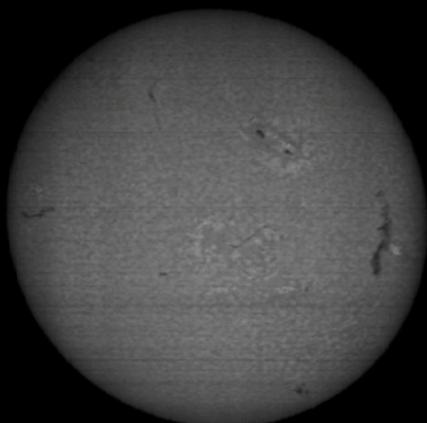
15-09-24



15-09-25

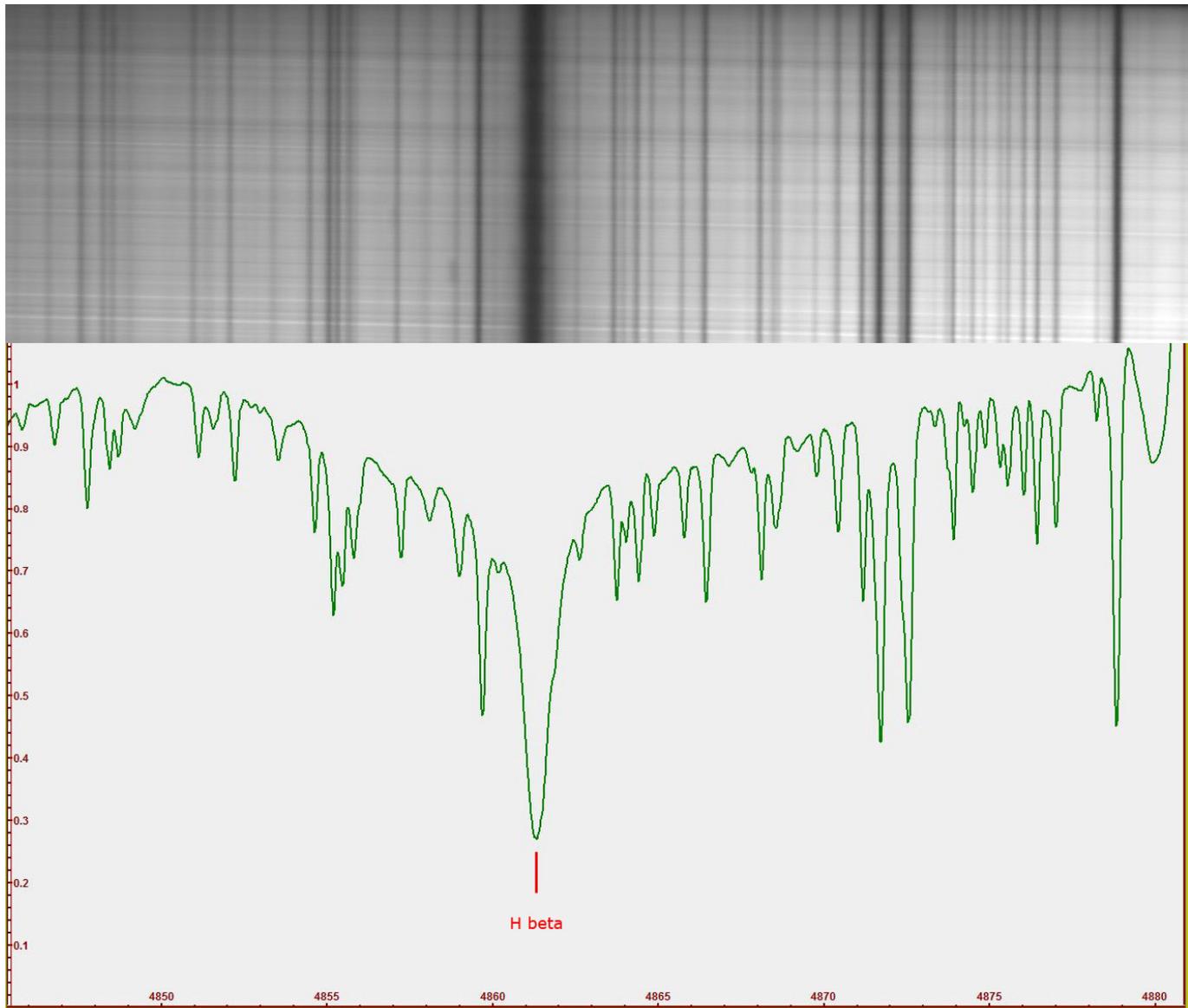


15-09-27



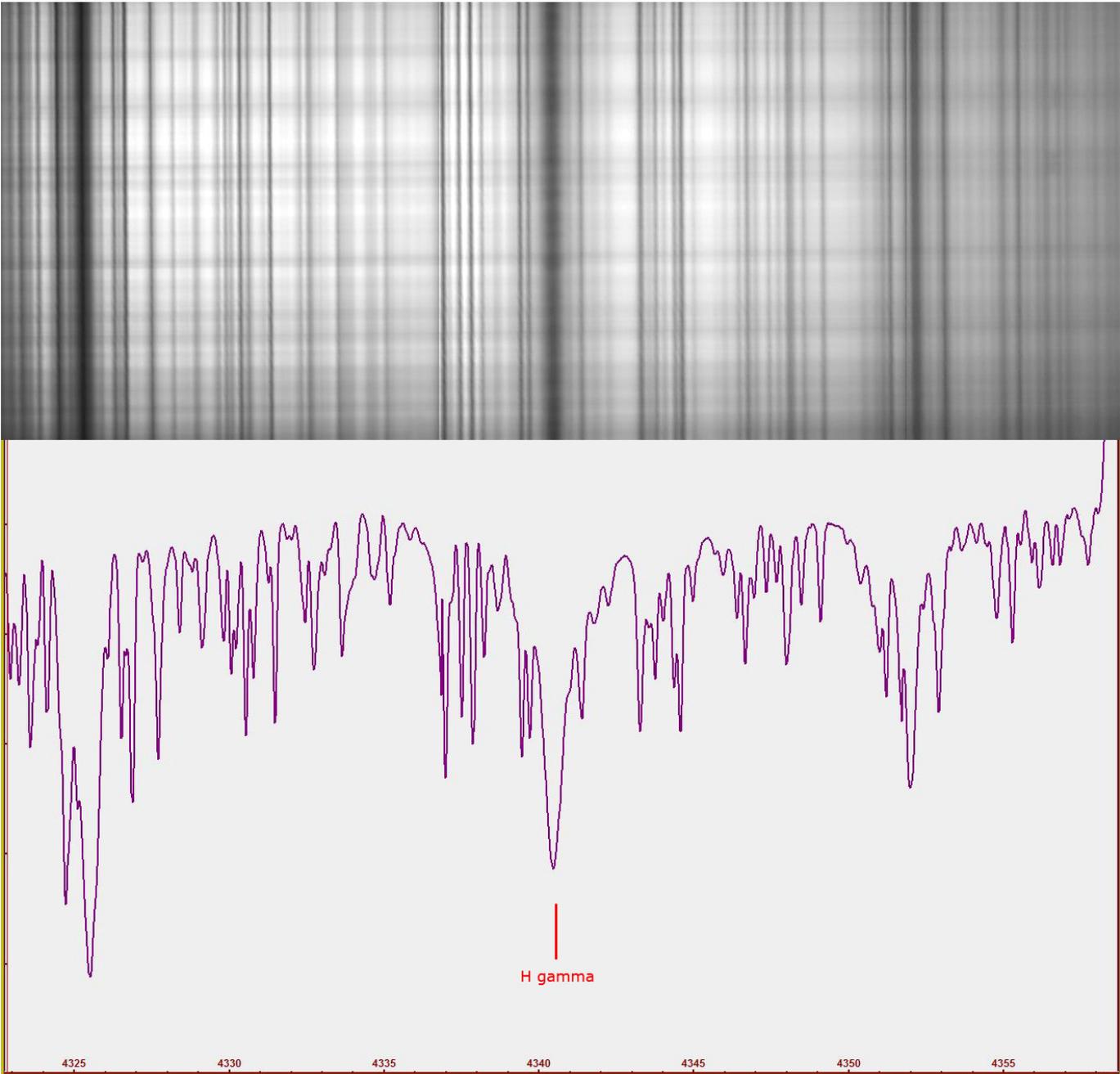
Sun in Hbeta light 486 Nm and AR 12 422 evolution September 21-27-2015 -
VHIRSS digital spectroheliograph Fulvio Mete, Rome, Italy

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

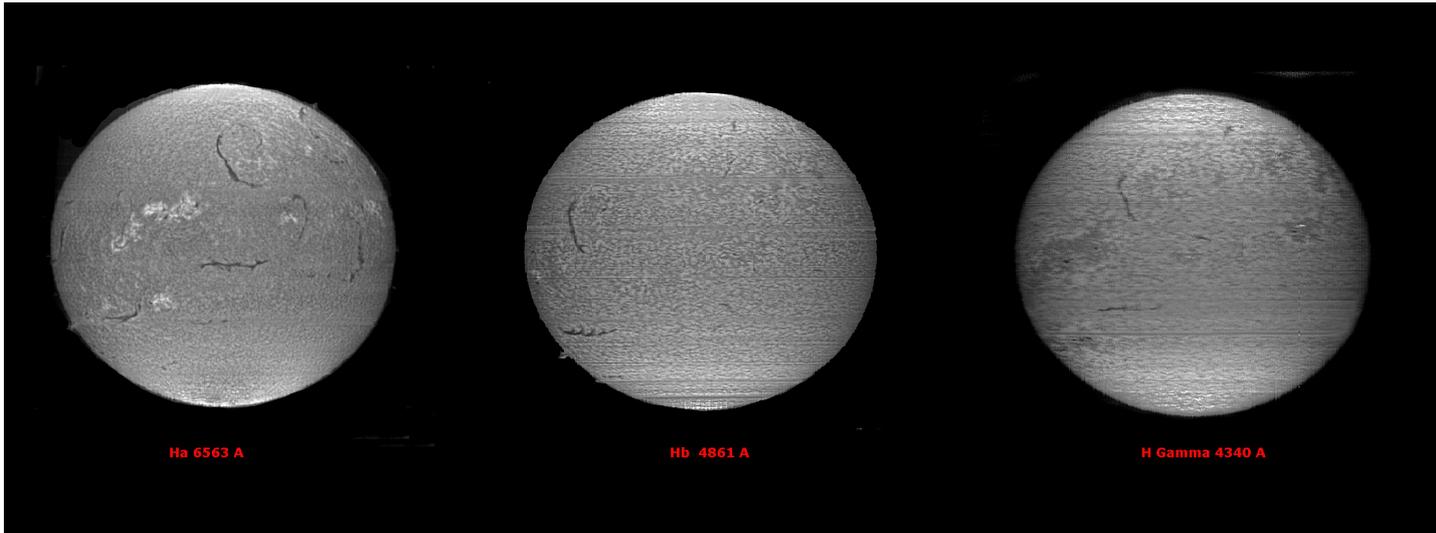


The H γ line

What I said for the line H β is also valid for the line H γ at 4340.47Å in the sense that in the spectroheliograms 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 $H\alpha$ in the lower wavelengths, the plage areas lose their bright white color to pass to darker shades of gray, while the filaments lose contrast.

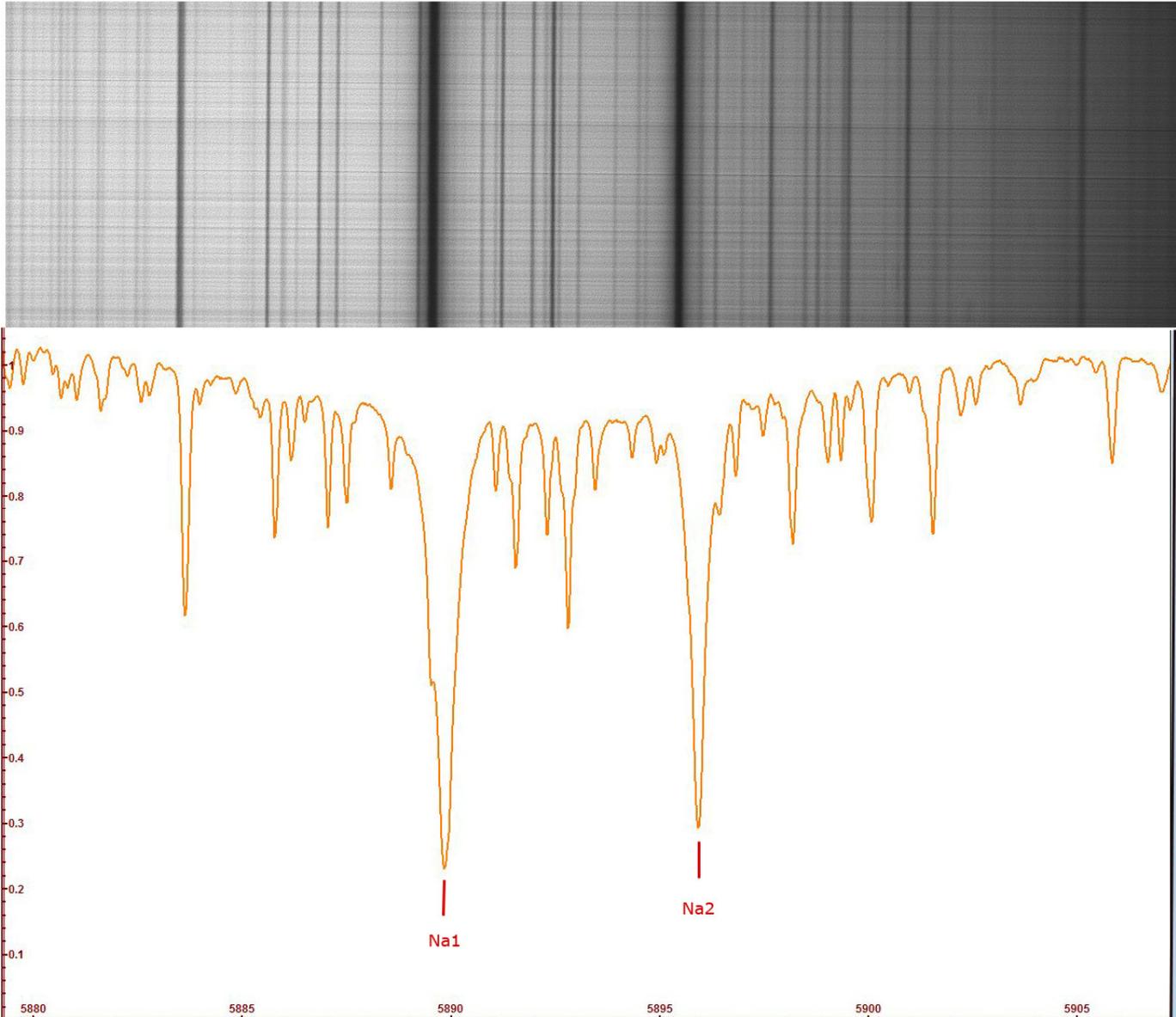


The Na 1 and 2 lines (sodium doublet).

These lines, respectively at 5889.97 and 5895.94\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.

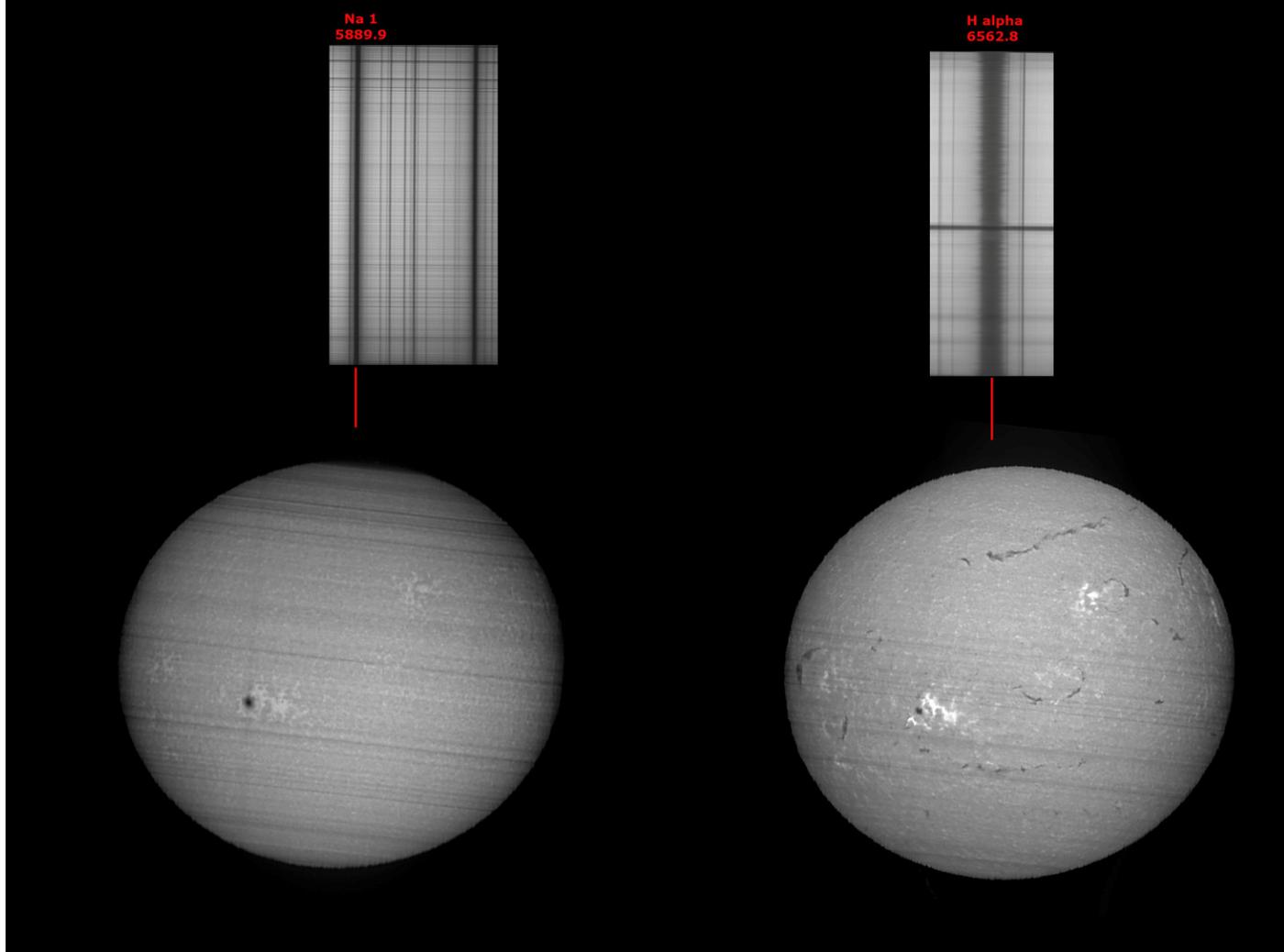
Incidentally, the lines in question were those used by the GOLF instrument (Global Oscillations at Low Frequencies) aboard the SOHO probe a few years ago, in order to measure the velocity of the photosphere along the line of sight for the whole disk in order to observing small oscillations, as well as, 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.

The image that follows shows 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 are due to the Earth's atmosphere).



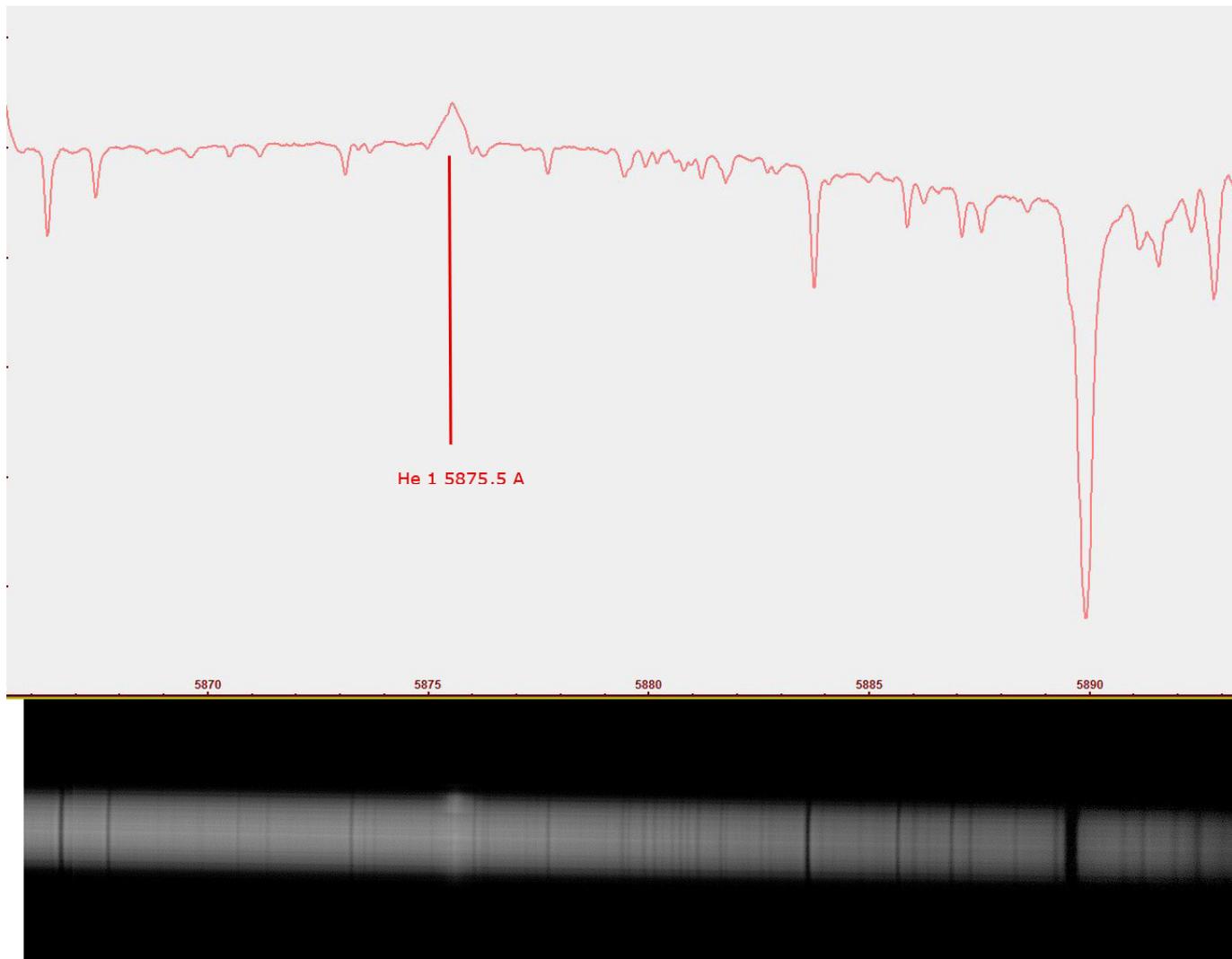
The following image, a comparison between the sodium-Na and H α spectroheliograms. This demonstrates, the differences between the low and high chromosphere and also between two very different elements: an alkaline metal (Na) and a gas (H) that is the first chemical element of the periodic table and the 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 Helium

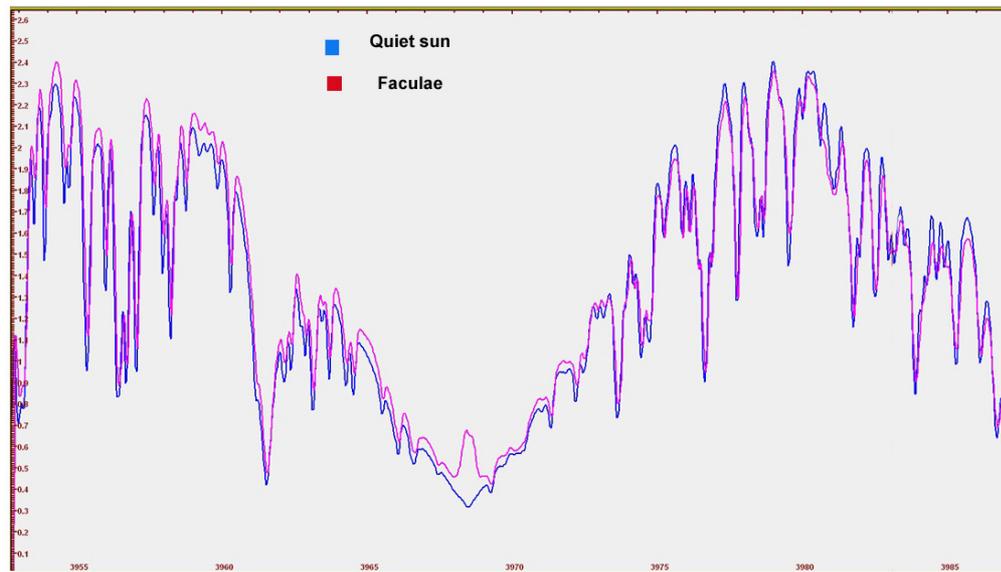
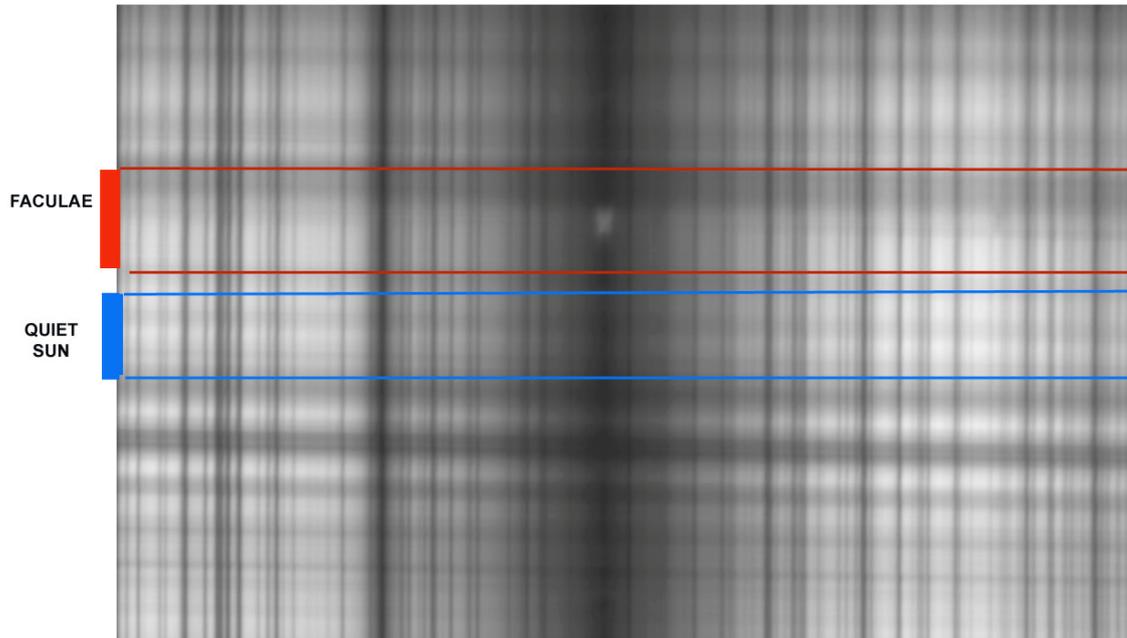
The elusive line of Helium at 5875Å in absorption is rather difficult to identify: the line in emission is much easier, and can be observed by placing the slit of the spectrograph on the edge of the solar disk.



The lines CaII K and H

These are the famous lines of Ionized Calcium at 3933.68\AA , and 3968.49\AA 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.

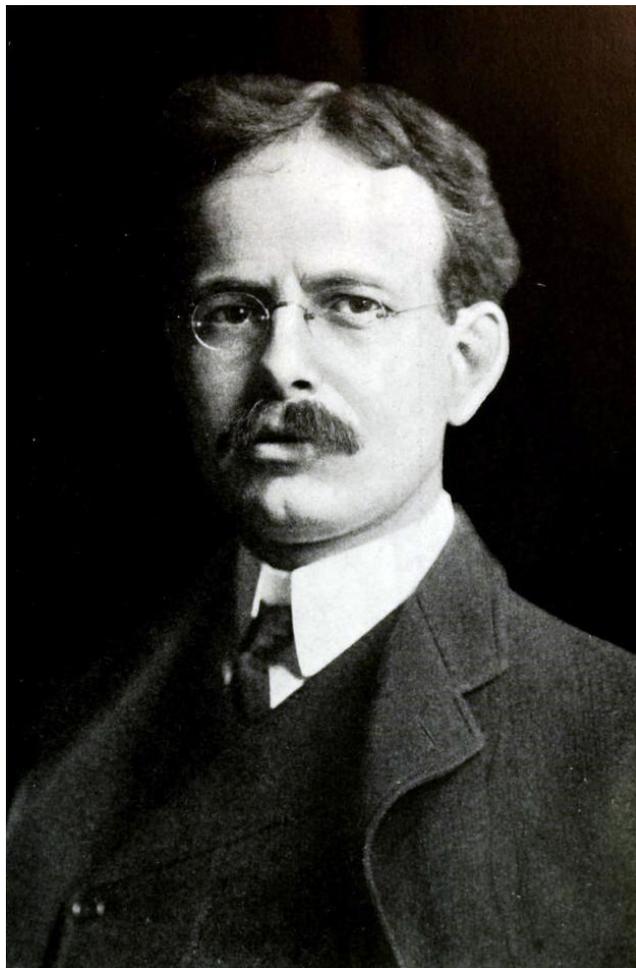
Appearance of Chromosphere in Ca2H light in quiet sun and faculae: note the spectral profile passing from absorption (blue) to emission (red).



Spectroscopy and Spectroheliography

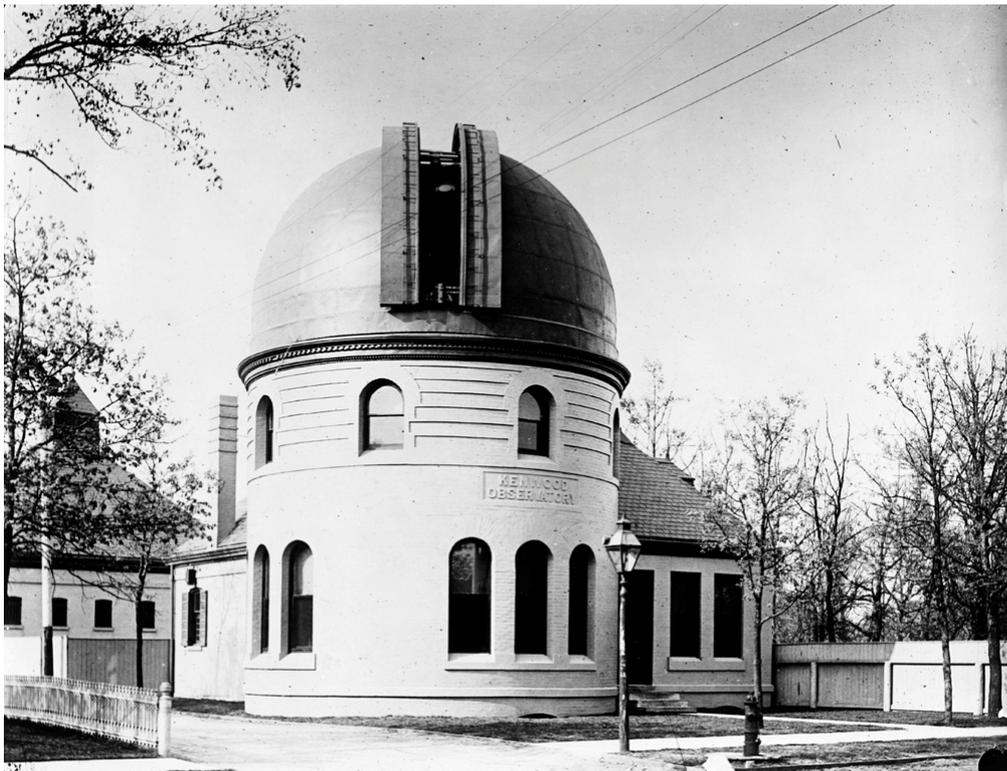
Spectroheliography can be defined as the capacity to make visual observations of the solar disk and its characteristics in the various wavelengths of the elements of its spectrum: in the case of photographic imaging it takes the name of spectroheliography. The resulting image is called a spectroheliogram.

The spectrohelioscope (SHS) (in photography spectroheliography (SHG)) 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.



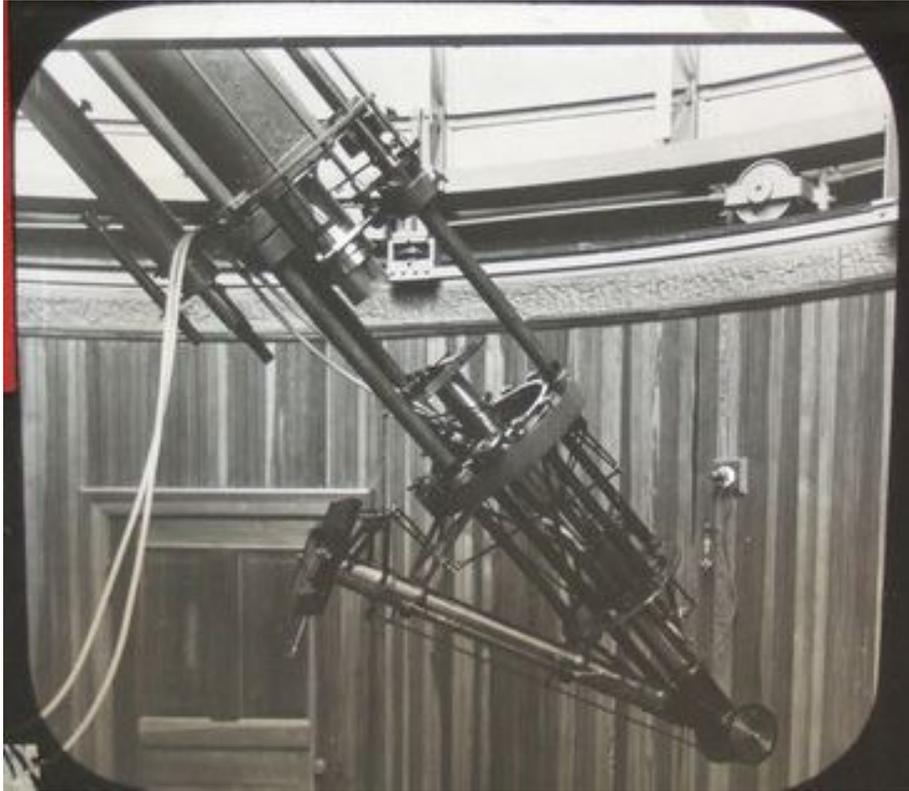
The SHG was, in fact, invented independently by Hale and the French Henri Alexandre Deslandres, but to Hale goes the merit of having perfected the invention creating a powerful means of investigation of solar physics. The development of the collodion plates, together with the invention and the availability 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 SHGs dates back to 1889, when he developed his first ideas on the subject, which were developed many years later into 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 his Kenwood Observatory. The spectroscope used two 1080mm focal length lenses as a collimator and an imaging lens, while the grating was a 10mm reflection with 568 l/mm. The entry and exit slits were 82mm in length, in order to receive a 50mm diameter solar disk image.



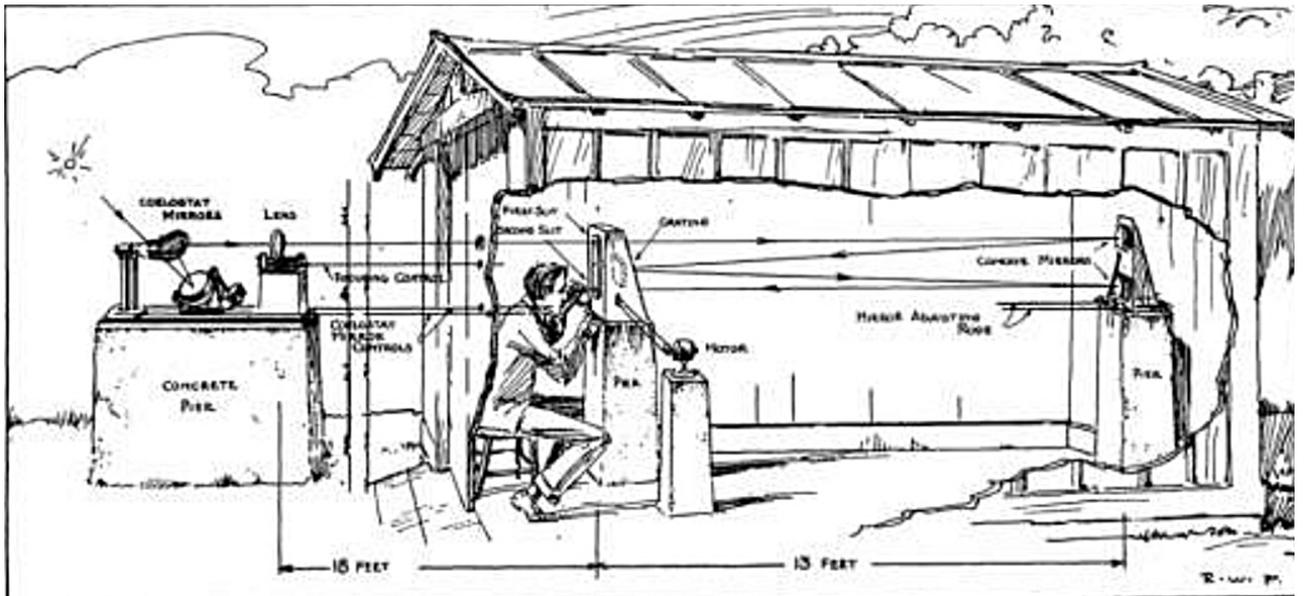
The Kenwood Observatory of G. Hale in Chicago (University of Chicago Photographic Archive, Special Collections Research Center, University of Chicago Library).

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



The SHG at the focus of Brashear refractor

Not many people know this, but Hale also visited 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 SHG. 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 Mount 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 SHG, Hale examined the possibility of using his SHG for visual observations, using it as a spectrohelioscope (SHS), and perfected this idea in 1924.



Hale's SHS layout: the only difference with a SHG is the replacement of the eyepiece in place of the camera, after the exit slit.

Terrestrial professional SHGs still in service in Europe are: the Meudon SHG in Paris, that of Coimbra in Portugal, and 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>

Here are some photos of the Meudon SGH in Paris (Source: BASS 2000). The SHG, with a lens of 240mm and 4000mm of focal length, gives a solar image of 86mm on the focal plane. Its purpose is to obtain images of the entire solar disk in the various wavelengths of interest.

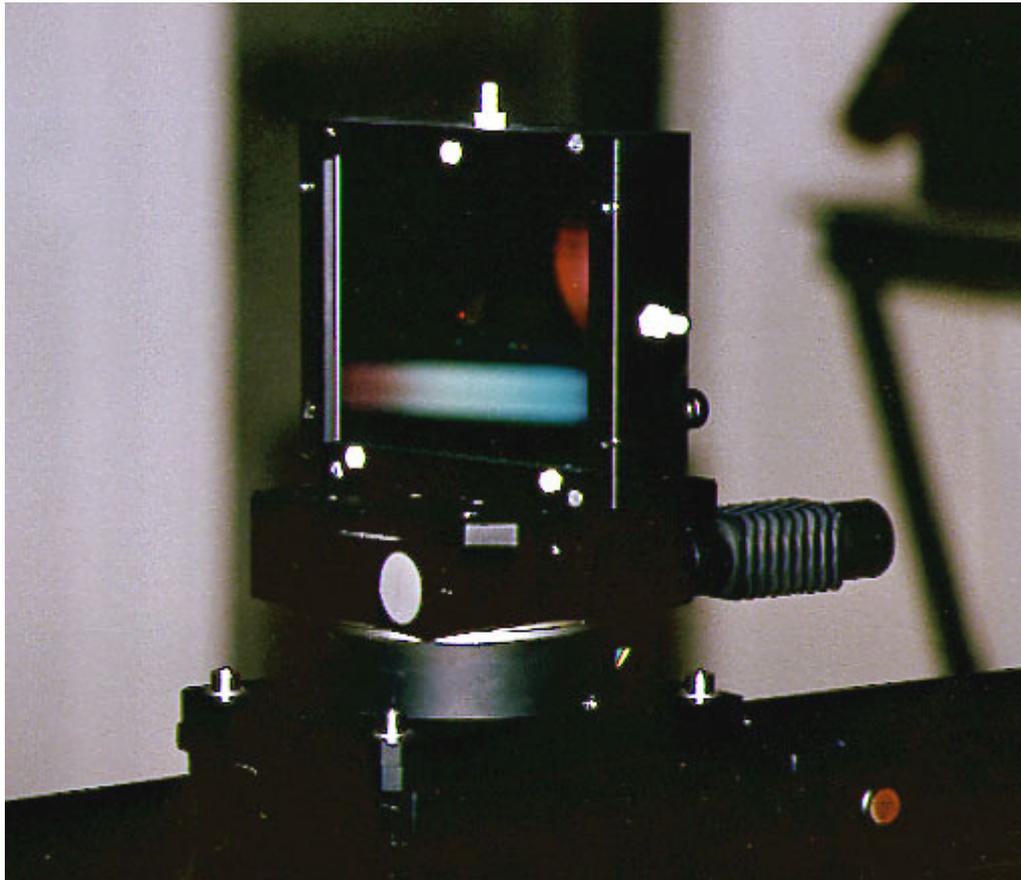


The cœlostate that powers the 240mm objective and the objective (below)





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



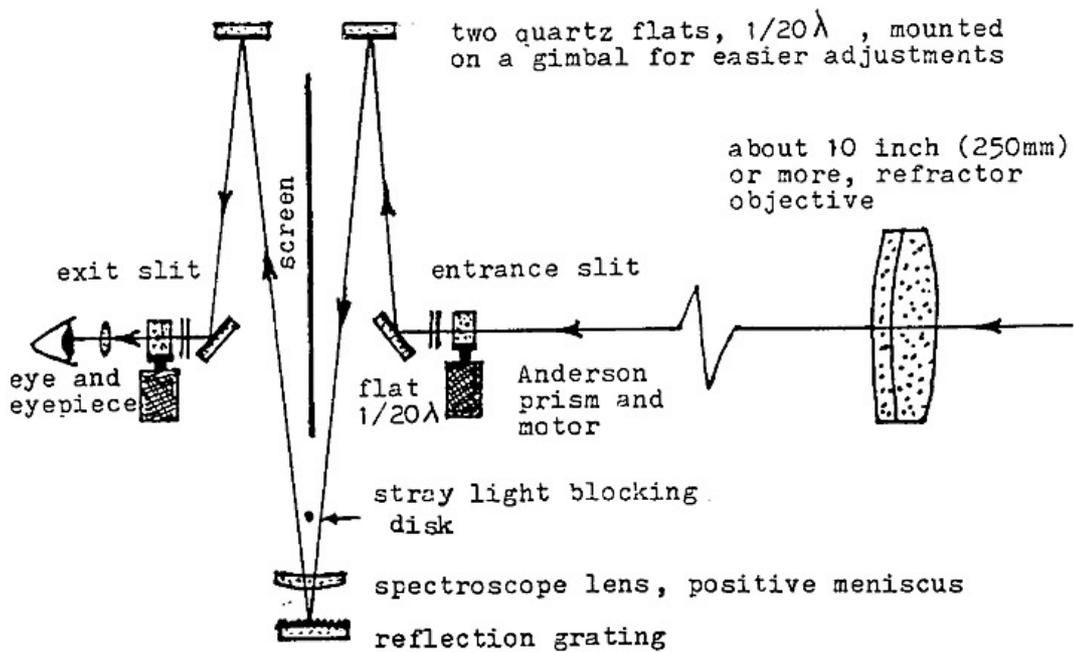
The diffraction grating, large in size but of only 300 l/mm. It's used in the 3rd order to further increase dispersion and resolution.

The amateur SHG

Classic" Amateur SHG"

But what is a classic SHG? In practice, it is a spectroscope, connected to a telescope that sends an image of the solar disk of adequate size on the input slit of the spectroscope, the diffracted sunlight is then selected in the line of interest by a second slit, the output slit. Immediately before and after the two slits, two image synthesizers are placed, (generally rotating prisms called 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 persistence of vision effect, the formation of 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 DIY, especially 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 to obtain an image on the input slit of the rather large spectroscop and then a final solar spectroheliographic image of adequate resolution. The figure shows an example of a SHS - SHG layout with a spectroscop in Czerny-Turner configuration and that uses two Anderson prisms as synthesizers.



The following figure shows the Anderson prisms whose synchronized rotation, before the entry slit and after the exit slit, allows us to obtain a solar image in the line under examination.

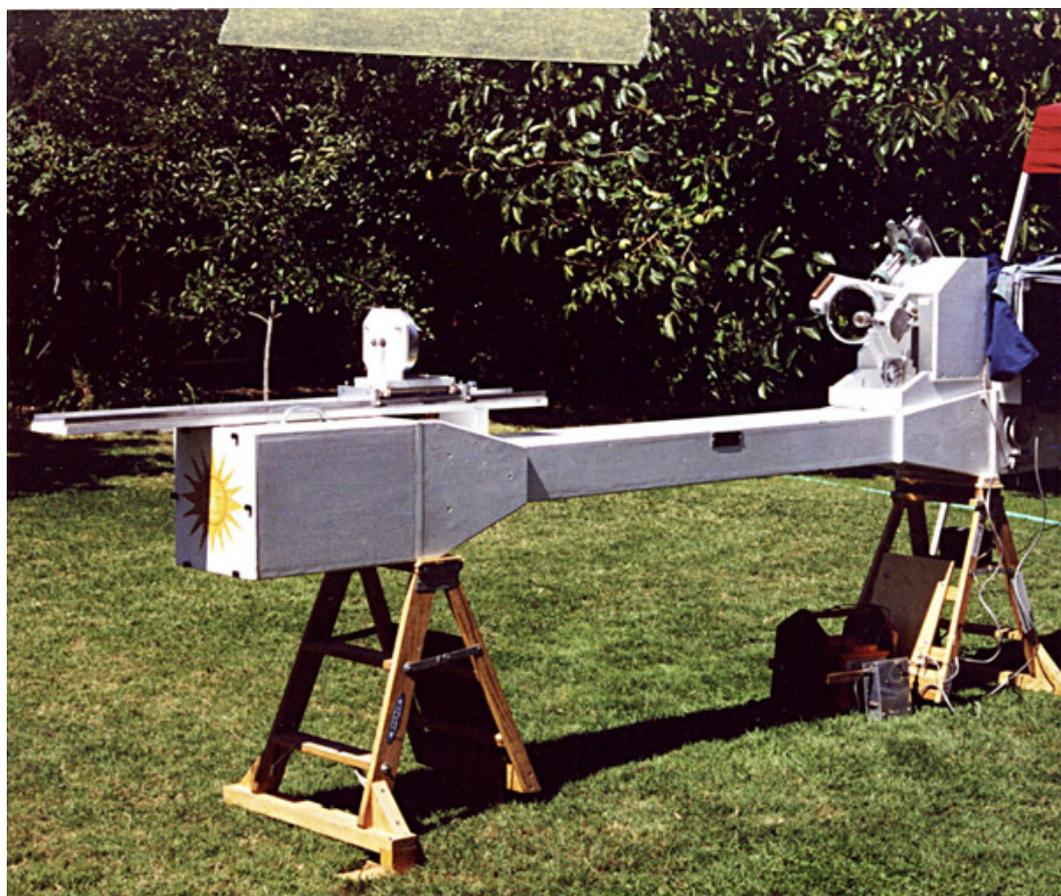
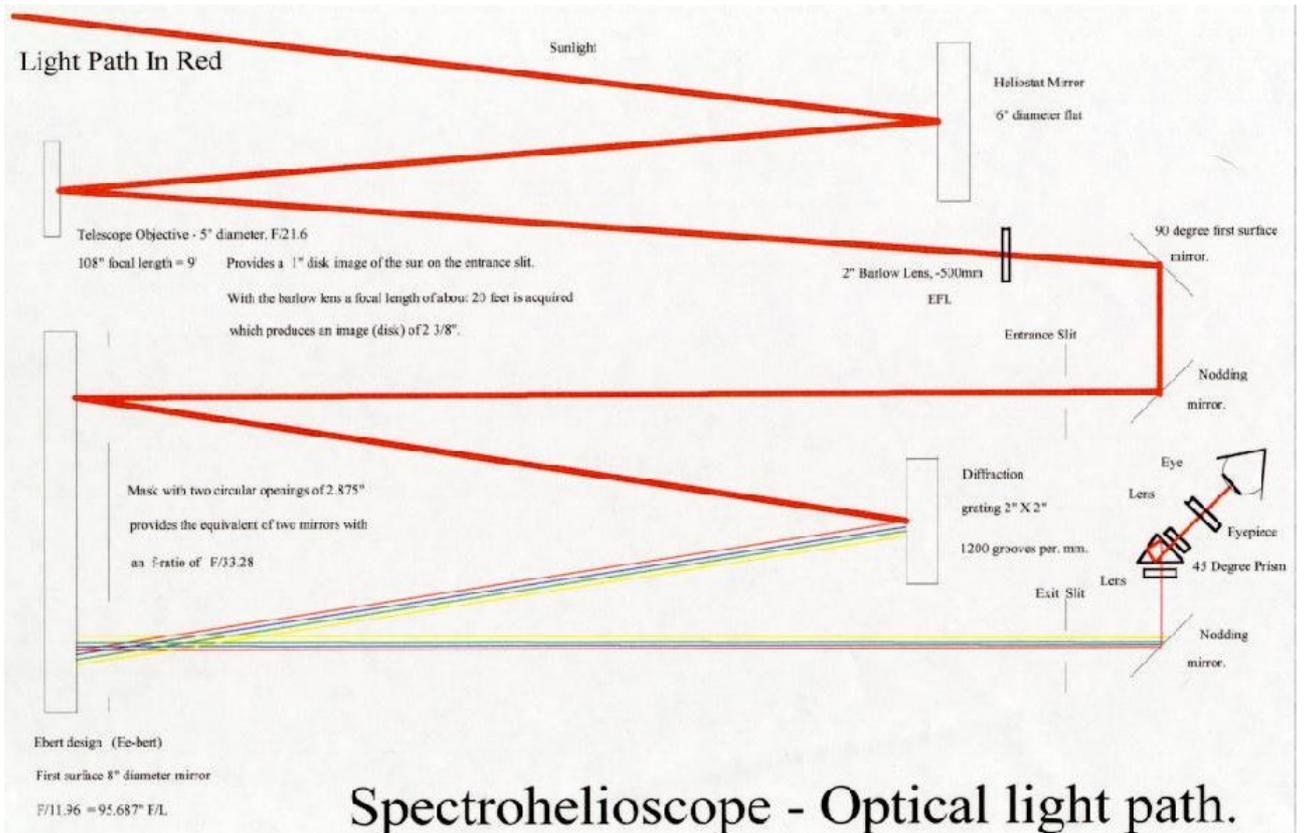


Anderson Prisms

Below is the design (the last in a series of projects) of a SHS from the well-known American Leonard Higgins. Built with the guidance and help of the equally well-known SHS expert Fredrick Veio (Source: Spectrohelioscope .org).

There is a long focal length refractor feeding an Ebert spectroscope. 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 prisms.

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



As seen in the example, the two essential components of the SHS/SHG are a telescope and a spectroscope. Telescopes come in a variety of optical configurations, but for the solar observation the preference is 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 narrow gap slits, 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 SHG

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

At the beginning the final yield of the images of the digital SHG was qualitatively inferior to that of the traditional ones, but, with the progress and development of the CCD sensors, the visible details are now practically the same, while the gain in size and weight and therefore ease of use and portability is simply enormous. Compare the classic amateur instrument illustrated above and my VHIRSS, weighing only 8.6kg and 110cm in length, transportable anywhere with the greatest ease. Naturally, the classical SHG 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 performance gap is very small or non-existent.

It is worthwhile noting and highlighting 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 DIY construction, unless you want to use high-resolution spectroscopes for stellar use, such as Shelyak LHires III with a 2400 l/mm grating, which, however, uses lenses with reduced focal length and a 4 gap reflective slit plate. It is therefore, not ideally designed for the SHG application.

Obviously those who already own such an instrument can use it, even if the reflective slits could create diffused light, and 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 DIY construction is currently the only one that can be used.

Components of a digital SHG

The fundamental components of a digital SHG are:

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

We will now review 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 to a narrow band H α or CaII K interference filter, like those that have had and continue to have wide use among the amateur astronomers. We can imagine that instead of a filter, there is the slit and the spectroscop. The big difference being that while the filter selects a single line, H α , CaII K or other, the spectroscop 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 the optical configuration, and more 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, 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, i.e. an IR-UV cut in front of

the corrector plate, but both solutions would be very expensive (about 1500€ for 20cm 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 4000-7000Å. A Canadian astronomer (P. Zetner) has achieved good results with a 10cm MTO Rubinar catadioptric, with an IR cut UV filter of this size and a wide band pass, which allowed the CaII K and H band to pass through (the normal UV-cut filters such 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 77mm UV-IR cut filter in the catalog costing about 150€, on which I cannot give any opinion never having tried it, but that would have a bandpass of 4000-7200Å 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

Newtonian

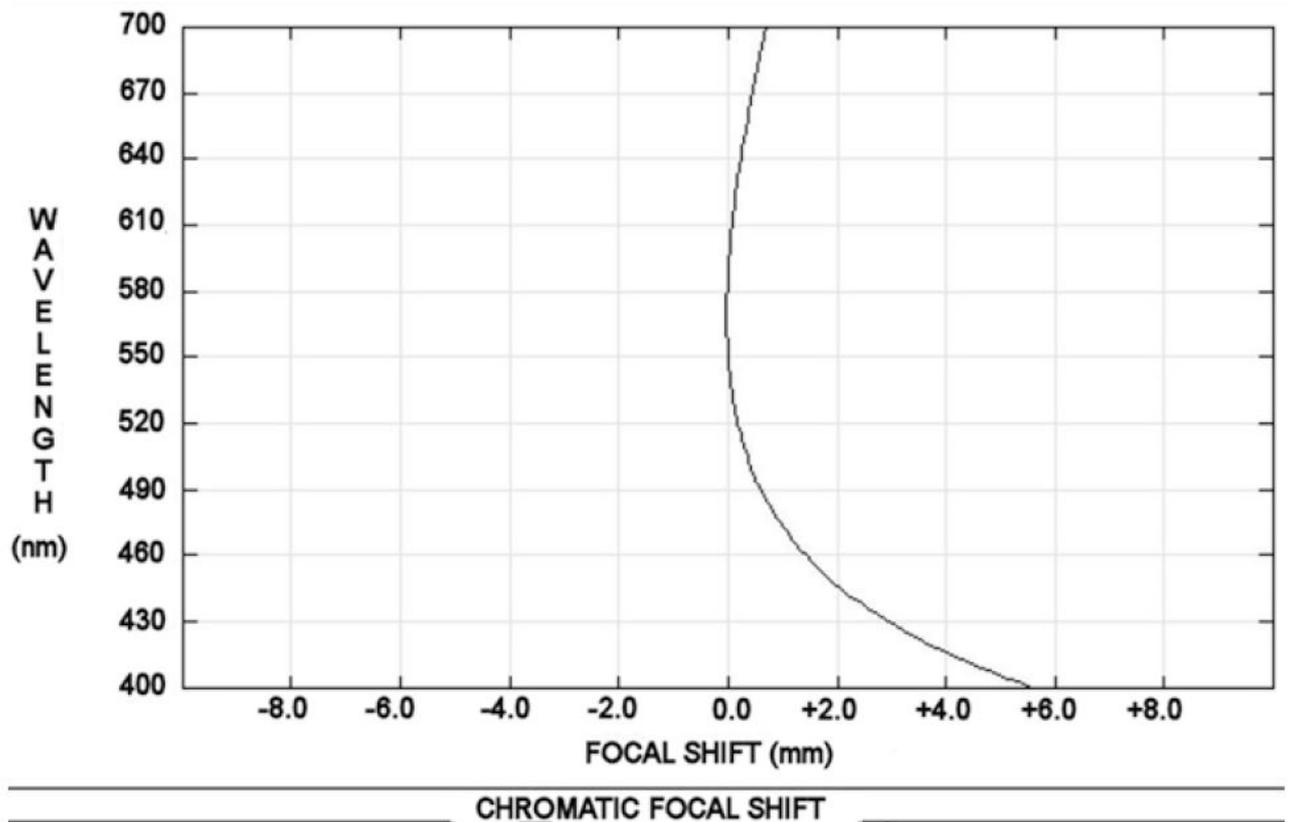
The Newtonian would in principle be the ideal instrument from the optical point of view to feed a digital SHG, if only for its lack of chromatic aberration. However, the "bent" configuration of the optical beam, as well as the proximity of the focus point to the tube tends to add complexity to the design of the instrument, making it necessary, among other things, to add a focus extender element (a telecentric) to bring the focus on the slit. The French astronomer Phil Rousselle, of whom I will speak later, has recently built a SHG which used a Newtonian 114/900 optical tube as a telescope; but the assembly is complicated and not within everyone's reach. This interesting configuration will be discussed later.

Telescopes with lenses: the refractors

a- Achromatic 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 residual chromatic aberration 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 focus 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. Clearly, it's not a tragedy, but it is nevertheless a nuisance.



In the image above, the focal shift of an achromatic 90/850 lens is shown (Source: Edmund Optics). As can be seen, the shift from $H\alpha$ is small down to 5200\AA , from that wavelength the shift becomes more and more, until it exceeds 6mm below 4000\AA .

b- Apochromatic refractors

These are the telescopes that are currently seen as being the best in class and which are readily availability, with a wide range of acceptable prices. Focal length ranges from 300 to 1200mm, in optical designs that are covered by the 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. I believe there may be, deterioration 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 air spaced triplets 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 are the best and the ones with the highest value for money.

Telescope constraints are the following:

-It must give a solar image of a diameter ideally 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 H α and CaII K. An instrumental resolving power between 1 and 2arcsec is sufficient, even taking into account that it is limited by the local seeing conditions that hardly allow better than 2arcsec. A good instrumental diameter is around 100mm, which provides a theoretical resolving power of 1.2arcsec. Considering that the Sun subtends on average 1920arcsecs, and that a focal length of 1000mm would give a 9.3mm solar image on the slit, on this one would have an image scale of 206arcsec/mm, or 0.2"/ μ m.

An objective of 100mm aperture between f8 and f10 would therefore be an interesting option, also considering the size and the bulk that it would bring to the SHG.

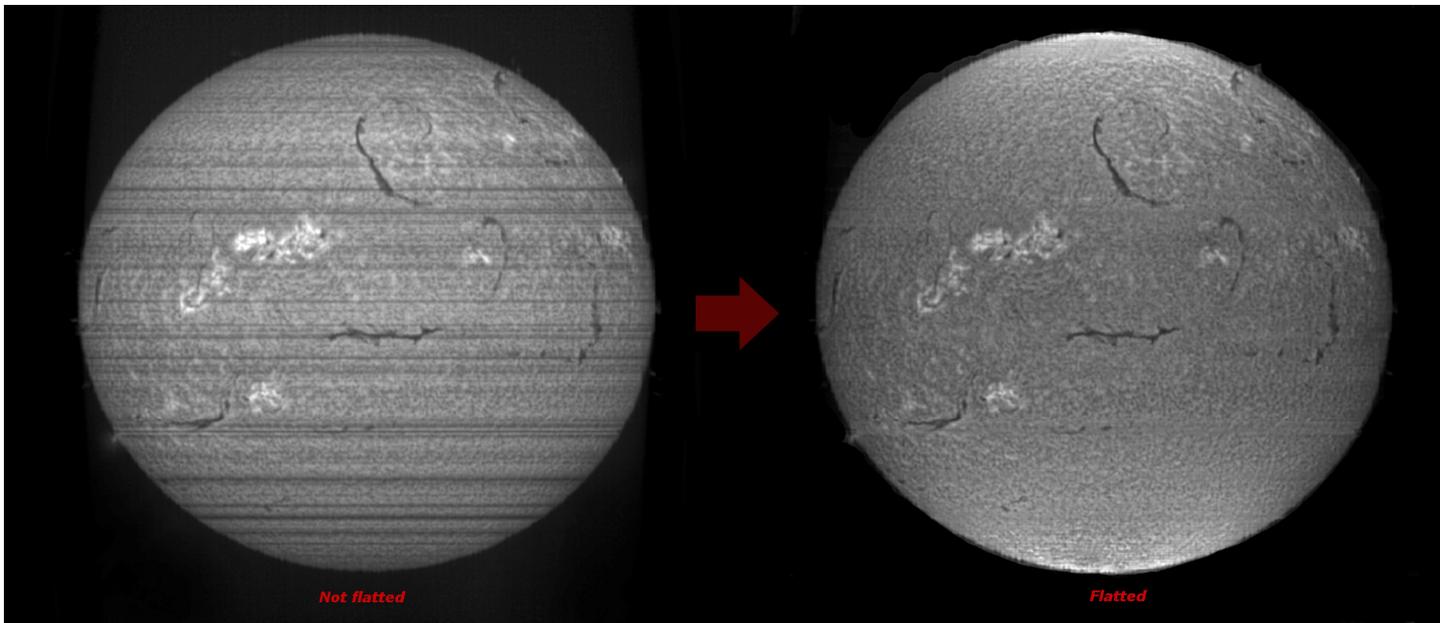
-It must not be an instrument with a group of rear lenses, potentially capable of deteriorating or breaking due to thermal stress.

The slit

It might be a surprise that I consider separately 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 SHG, 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 minimum possible (10-15 micron, for example) is a direct function of the quality of mechanical capabilities of the assembly and the quality and accuracy of the jaws. To understand what I mean, it is worth

looking at the comparison in the following figure, between a solar disk raw spectral image obtained with one of my SHG with a slit with a very narrow slit gap, but not machined to optical tolerances ($1/4\lambda$), and the same image after making a synthetic flat.



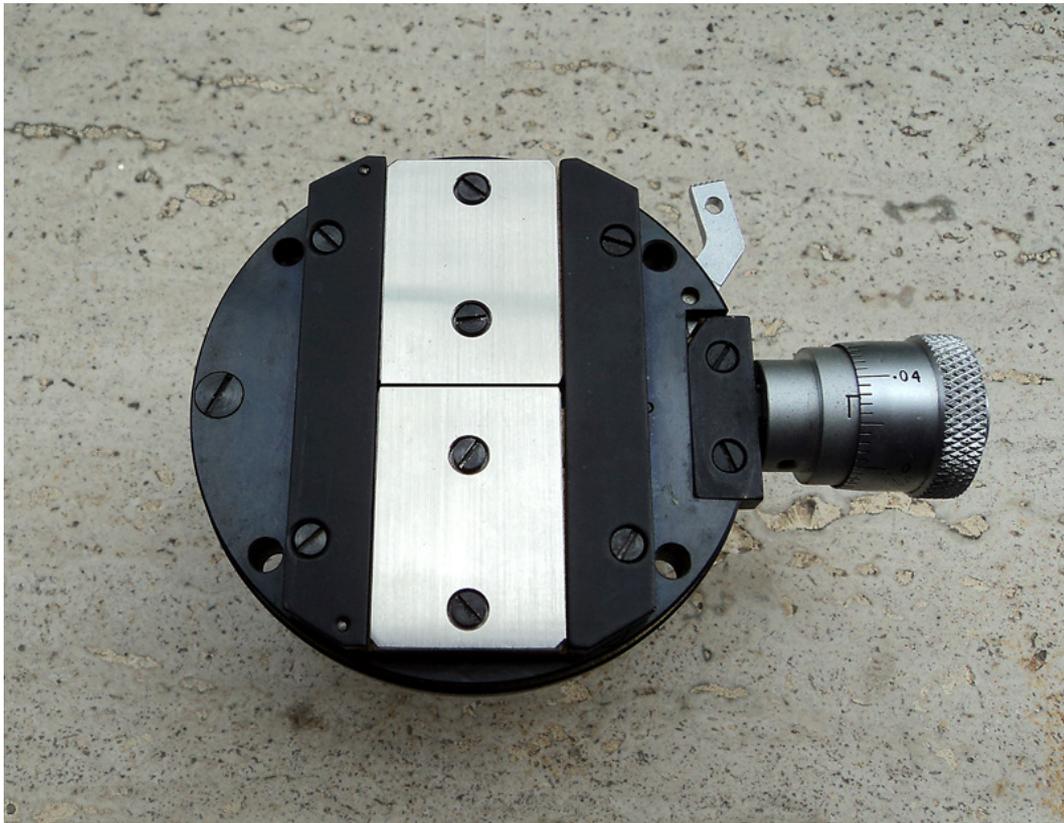
As you can see, the horizontal lines (transversalium) caused by small imperfections of the edges of the jaws are reflected in a merciless way on the quality of the final image. But then, just work the edges better, I already hear the reader answer the question, the right answer, but there's a catch. The machining of optical tolerance slit jaws, involving sophisticated and complex processes, would cost more than the same spectroscope, so it is necessary to use different alternatives 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>

The images that follow show a professional slit, adjustable with a micrometer purchased by myself for 100€ from the retailer mentioned above. The slit was then improved by disassembling and finishing the edges of the jaws and adding a 31.8mm (1.25") male support. The micrometric mechanical system of closure acts in a uniform way, so as not to move the parallelism of the blades at very tight closures.





On the new market, such slit would cost somewhere in the region of 500 to 1000€ (\$570-1150), as much as a small apochromatic 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, Surplus Shed, offers at very low prices adjustable slits made in India with slit blades 10mm in length (about 8mm free) which, although not the best from a mechanical point of view, are acceptable and capable of improvement.

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



2- To improve the mechanical quality of surplus slits

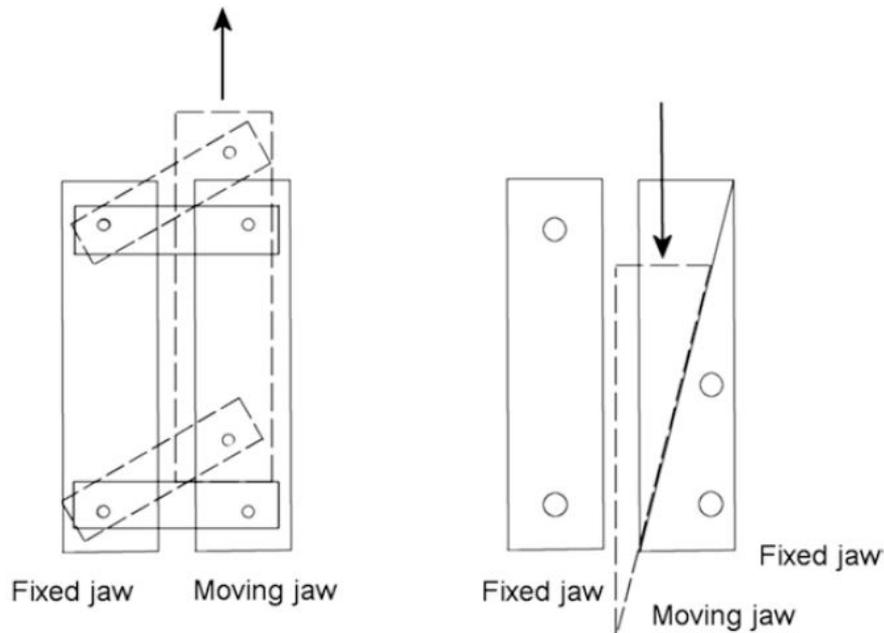
To improve the quality of Surplus Shed's low-cost slits I normally do the following:

- a) I remove the brass slit plates;
- b) Examine them under the microscope at about 500x 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 used by coachbuilders, 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- The design and DIY construction of the jaws.

This is an opportunity which I think should be best avoided, as the complexity of the job does not guarantee better results than those already discussed. However, if you want to give it a go, a couple 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 answered 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 surplus slits, especially if modified as described above, can carry out their task adequately, also because they are easily more than 8mm 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 100mm telescope without any rejection filter, can reach 7.85W.

The fixed slits, often produced 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 3mm and a very thin support, which, if not adequately protected, could tend to the deformation under thermal stress. On the other side, their edges, obtained by laser, have a high level of precision even with very narrow closures: these are available down to a minimum of 5 microns 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 3mm slit in front of an image of the Sun of 6mm in diameter would give us, the possibility of covering only half of the solar disk in the final spectroheliogram image. The Sun covers on average about 32arcmin (1920arcsec) at 1 AU, but, since its distance from the earth varies according to its orbit during the year, its apparent diameter varies from 31.5' in January to 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 1000mm, D will therefore be equal to 9.48mm in January and 9.17mm in July, an optimal diameter for a 10mm-long slit. For a focal length of 500mm it would be on average 4.7mm, suitable for a 5mm slit.

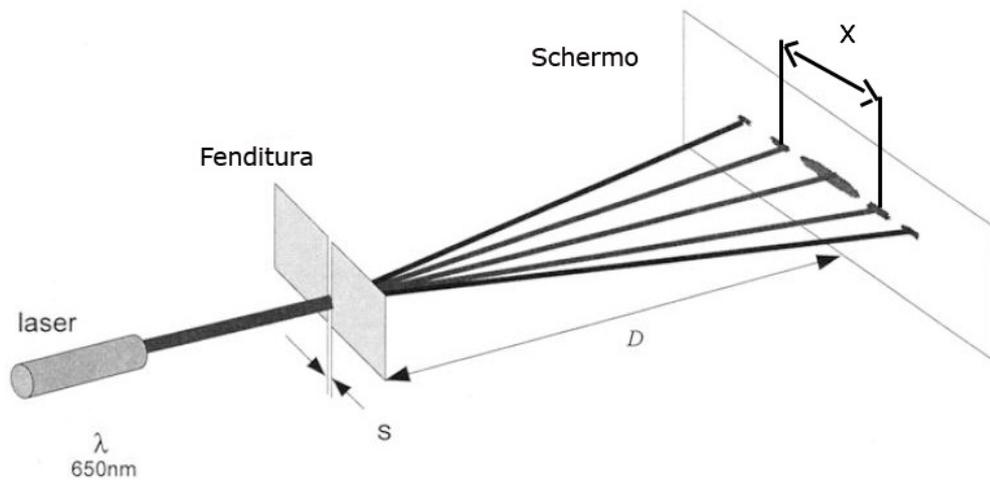
As for the opening of the slit, taking into account the above, a focal length of 1000mm would provide an image scale of $(1920/9.325)$, 205arcsec x mm, or 0.2arcsec per micron, which means that an opening of the 10 micron slit would provide a spatial resolution of 2", sufficient to record details on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

A focal length of 500mm would provide an image scale $(1920/4.665)$ of 412arcsec/mm, or 0.4arcsec per micron or a resolution of 4" at 10 micron. To satisfy 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 μ m would match well enough with a camera with pixels at 4.4-4.65 μ m like DMK 41 and 51, but also with cameras like ZWO ASI 174. Of course there is a downside, and gaps of 10 μ m with an adjustable non-professional slit are possible, but often imperfect to the point that makes it preferable to use a 15 micron gap.

The measurement of the slit gap

In commercial slits not provided with micrometers or other measuring instruments, the problem of measuring the size of a given slit gap could be real. This can be determined 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 micron is:

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

Where:

- λ is the wavelength of the laser in \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.

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

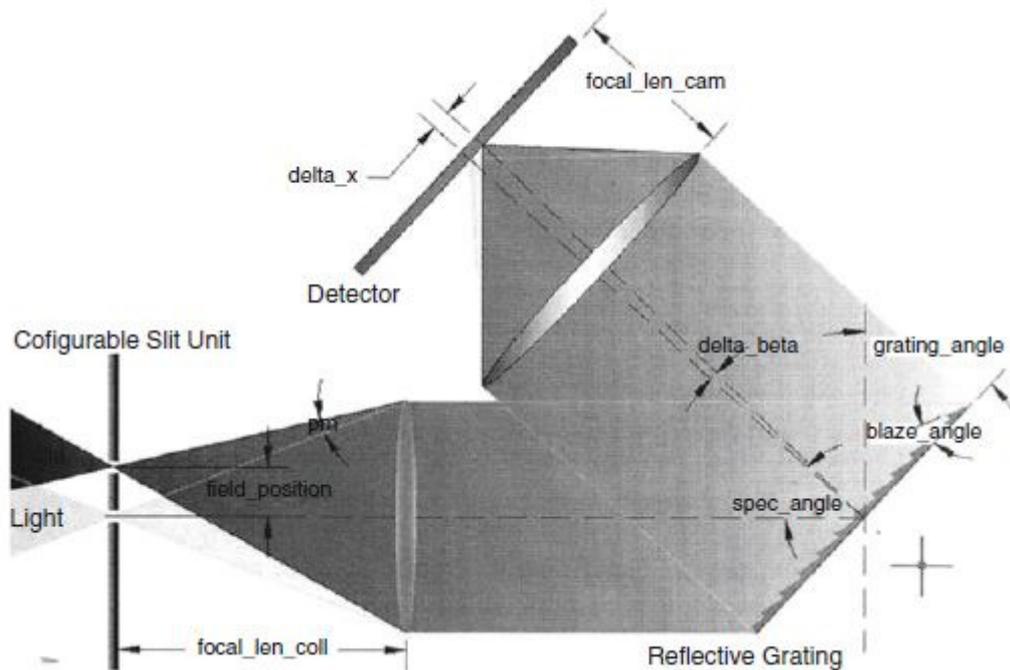
$$S = 6500 \times 3 \times 400 / 10000 \times 40 = 19.5\mu\text{m}$$

Spectroscope configurations for the digital SHG

I will discuss here the main configurations of spectroscopes most commonly used for the SHG.

1- The classic spectroscope

This configuration has been and is perhaps the most widespread in many DIY 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°), which collects the diffracted optical beam coming from 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.

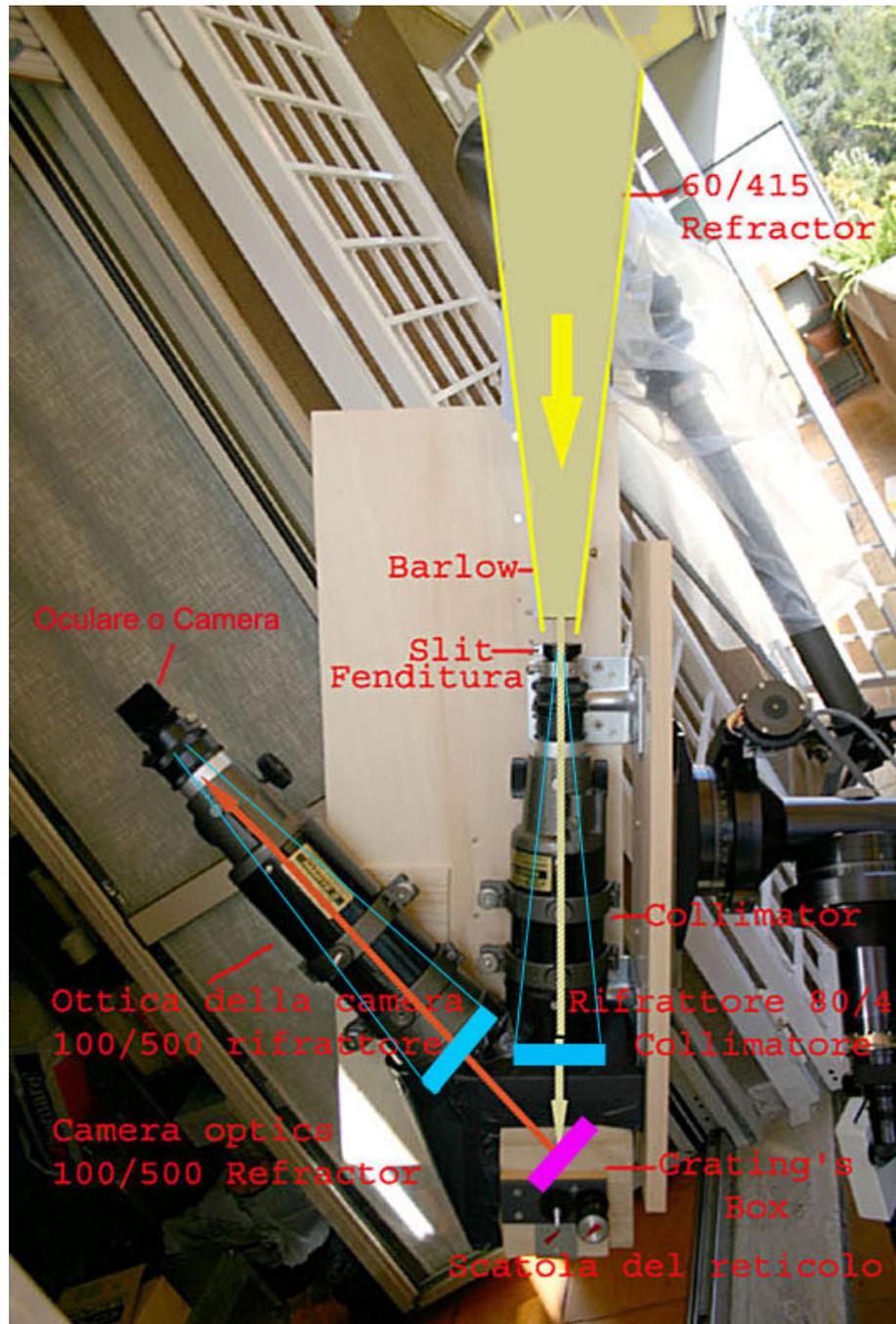


An example of the layout of a simple classical refraction spectroscope (Source "Spectroscopic Instrumentation" by Eversberg and Vollman).

The mirror configurations, as used in the SHG, 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 collimating cells and careful collimation with the others optical components, having, on the other hand, the merit of being total achromatic. 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 SHG design.

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



The photo above shows an example of a DIY Hires spectroscope 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 SHG led me to find other less challenging designs.



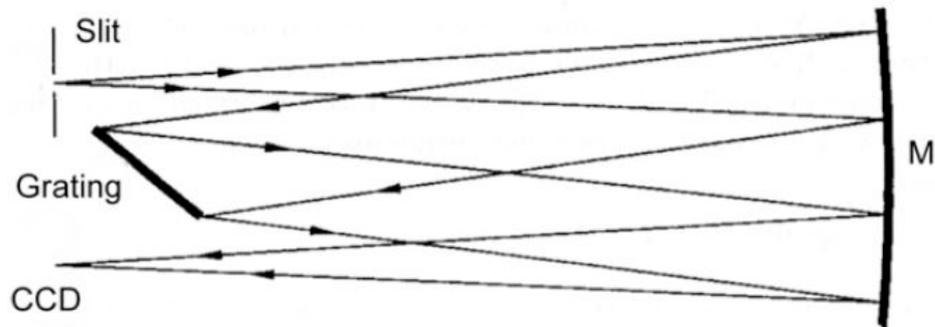
In the image above a spectroscope in the classical version that composes the model of the SHG used by the French amateur astronomer Daniel Deorneau, whose merit, together with Rondi, is to have introduced the principle of digital spectroheliography in the early 2000s, also creating a special computer 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-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.

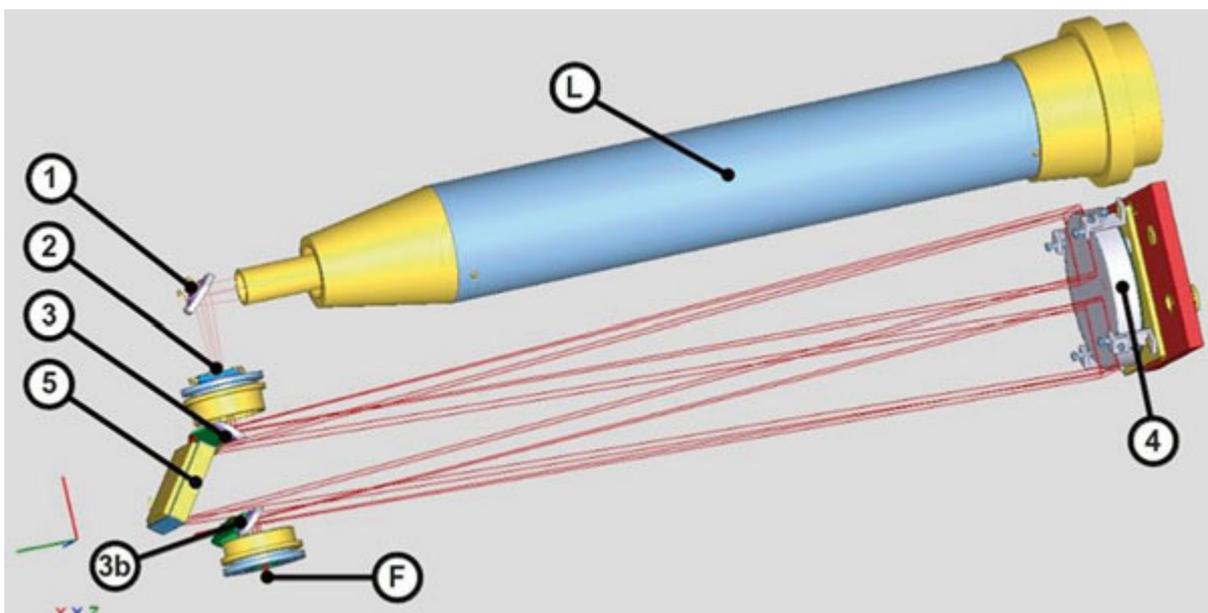
Let's take an example: say we want to use an f8 telescope and a square grating with 50mm sides. The f-ratio of the collimator will also be f8, with a diameter of $50 \times 1.4 = 70\text{mm}$. We could therefore use a 70mm f8 achromatic lens, 560mm focal length.

2-Configuration Ebert-Fastie



This is a fairly widespread optical configuration in spectroheliography, such as that mentioned above by F. Veio. A spherical mirror of sufficient size and high focal length (with a high f-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 some residual coma and the spectral lines are curved (smile). The dimensions of the mirror must be roughly 3 times those of the grating (diagonally) and the f-ratio of the mirror must be at least 2 times faster than that of the telescope. If this design is used, say for an f10 system, you will need a mirror at f5. It is still useful, in case of f-ratios below 8, to evaluate the use of parabolic mirrors.

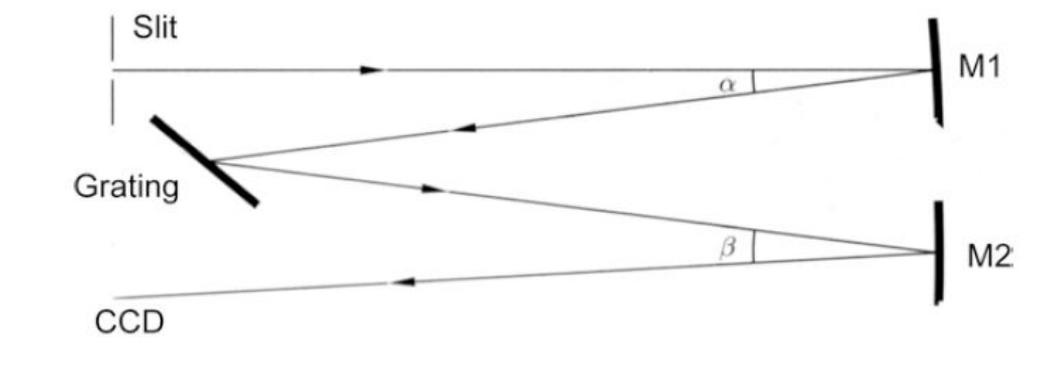
This configuration was the one used by the French amateur astronomer André Rondi in his SHG.



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

Rondi's project, while proving excellent on a practical level, is of considerable optical-mechanical complexity, in my opinion it is essential that the four mirrors, the main and the other three mirrors are 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

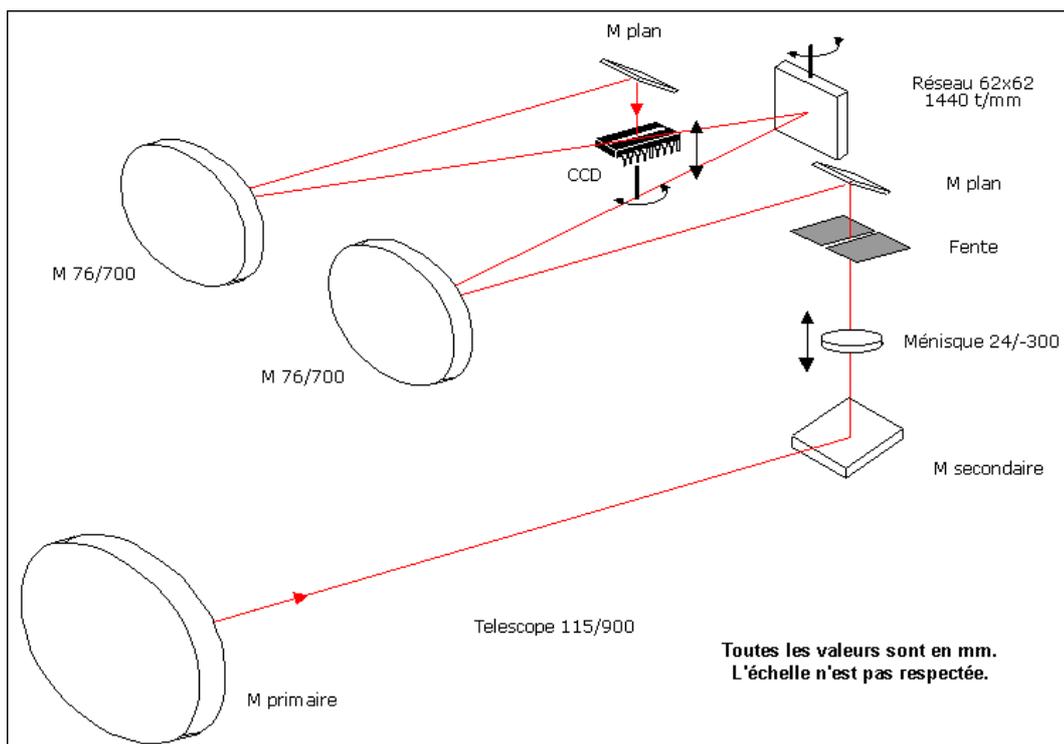


This is an optical configuration conceptually similar to the previous one, from which it differs for the use of two mirrors, one as a collimator, and one as an imaging optics. In order to reduce aberrations such as astigmatism and coma, the mirror used as a collimator (M1) must meet the following requirements:

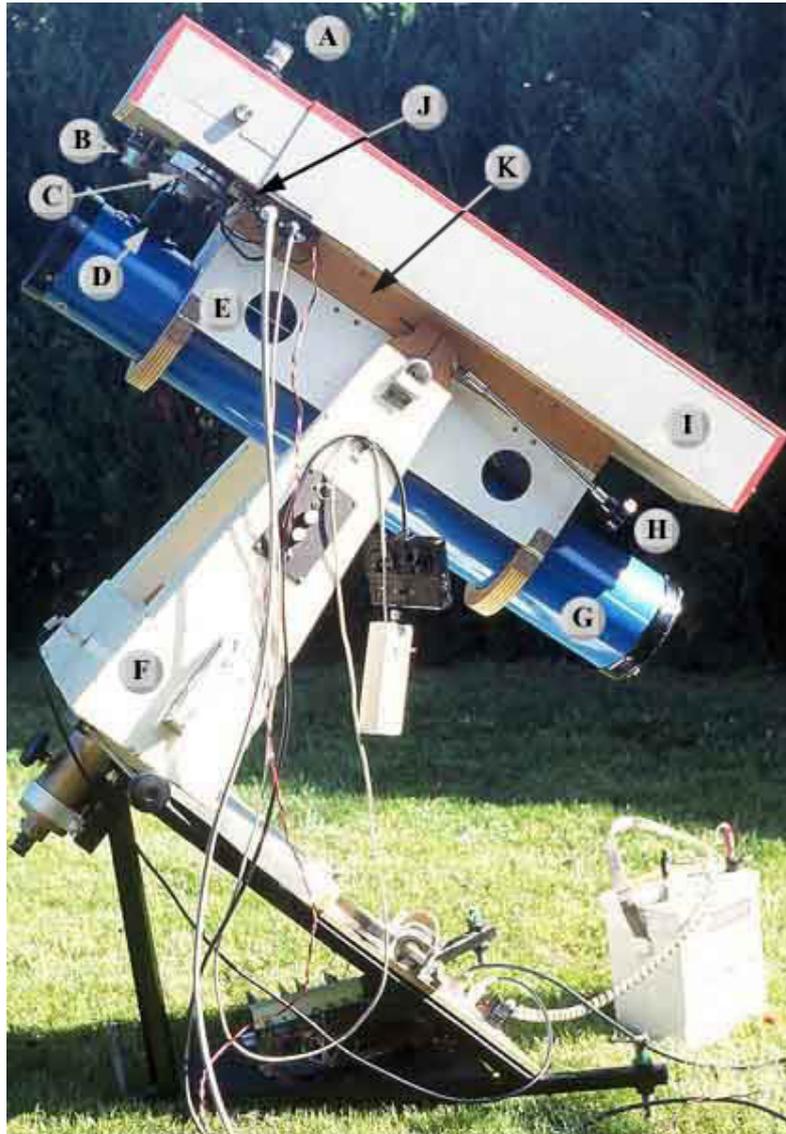
- Be larger than the grating and equal or larger than the Imaging mirror M2
- Having an f ratio similar to that of the telescope

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

This type of configuration is used in the SHG built by the well-known French amateur astronomer Phil Rousselle, who also used a commercial 114/900 Newtonian reflector as a telescope. The diagram below shows the layout of the instrument.



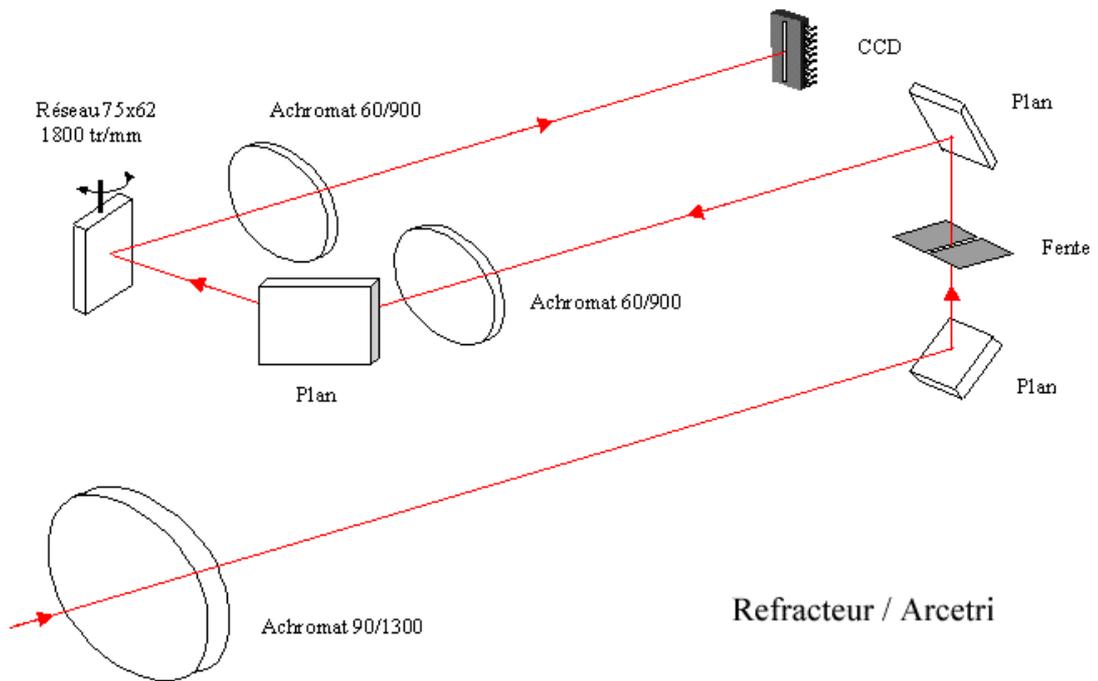
It is an "all-mirror" instrument with challenging construction complexity, which nevertheless produced good results, even if it was subsequently replaced by a lens system. In the figure below we observe the complexity of the fork mount also built by Rousselle.



"Arcetri" configuration

In some ways conceptually similar to the previous one is the configuration "Arcetri", used by Phil Roussele in his latest build. 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 builder to make considerable sacrifices for its 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 built by Rousselle.



Auto collimating Littrow configuration

1-Littrow configuration: why?

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

a-What optical configuration to choose for high resolution?

b-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 mandatory that such an instrument should be transportable from one place to another, but this feature, in my concept design, would have added extra complexity to the project. The more sophisticated configurations, moreover, with a number of optical elements, presupposes careful collimation, often difficult to achieve satisfactorily and can be a very laborious job.

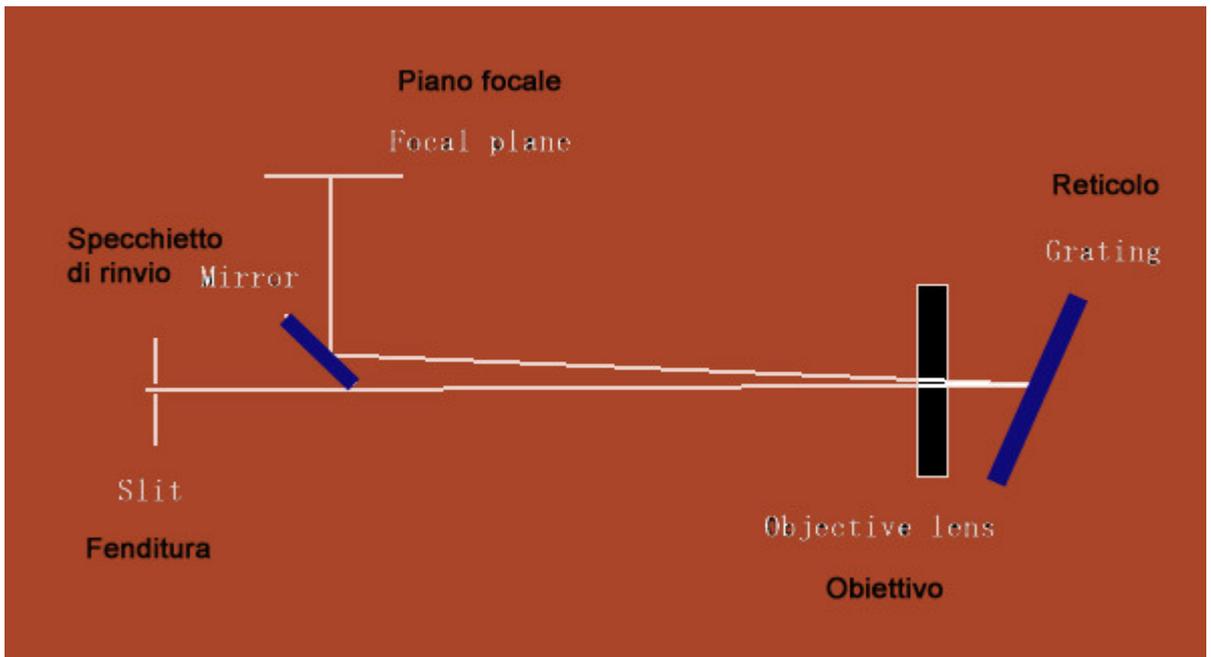
In the belief, therefore, that what does not exist does not create problems, my ideal configuration should have the minimum possible number of optical components. This last requirement is present in only one of the spectroscopic configurations, the Littrow.

This design was conceived and developed by the Viennese astronomer Otto Von Littrow in 1862 and constructed, in an absolutely brilliant way, using 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 pick-off mirror. This configuration, minimizing the angular deviation, has two enormous advantages:

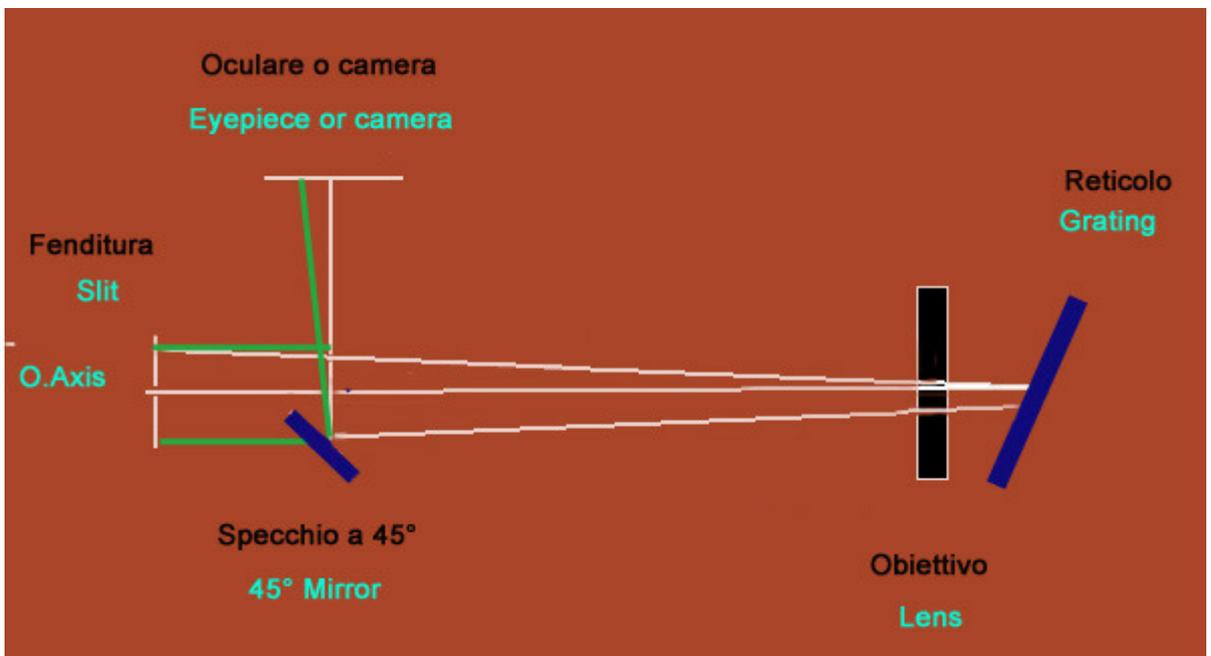
1- High dispersion and resolution;

2- Extreme instrumental compactness (compatible 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° pick-off mirror near the camera



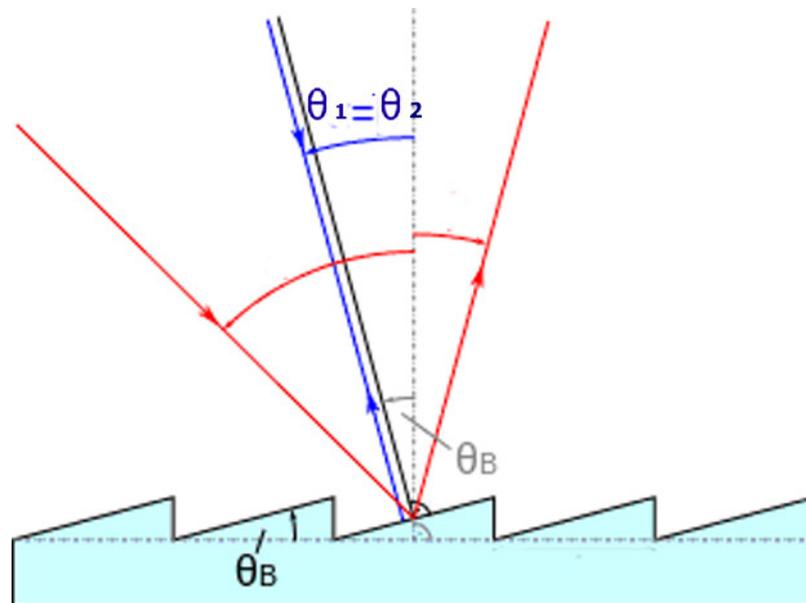
Littrow layout with lens objective, and 45° pick-off mirror far from the camera, used in my VHIRSS SHG.

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 (i.e. the angle of the grating grooves).

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

Furthermore, in the Littrow configuration the anamorphic factor, i.e. the ratio between the angle of the diffracted and the incoming beam θ_2/θ_1 is 1.



The general formula of the grating

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

where m is the spectral order; λ the wavelength and r the number of lines per mm of the grating
for the Littrow it becomes:

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

from which:

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

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

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 grooves 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 5000Å is reported with an angle of 17°. Applying to the present case the formula (3) we have, in the 1st order:

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

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:

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

where r is the number of l/mm, m the spectral order, $\pi/180$ the conversion factor from radians to degrees.

This gives:

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

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 θ_b equal to 0, ($\cos \theta_b = 1$).

A Littrow for the SHG

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

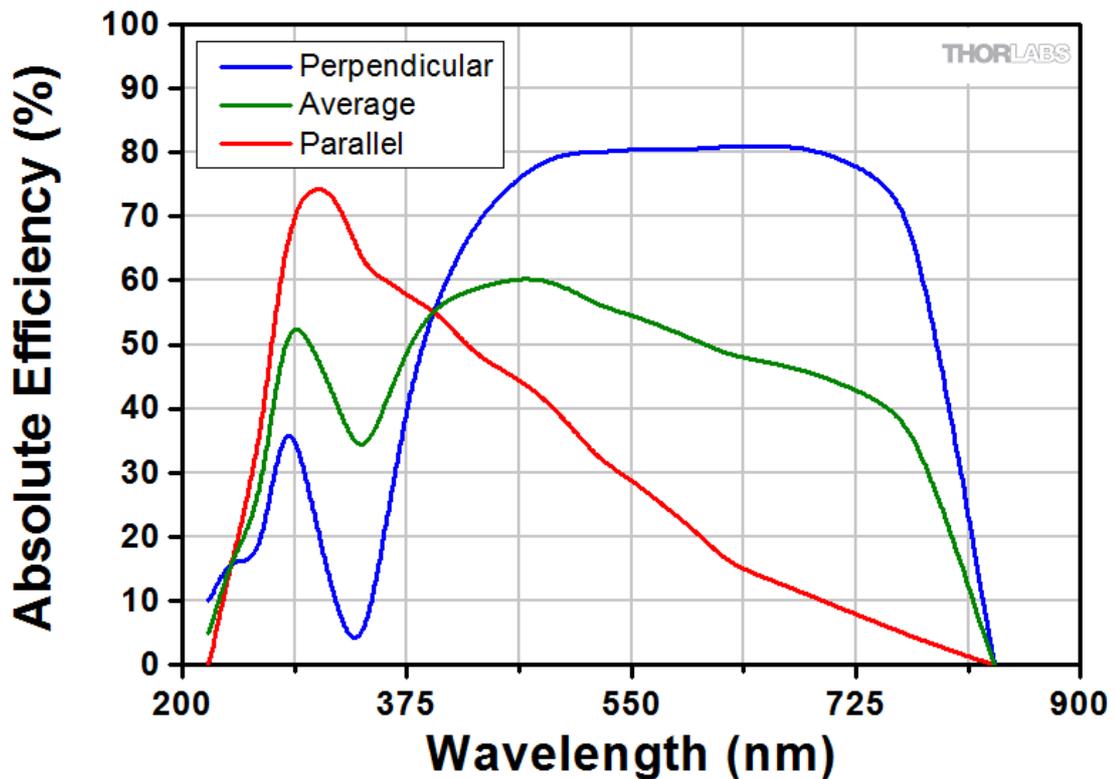
- The number of lines per mm of the grating (increases as they increase)
- The physical dimensions of the grating in the hypothesis that its surface is completely covered by the incoming optical beam. (increases with the size of the grating)
- The aperture of the slit (increases with decreasing slit aperture)
- 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, as big as possible, and at the same time with an acceptable cost, in a word an excellent quality/price ratio. Correspond to these requirements 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 50mm format (Thorlabs); for them I recommend a blaze angle of 500nm. The blazed square holographic gratings of 50 x 50mm by 2400 l/mm in the catalogs of the main suppliers, Edmund Optics and Thorlabs are sold at fairly reasonable 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, whereas the blazed holographic gratings do not have such drawbacks.

The figure that follows shows the 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.

Visible Holographic Grating: 2400 Grooves/mm



It is now 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 using an adjustable slit of good quality).

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

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 f8 telescope to project the image of the solar disk on the slit, it will be necessary to have a spectroscopic optic of similar focal ratio, while its diameter it must cover the diagonal of a square grating of 50mm (50×1.4) and therefore be at least 70mm in diameter. A target of 80mm will be even better, and will have to be at least f7-7.5. 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 80mm to f7.5 ED lenses (600mm 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 price in relation to their excellent performance.

Spectroscope parameters

It will then be necessary to establish the parameters of an autocollimating spectroscope equipped with a 2400 l/mm, 50mm square holographic grating, a 600mm focal length lens, a 30 micron aperture slit and a camera with pixel of 4.65 μ 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:

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

2 - Linear dispersion:

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

$$DL = \cos \theta / (r.m.F_{cam}) \quad (5)$$

where F_{cam} is the focal length of the optics therefore:

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

for 4.65 μ m pixels:

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

3 - The theoretical resolving power at 5000 and 6563 \AA

The relationship of the resolving power is:

$$R = \lambda/\Delta\lambda = m \times n \quad (6)$$

Being:

$$\Delta\lambda = \Delta Lf \times DL \quad (7)$$

where ΔLf is the width of the slit projected on the sensor plane

For a 30 micron slit opening

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

at 5000 \AA :

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

at 6563 Å (H α line):
 $R = 6563/0.21 = 31252$

For a 15 micron slit opening:

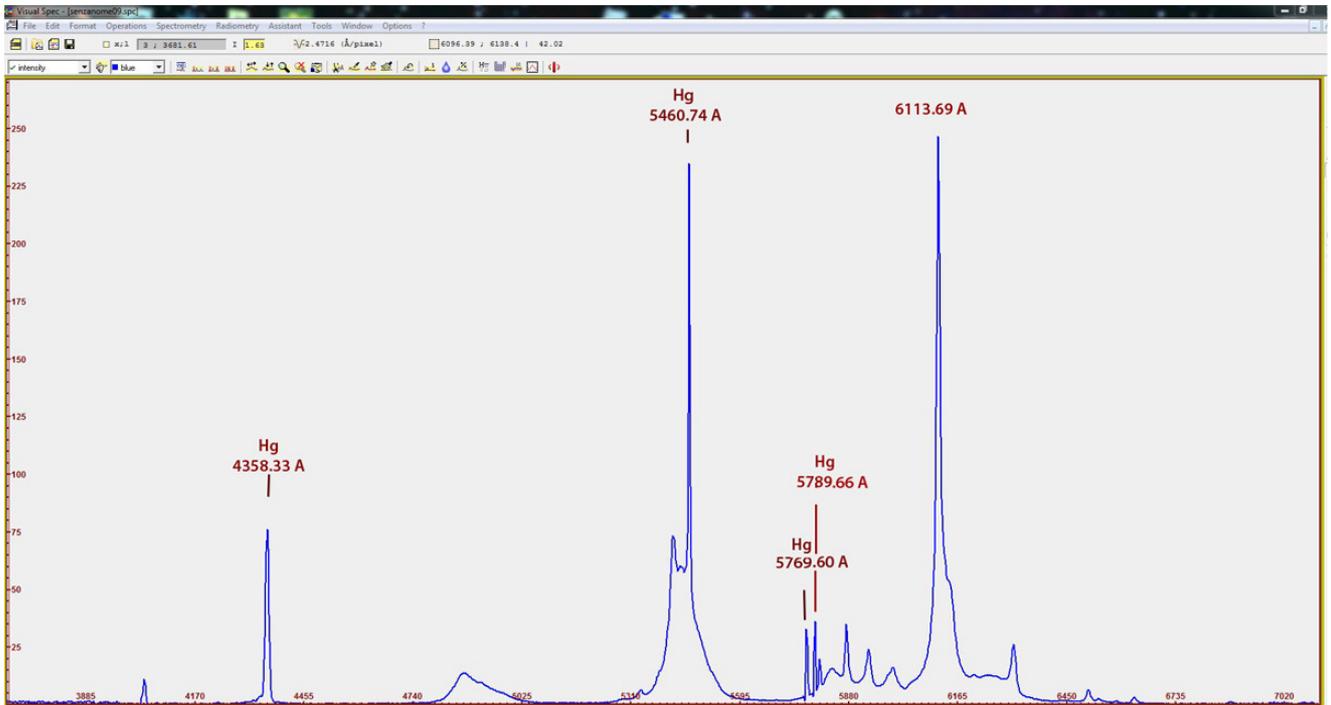
$\Delta\lambda = 0.015 \times 6.94 = 0.10$
 $R = \lambda/0.10 = 5000/0.10 = 50000$

at 6563 Å (H α line):
 $R = 6563/0.10 = 65630$

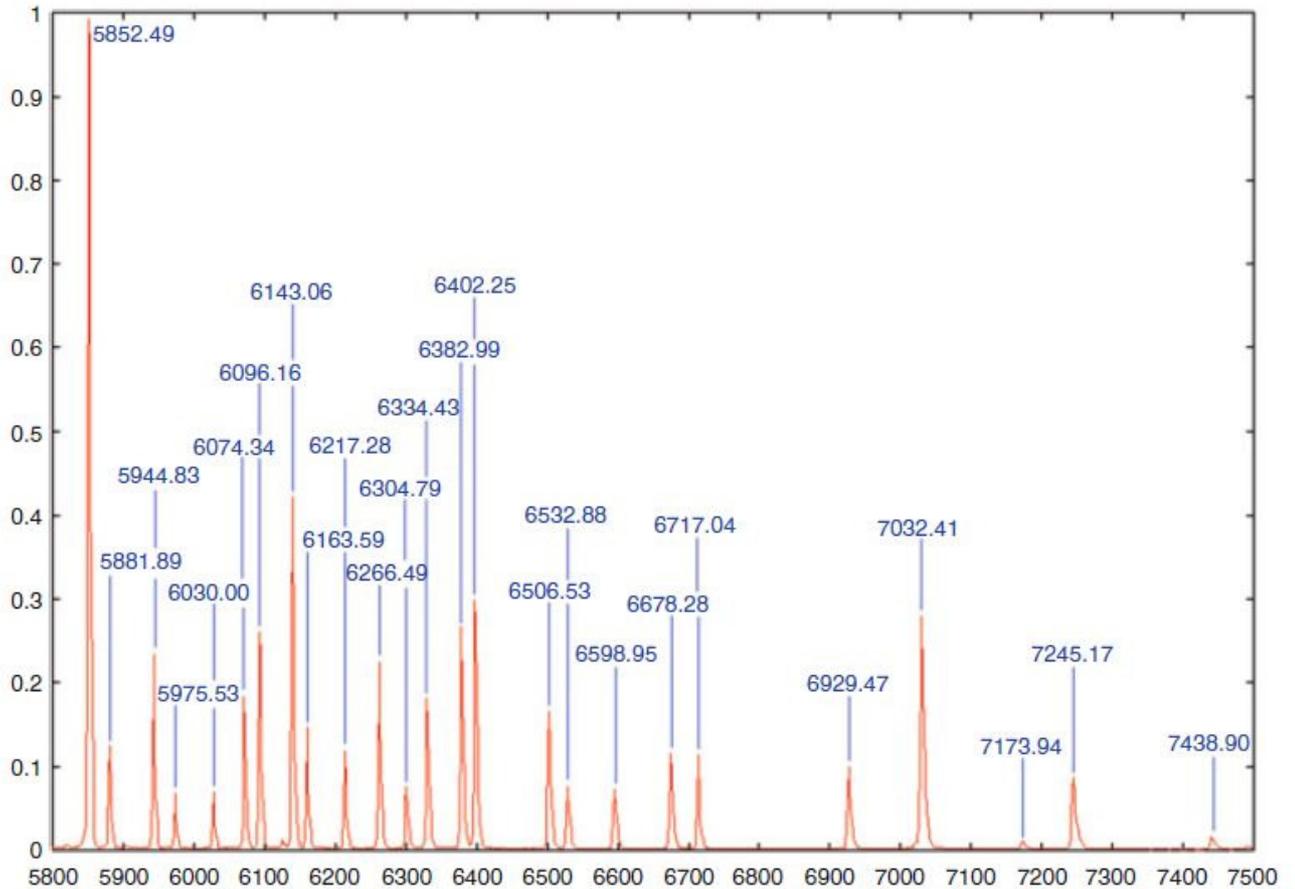
The theoretical values of linear dispersion and resolution previously calculated agree in principle with those I have obtained in the field with the VHIRSS and Solarscan spectrographs (both having 2400 l/mm gratings). Also the actual values in the field of the linear dispersion and of the resolution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

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 the local seeing. If you want to measure the actual resolution 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 writers 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 recording. While this solution would provide a safer data of the generic resolving power of the instrument at the time of imaging, in my opinion would not provide equally reliable data on the effective resolution of the SHG image, provided by the absorption lines. Nothing, however, forbids that resolutions cannot be measured in both ways, capturing any differences.

Below is the spectrum of a low energy fluorescent lamp obtained with my Spec 600 stellar spectroscope and one of a neon lamp (Source: C. Buil).



Low energy fluorescent lamp spectrum



Neon lamp spectrum

Parameters of the telescope to be used with the Littrow

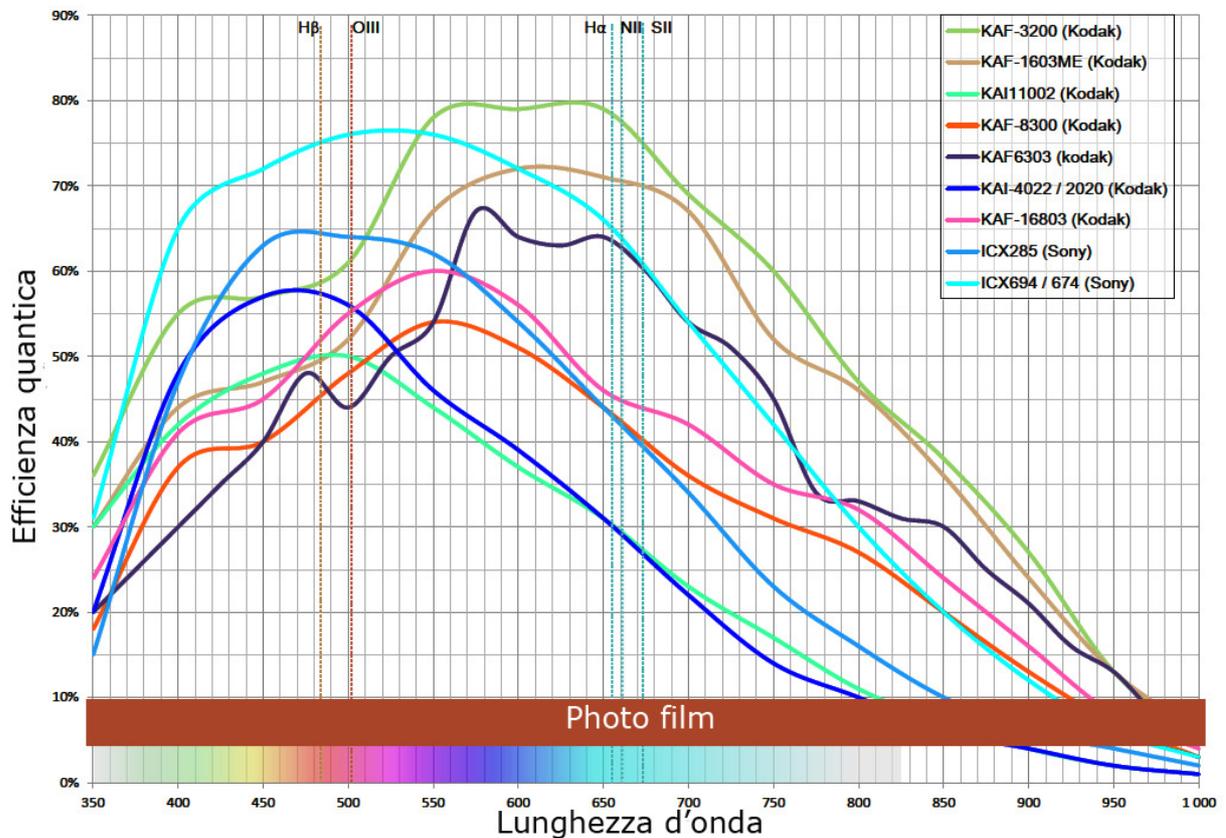
We hypothesize in this regard to use a telescope at f7.5-8 that at the same time gives an image of the solar disk on the slit not exceeding 8mm (better than 7mm), if you want to use low-cost slits from Surplus Shed, appropriately modified as mentioned previously. The focal length should be kept low, 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 500mm, with a 4.7mm 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 apochromats. Personally, for my VHIRSS SHG I have used an excellent doublet of military origin of 60mm and 480mm focal length that in numerous tests has laterally outperformed for definition and contrast different refractors ED of the same diameter. With some sensors, the focal length can also go up to 560mm, 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 350-450mm without appreciable decrease in overall system resolution: with Solarscan I used a 355mm focal length Takahashi FS 60C.

The CCD or CMOS camera

The type of sensor

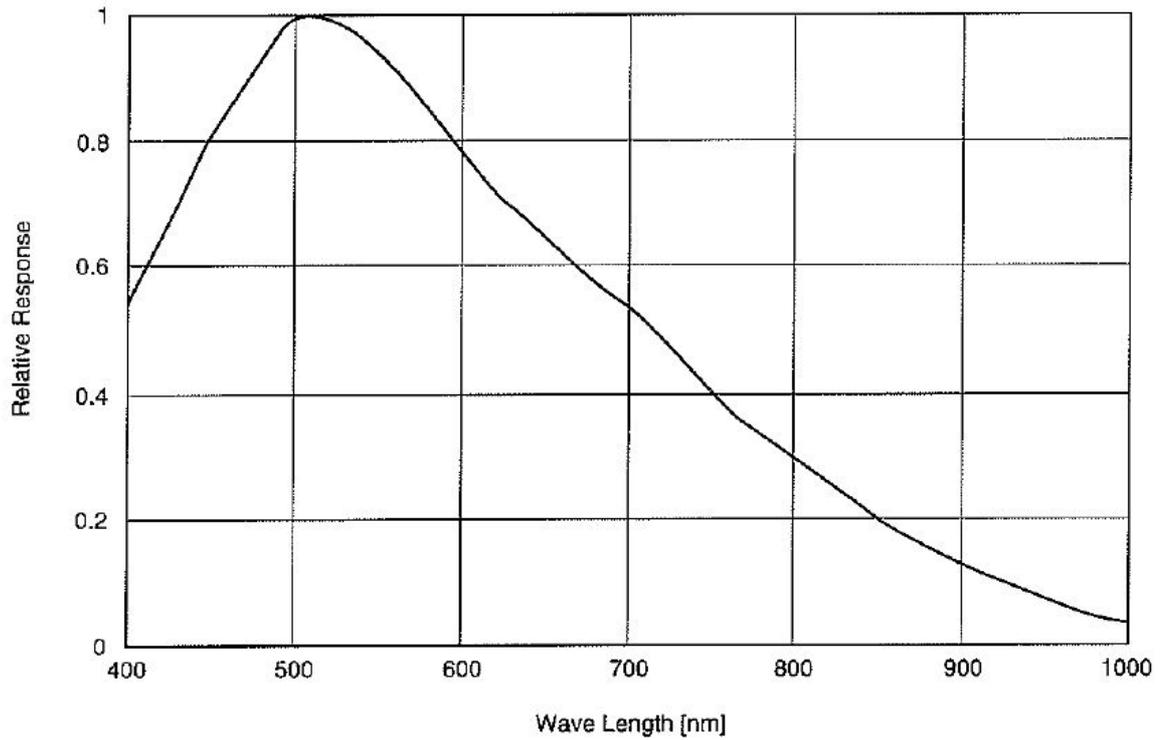
It is the last of the components for our digital SHG, but perhaps the most important. The key to the success of the digital spectroheliography was precisely the advent and the success of CCD and CMOS sensors, whose quantum efficiency (QE) exceeded enormously that of the old photographic plates used, at the end of the 1800s for the first experiments in spectroscopy and that of the most modern photographic film of recent years. Given that quantum efficiency describes the response of the sensors, i.e. the ability to convert photons into electrons across the spectrum, the QE 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 so that the professional astronomical films were hypersensitized for red (the famous Kodak 103 AO film).

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

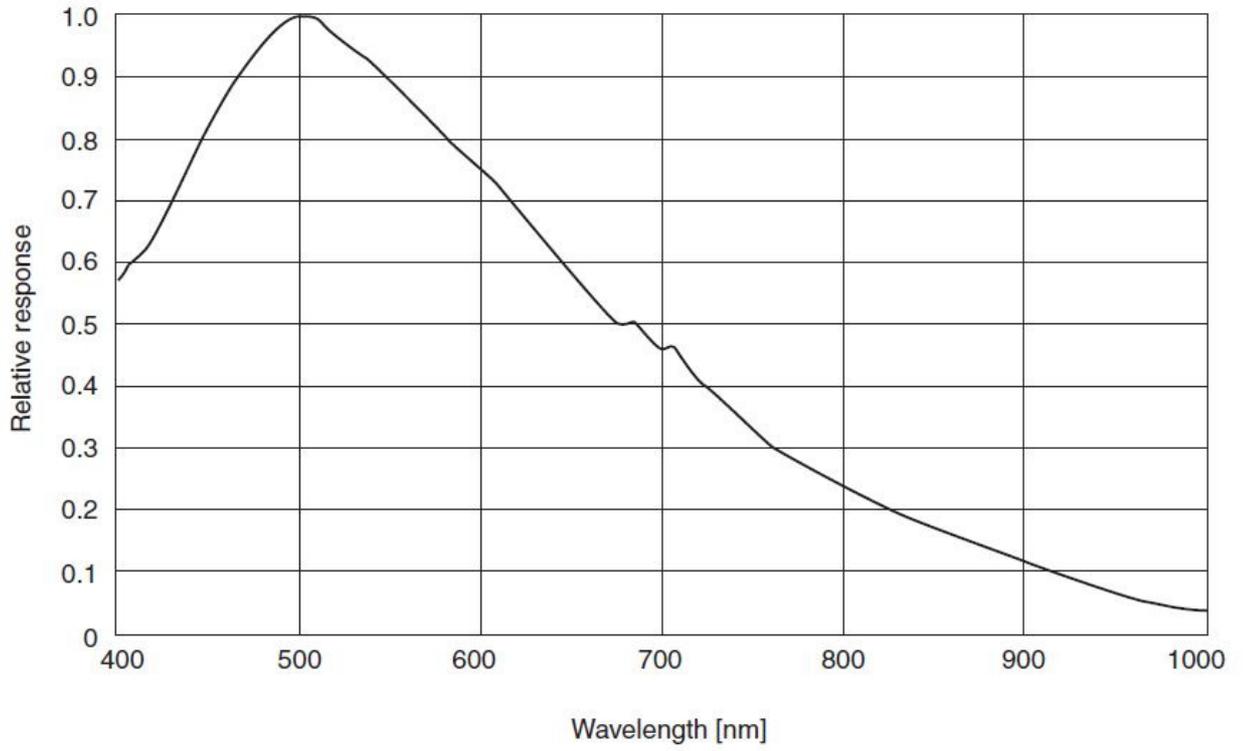


Here, however, we are not talking about CCD or CMOS cameras that give single images, but cameras able to record movies, or the video of the passage of the solar disk on the slit. These range from simple and inexpensive webcams to sophisticated and therefore expensive astronomical cameras such as the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

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



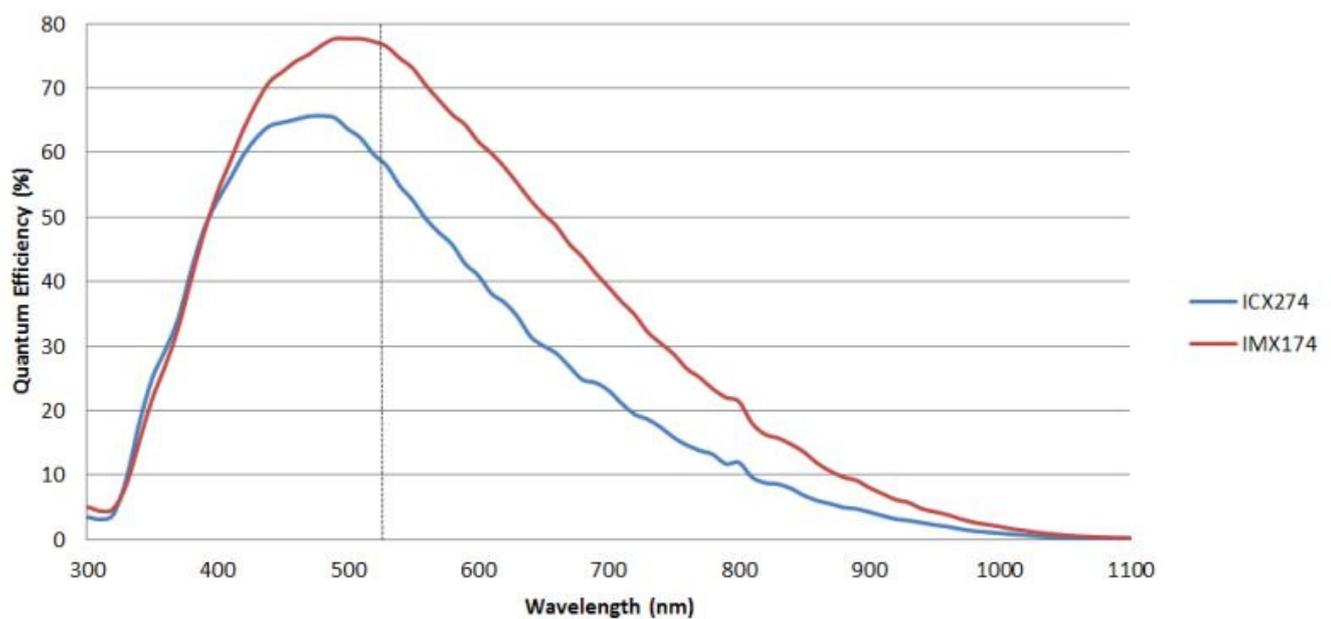
The relative response of Sony ICX 205 AL CCD sensor of the IS. DMK 41
(Source: Sony)



The relative response of Sony ICX 274 AL CCD sensor of the IS. DMK 51
(Source: Sony)

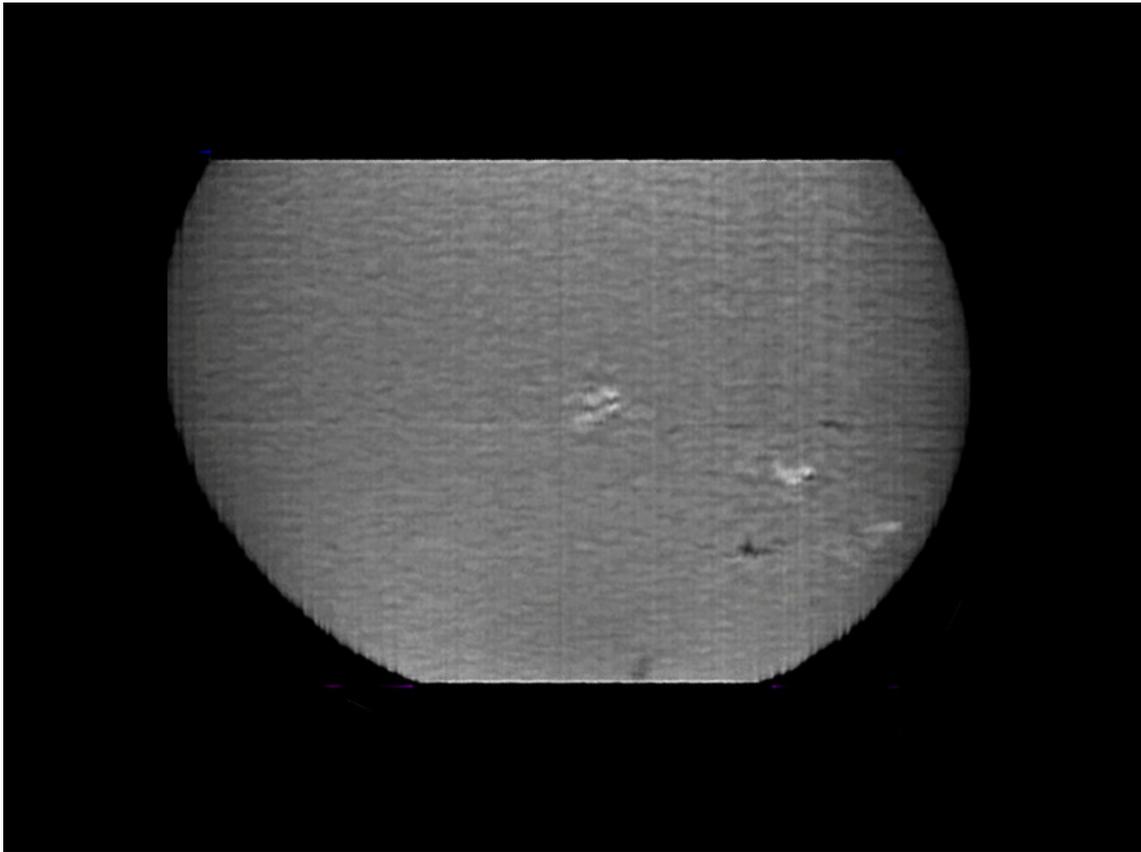
As can be seen, the QE of the two cameras fully meets the needs of the digital SHG, being about 52-53% in the spectral region of the calcium lines and 60% in that of the H α line, with a peak at 5000Å, in the H β zone. Obviously the DMK 51 has a larger sensor, which allows us, all things being equal,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

An even more exciting is the CMOS Exmor IMX 174 LLJ sensor from Sony (ZWO ASI 174), whose QE is shown 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 (with 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 2.7mm sensor and a 500mm telescope that projects a 4.7mm solar disk image on the slit, the recorded AVI file will have a coverage of $3.6/4.7 = 0.76$, i.e. it will cover about $\frac{3}{4}$ of the disk, obtaining a partial image, like the one below, which was my first solar image recorded with a Philips Toucam webcam.



If, however, we use a DMK 51 with a sensor of 8.50 x 6.80mm, then the coverage will be: $8.5/4.7 = 1.8$, this is 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. Alternatively, 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 consider a 500mm telescope projecting a 4.7mm solar image, a webcam, a classic spectroscope with a 200mm focal length collimator and a 200mm imaging lens: let's imagine we now change the focal length of the imaging lens from 200 to 100mm: 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 sit within the chip of the webcam.

The pixel dimensions

The night time seeing, as we know, is characterized, even in winter, by disturbances in the 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, the cause of poorer day-time observing conditions compared to the nighttime 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 long-term nighttime observation, is the seeing and not the diameter of the optics which determines the attainable resolution, also using exposure times and integration closer to those of planetary imaging than to those of the deep sky can help. 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 μ m pixels (DMK 51).

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

With 4.65 μ m pixels (DMK 41)

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

For 5.86 μ m pixels (ZWO ASI 174) would be

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

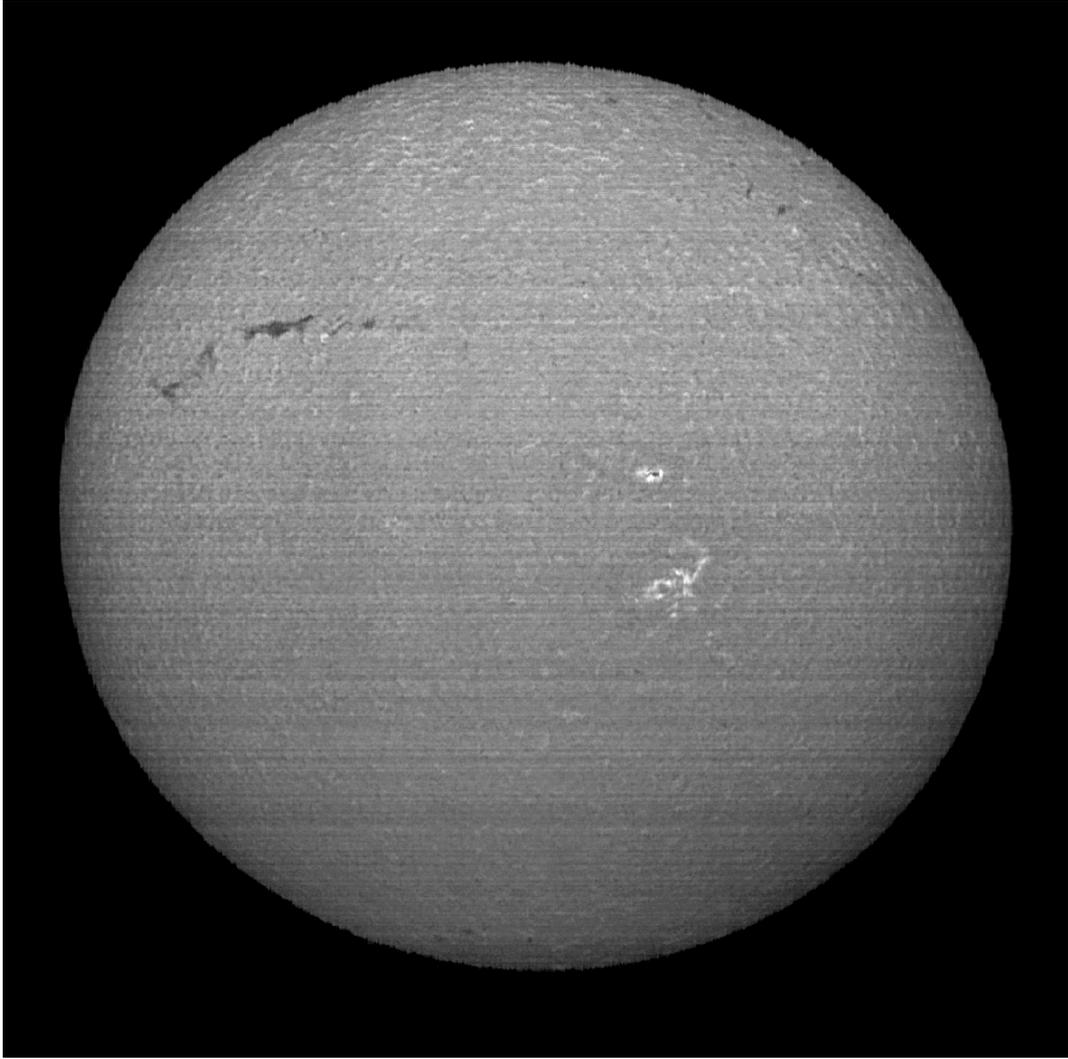
All this, working in harmony with an opening of the slit of 10-15 microns as previously mentioned.

The frame rate

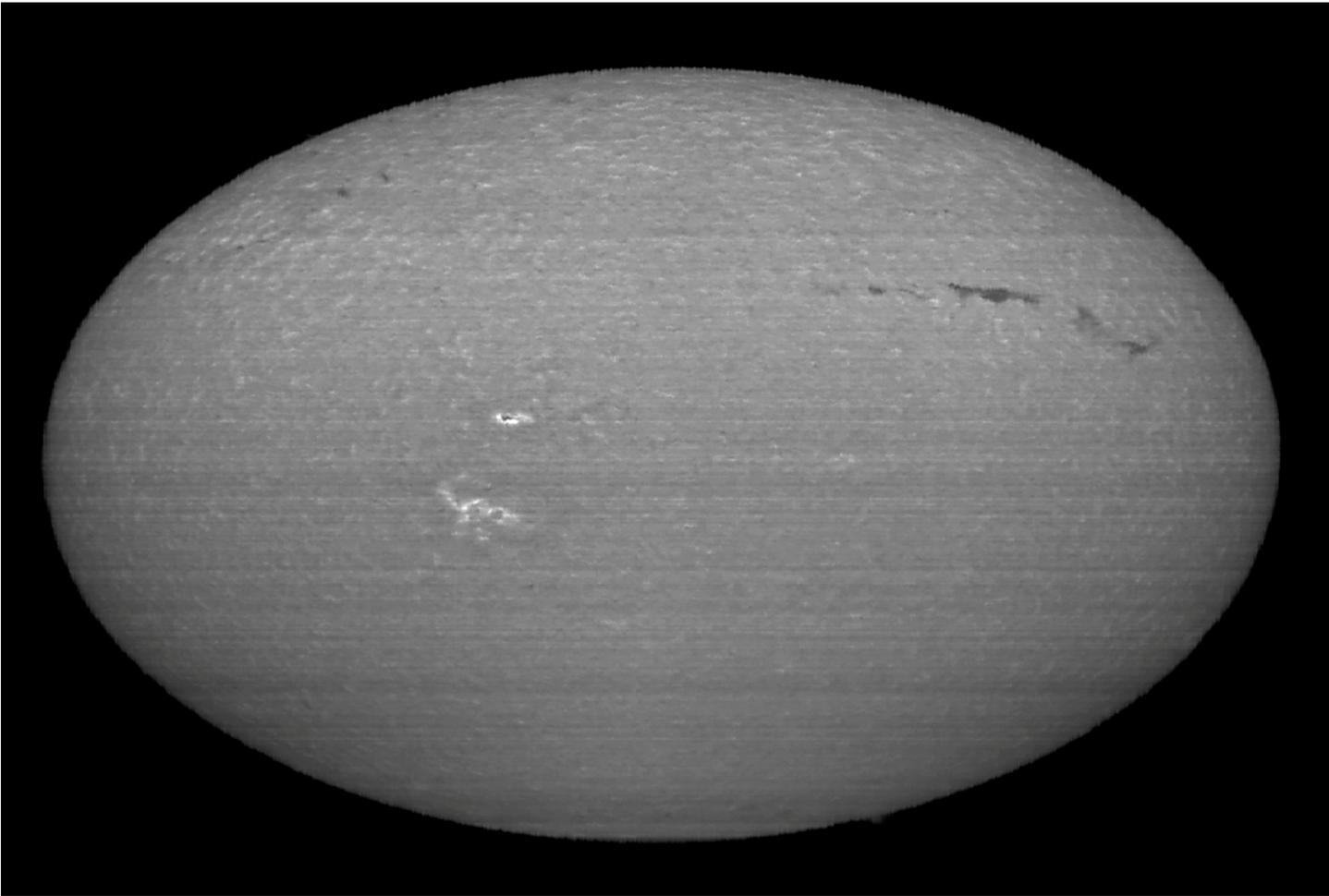
The frame rate is important because it depends on the resolution in pixels of the image along the x axis. In my solar scans I always let the solar disk run across the slit with the motors of the equatorial mount off, this gives the average duration of the sun's passage on the slit of 1920arcsec/15arcsec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

With a DMK 51 (oriented with the longer side of the chip along the RA axis) and a frame rate of 7.5fps I get a solar image that extends along the X axis for 128 x 7.5 = 960 pixels, disk only, and 160 x 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 then looks like this:



With a frame rate of 12fps 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, as the frame rate increases so does the resolution along the X axis, and 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 which are not very powerful with IS DMK, which have a USB 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 USB 3.0, this problem does not exist on the latest generation PCs.

Final note: the exit slit

As we have seen, the traditional SHG projects have two slits, one at the input and one at the output, for reasons linked to the synthesis of the images. In the digital SHG 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 at entry and return.

An extremely easy solution is to use at the output of the instrument an interference filter centered on the wavelength of the line in which we want to obtain the image: this is worth, during the recording phase, to eliminate a good part of the diffused light and increase the contrast. This filter can be inserted into the 31.8mm (1.25") nose of the camera.

A second solution, at least with H α imaging, may be to use a deep red rejection filter (normally used in solar H α imaging) placed in front of the telescope lens, i.e. along its optical path. Also, the common 2" 35-12nm bandwidth filters placed at about 30cm from the focal point may be useful for this purpose. However, in this last case it is necessary to consider that in the longer term 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 found 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, i.e. 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 500mm and a focal ratio of f7-8.
- 3- The slit, to accommodate the solar image of the aforementioned telescope should have a length of at least 6-7mm, and opened at 10-15 μ m.
- 4- The spectroscopy optics should have a diameter of 70-80mm at f7: ED refractors from 80mm to f7-7.5 are the ideal candidates.
- 5- The grating should be a holographic one, 2400 l/mm and 50 x 50mm square.
- 6- The camera should have a quite large sensor and medium-small pixels between 4 and 5 μ m.

Of course, these considerations are indicative and are not locked in stone. For example, in my three main instruments (VHIRSS, POSS2 and Solarscan) in conjunction with identical spectroscopy optics (Three ED80mm f7.5 refractors) I have used different telescopes, although of excellent quality (a 60mm f8, a 70mm f5, and a 60mm f6) 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 80mm f6.5 as a telescope and optics of the spectroscopy.

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 already set-up on the H α and another on the CaII 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 DIY activity has overcome any inconvenience. After all that, let's talk about the individual instruments.

1 VHIRSS (Very High Resolution Solar Spectroscopy): 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 α -Na-H β spectral area;

2 POSS2 (POrtable Solar Spectroscopy2): Littrow now dedicated exclusively to shooting in the CaII K and H ionized calcium band;

3 SOLARSCAN is the main and better instrument from the construction point of view, as it was manufactured to my requirements in an excellent way by Avalon Instruments of Pomezia (Rome). It was initially used as a SHG, and subsequently modified by me for the imaging of the Zeeman

effect in Iron lines on sunspots and the measurement of magnetic fields of the same sunspots;

4 HIRSS2 (High Resolution Solar Spectroscope2) is now used by me only for experiments of various kinds, among which are some in the field of quantum mechanics.

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

DIY digital SHGs in Littrow configuration

But let's now examine in detail some digital spectroscopes built by the author. 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 SHG 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 abilities count, but also and mainly a certain experience in spectroscopy and its practical applications. This does not mean that even a spectroscopy novice cannot try to build such an instrument; simply he/she will encounter more difficulties and will take more time in the development of the project and in its construction. 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. The design 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 110cm 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

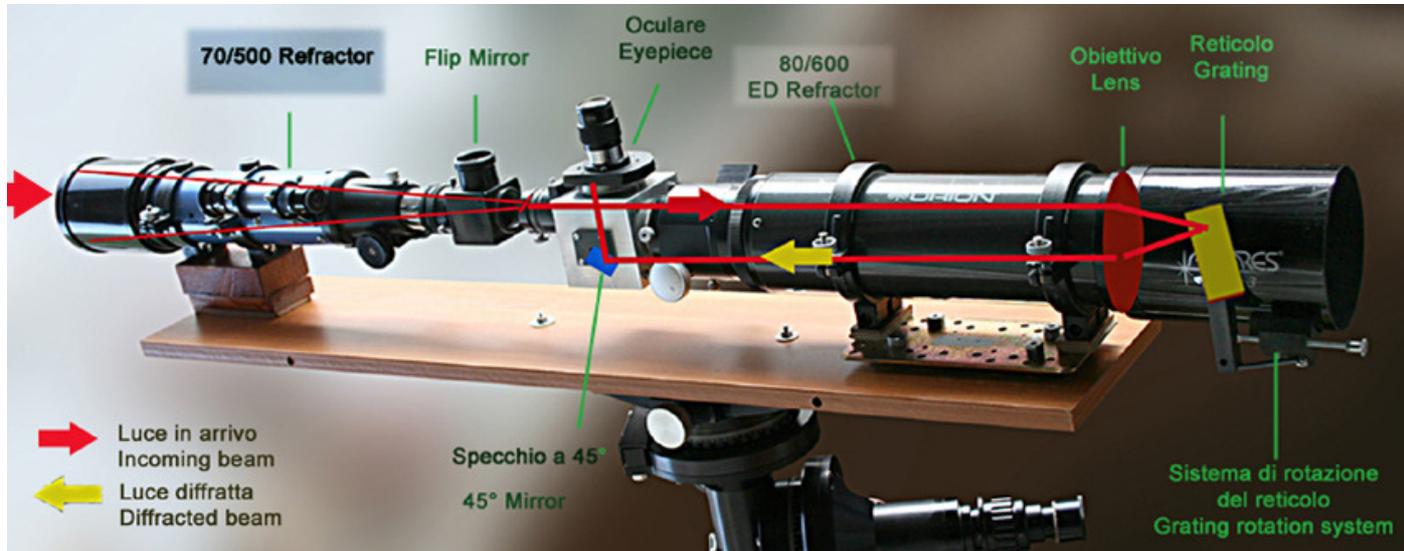
The initial project

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 excessively bulky. I therefore decided its design based on 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 ED80 as I had to pierce it to mount the grating axis, and I preferred to use a piece that was no longer useful.
- The Orion ED80 refractor tube
- The 80 x 80 square aluminum case containing the 20mm square flat mirror and the adjustable slit.
- The SW 70/500 refractor OTA used to send the solar image to the slit

- The 20 x 100mm laminated multilayer plywood strip used as a support for the rings of the two refractors, so that the optical axis of 70/500 was aligned with the center 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 quality of the 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 decided then to use a square steel plate of 30mm x 3mm thick x 1m 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 rock stable rigid platform.

The second was the telescope that sends the image on the slit, initially a SW achromat 70mm diameter and 500mm 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, and found, among my innumerable optical devices, a 60mm and 500mm 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 two 66/400 EDs, and this objective outperformed all three as to definition and contrast, I then 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 detail of construction notes:

1-The grating

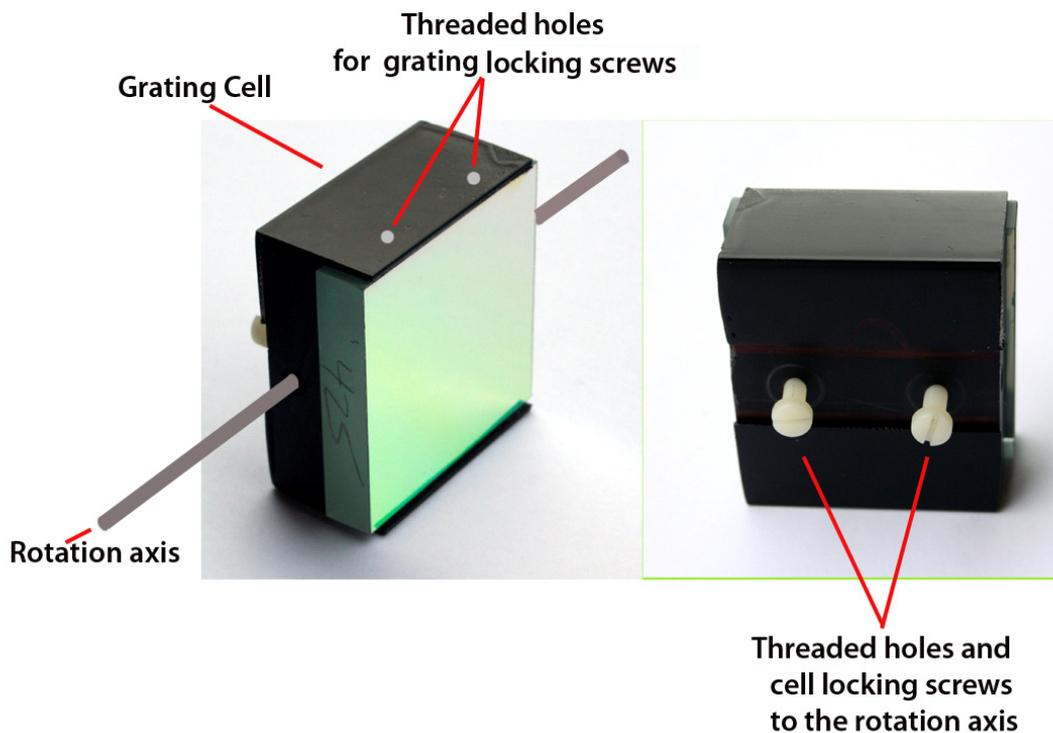
The chosen grating was a holographic type, not blazed, of 2400 l/mm purchased from Edmund Optics at the price (at the time) of 250€. It is the grating with the greatest number of grooves per mm in the visible available, and thus allows to obtain the maximum resolution possible, provided, of course, that its surface is entirely covered by the diameter of the collimation optics. This grating has proved to be of excellent quality, representing good value for the higher cost. Moreover, the diffraction grating constitutes the heart of a spectroscope, and wanting to save money on it is like buying a sport car with a 50cc engine. Obviously the grating must be handled with the utmost care, handling it from the sides since any fingerprints or marks on its surface are permanent and not removable.

2-The grating cell

This is an important element, as it must constrain the grating in a perfect way without forcing it into its seat.

I milled a block of black PVC 50 x 60mm in my possession about 20mm thick for a depth equal to the thickness of the grating (9mm) 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 (handling it from the sides) on the double-sided adhesive, the grating is securely fixed. It can, in principle, be secured even better, by threading an M3 hole in the upper and lower parts of the cell, so as to accommodate two plugs 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 plugs would be recommended).

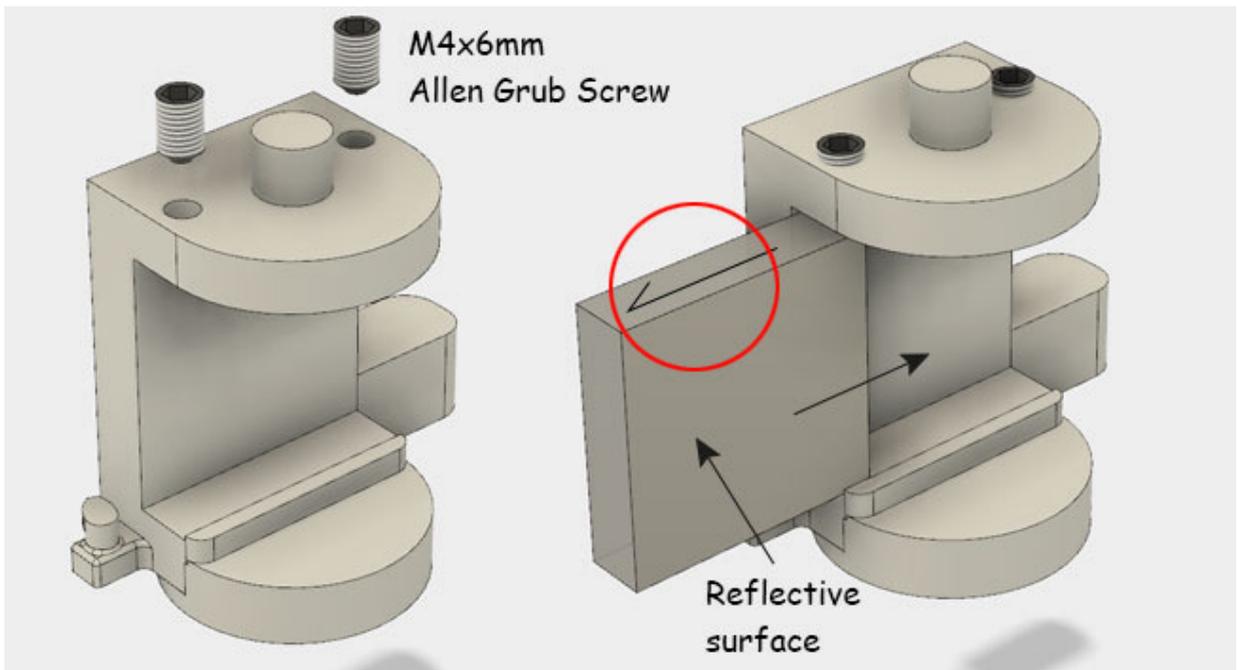
The cell was then drilled longitudinally with a 6mm hole to accommodate the rotating rod, and in its rear part, along the axis of the longitudinal hole, drilled with two M4 threaded holes to accommodate lock screws to hold the rod secure in the block, providing the axis of rotation of the grating.



It should be noted, that with the increasing popularity of 3D printers, the grating cell (as well as other minor components) could now be conveniently printed in PLA or PVC with a printer of good resolution, as seen in the project "LowSpec" by the Dutch amateur astronomer Paul Gerlach, at the link:

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

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



The layout of 3D plastic cell for the grating of the LowSpec spectroscope

Note: 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 spectroscope for maximum efficiency. The diameter of the axis of rotation can be chosen as desired, 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) must be carried out at the minimum distance from the spectroscope optics compatible with the complete rotation of the grating.

3-The Collimation optics

As mentioned, the optics used for VHIRSS was an Orion ED80 (practically equal to SW ED80), 80mm in diameter and 600mm focal length purchased at 250€, with excellent performance, definition and contrast. Due to its versatility for this use, a similar optics were also adopted for my other two SHGs, 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 spectroscope.

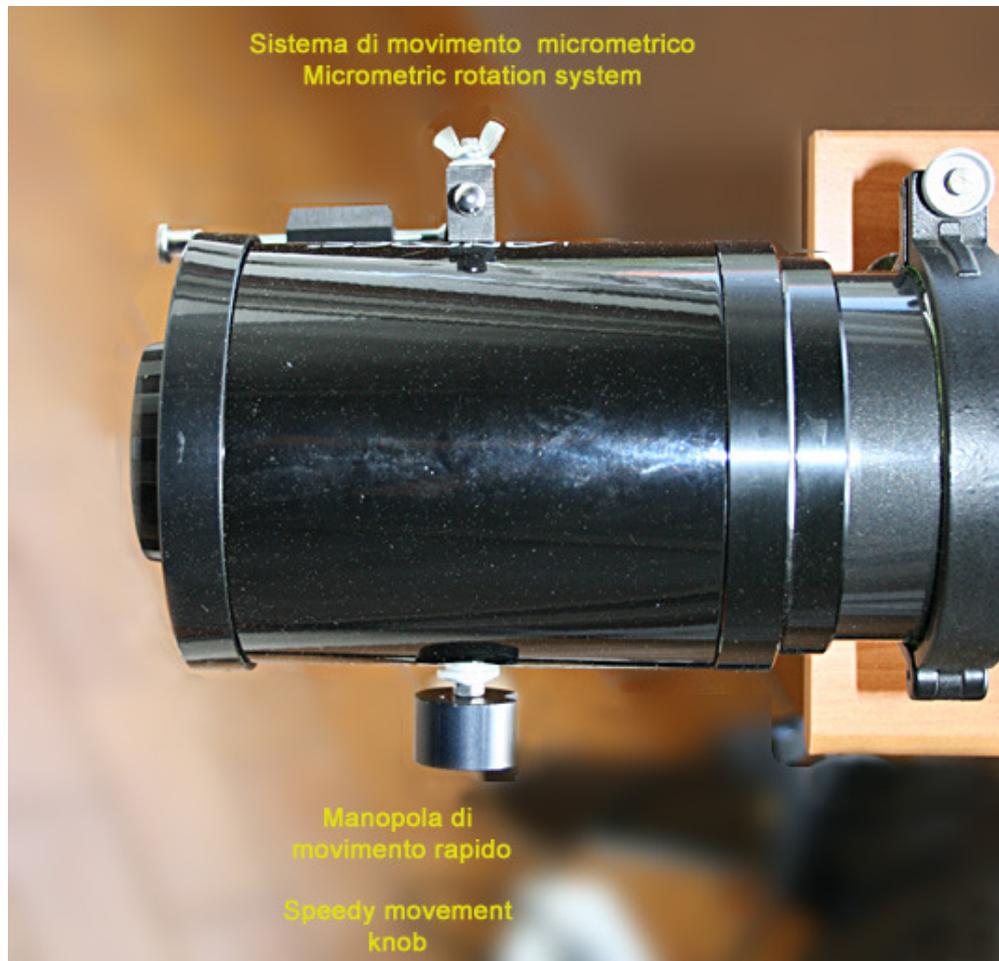
In my case, not wanting to pierce the original lens hood of the Orion 80ED that constituted the optics of the spectroscope, I used the lens hood of an old 100/500 Antares achromat refractor already in my possession. About the drilling of the Box (in my case the lens hood), it is best to specify that the holes in which the axis rod should be housed must be absolutely aligned. Best results would be obtained with a long drill bit and a column drill press. In the image that follows we observe the hood drilled with the rotating rod.

Regards 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 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 5-600mm, the length of the Spectrum is significant, 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 to 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 is done in Solarscan.

The picture below shows the detail of the two systems of adjustment of the grating cell movement.



The following figure shows 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 aluminum), once it is joined to the axis by tightening the clutch screw, is controlled by a screw with a spring to maintain contact.

It's quite a zero cost system, but very effective and easy to build, and faster than the usual micrometer. It can be modified or improved according to one's ideas.



5-The Relay box

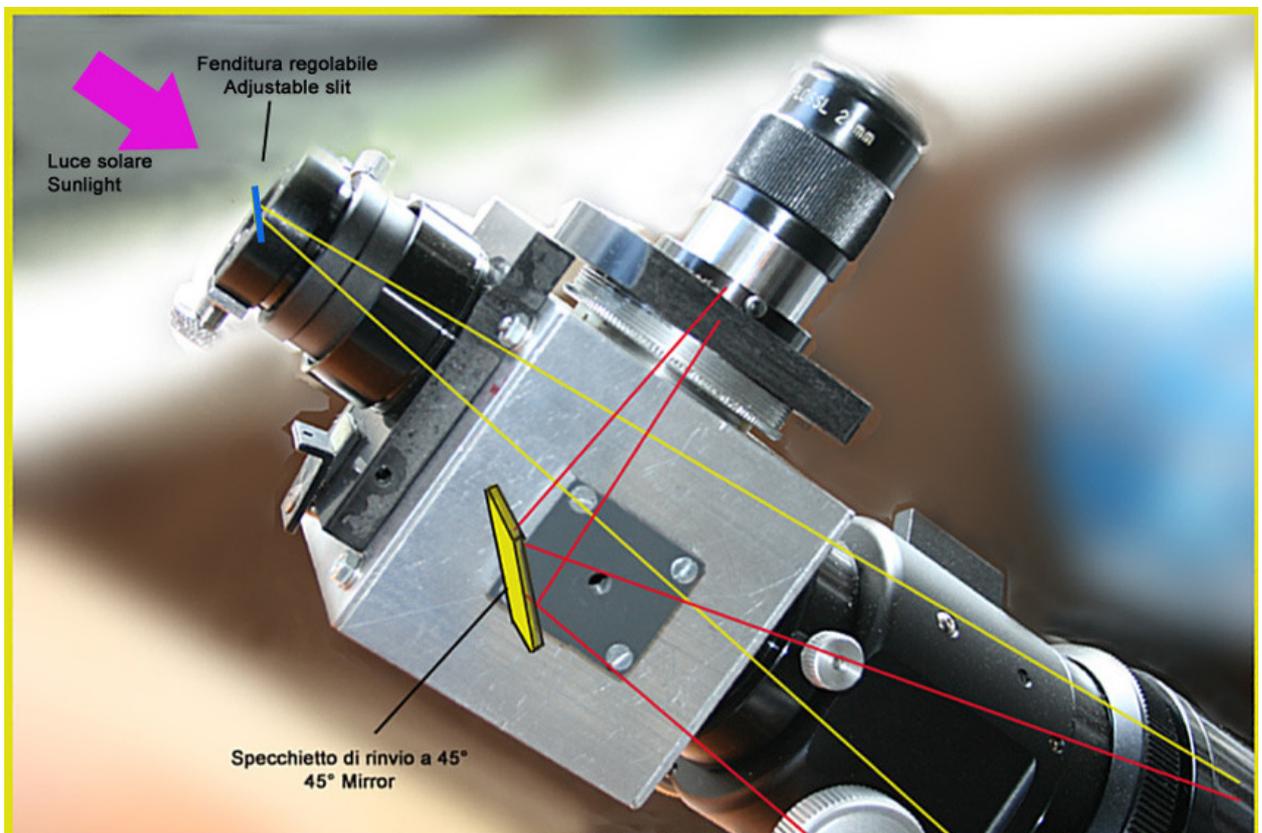
This is also an important component of the instrument. In some cases it may be convenient to adapt an off-axis guide that can also be found on the used market at affordable prices.

Obviously, the connection on the eyepiece holder of the spectroscope must be that of the internal diameter of this, of 50.8mm (2"), which is however restricted to approximately 38mm by the male adapter 42mm x 0.75 (T thread)/50.8mm. For a box I used a piece of aluminum square 80 x 80 x 3mm thick closed on two sides with closure plates also of aluminum and locked together with M3 screws. The box was then drilled on three sides and threaded 42mm x 0.75 (T thread) to allow, as seen in the figure, the attachment of the 31.8mm (1.25") 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 off - axis with respect to the optical axis of the OTA, but we will talk later about this interesting point.

The front surface mirror that redirects the beam to the camera (the return light beam coming from the grating and the collimator 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 70mm before the focus, (or 530mm behind the objective). Given that the largest of the mentioned sensors measures 13mm (Sony Exmor ZWO ASI 174), a mirror size of 15 x 20mm would be enough.

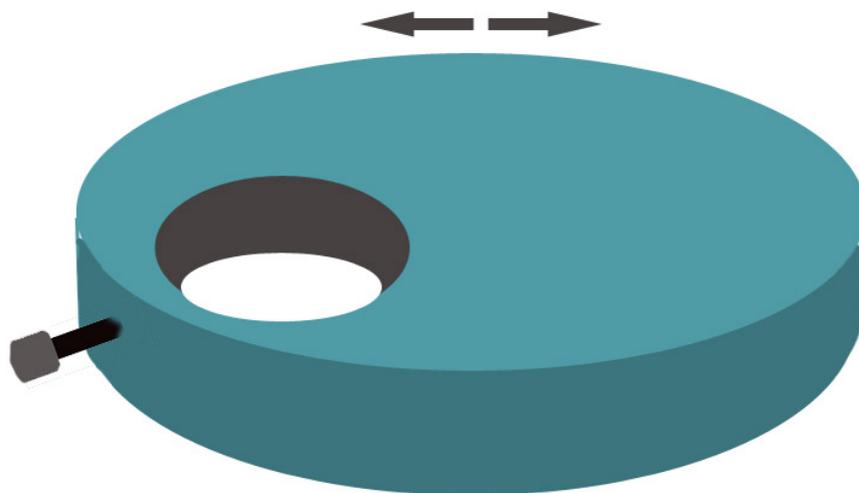
It is obviously necessary, when positioning this mirror into its cell, to be careful that it has a length such that, when placed at 45°, does not interfere with the light beam coming from the telescope through the slit. Of course in place of an aluminized mirror we can also use a prism of suitable size, 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 Newtonian diagonals: 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 adjusting screws at 120° in the base of the camera-eyepiece holder.



One of the features of VHIRSS compared to other DIY Hires spectroscopes is the positioning of the slit off the optical axis. This variation was dictated by the intuition that a larger angle could allow for a linear dispersion and a better resolution. The displacement of the center of the slit with respect to the optical axis was about 7mm, equal to one degree on the plane of the grating. In the formula of the linear dispersion (5), Page 99, it replaces the angle that is usually = 0 in the Littrow configuration. With non-blazed holographic gratings we obtain, with the slit closed to 30 microns, a dispersion of 3.75 \AA/mm , equal, with a camera with pixels of $4.65\mu\text{m}$, to 0.017 \AA/pixel and a resolution R of 59660 in $H\alpha$. These values agree with those I obtained in the field with VHIRSS and the DMK 41 in the $H\alpha$ zone for the dispersion (0.019 \AA/pixel) and resolution R (43700) and much higher than theoretical calculated for this opening of the slit at Page 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 31.8mm (1.25") 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° and therefore slightly tilt, however this system does not excite 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 down side of costing about 175€, while the device that precedes, if made in black PVC by a machinist, should cost around 20-30€.



It is good to specify that, in case you do not opt for the solution of the off axis slit, 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 50.8mm (2") to be able to enter the eyepiece port of the spectroscopy optics focuser (in my case of the Orion ED80).

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.

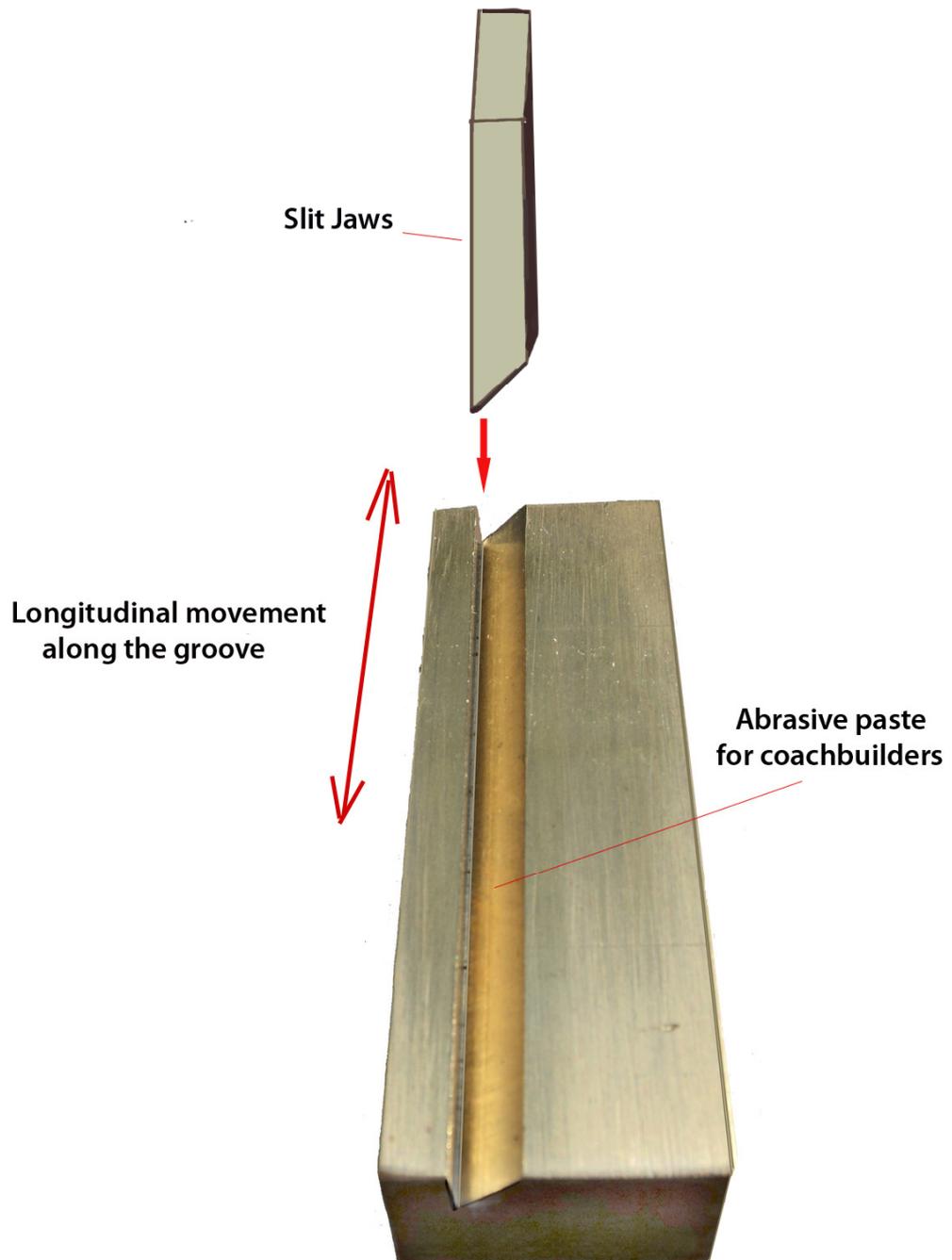


6-The slit

Lastly I come to the discussions on the slit. 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 the quality of the 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 SHG. Many recommend the DIY machining of the jaws, but this is not easy without owning and being able to use a mechanical workshop with milling and grinding machines.

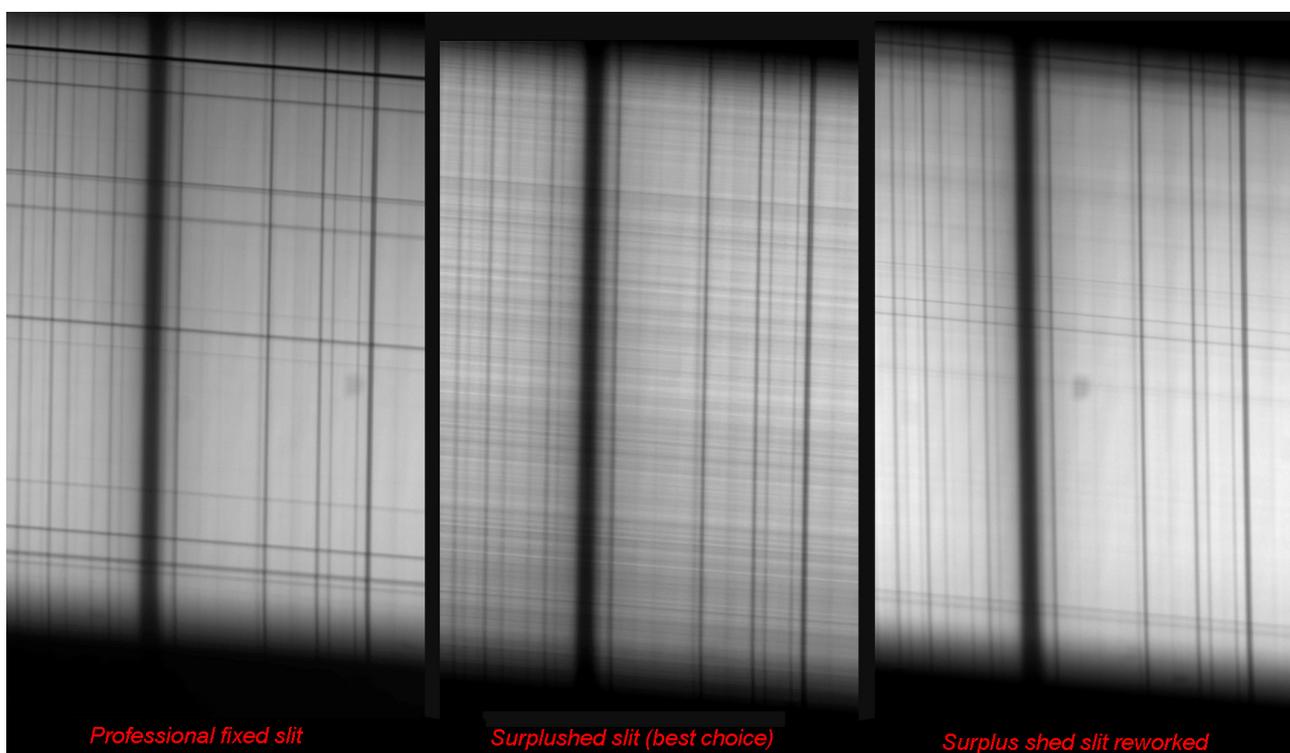
For VHIRSS I adopted a hybrid solution, that is, to buy a low-cost commercial slit and to improve the finishing of the blades by myself.

The slit is that of Indian production and marketed by Surplus Shed <https://www.surplussed.com/pages/item/m1570D.html> the one we talked about previously. It was disassembled and the blades studied under a 400X microscope, after which the edges of the slit were worked by rubbing them on a specially made brass tool, using an abrasive paste for coachbuilders. After a few passes at medium pressure, the improvement was 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 used by coachbuilders, if you do not have cerium oxide.

Below is a comparison of this modified slit (on the right) with one of the best of Surplus Shed (in the center) and with a fixed professional (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 clearly seen. 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, flat 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

disk of PVC of outer diameter equal to the inner one of the lens hood and, at its center, a 31.8mm (1.25") hole to accommodate by pressure or with a locking 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.

VHIRSS is currently operative for spectroheliography in H α light at 6562.8 Å, and for this purpose it has been equipped at the output of the telescope focuser with a 10nm H α filter that selects the incoming wavelength and reduces diffused light, increasing the contrast. Be careful, anyway, to place the filter not 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), keeping in mind that such IR-UV cut will need to be removed in case of CaII K line observations.

A bit of accounts

At the end of this discussion on the construction details of instruments like VHIRSS, someone could say "yes, that's fine, very interesting, but how much would it cost? Probably not all fans of DIY can afford it" the question would be legitimate, so I will try to answer, even if approximately, about the possible costs, distinguishing two cases: the purchase of some of components on the second-hand market, as in my case, and the purchase of each of them new, from suppliers in the sector. My VHIRRS cost about 600€ (about \$680), but basically buying only the grating (new) and the Orion refractor (used) and using components already in my possession, and understanding that not all amateur have this luxury.

1- Mixed purchase, new and used

The components of the SHG 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 used as the telescope (used) \$250
- Refractor SW ED80 or similar as optics for the spectroscope (used) \$300
- Off-axis guider (used) \$100
- Edmund holographic grating 2400 l/mm (new) \$300
- Steel bar from 1 meter 30x3mm or similar (new) \$10
- Small metal parts and small accessories etc. \$40

Total: \$1000

2- Purchase of new only

- Refractor 66/400 ED or similar to use as a telescope \$400
- Refractor SW ED80 or similar as optics of the spectroscope \$500
- Off-axis guider \$200
- Edmund holographic grid 2400 l/mm (new) \$300
- Steel bar from 1 meter 30x3mm or similar (new) \$10
- Small metal parts and small accessories \$40

Total: \$1450

In this hypothesis we assume the use of ED refractors (which I still recommend). We could also use 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 imaging have some.

Let's weigh up the cost to benefit: with an overall cost around \$1000-1500 or the cost of a low-end H α filter you would get an instrument that would be able to image the sun not only in H α light, but in all the wavelengths of the elements of interest (H β , H γ , Na1 and 2, Mg, Fe1, 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 to the same exact criteria, even if the first telescope was the 80mm and 400mm focal length (f5) then a 70mm Celestron, 400mm focal length (f5.7), both with achromatic objectives. To reduce the problems arising from the secondary spectrum, for imaging in the near UV (CaII K and H) to which the instrument is dedicated, a narrow band filter (about 50nm) centered on 400nm was inserted before the focus of the telescope.

The spectroscope optics are a SW ED80, practically the same as the ORION ED80 of the VHIRSS.

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

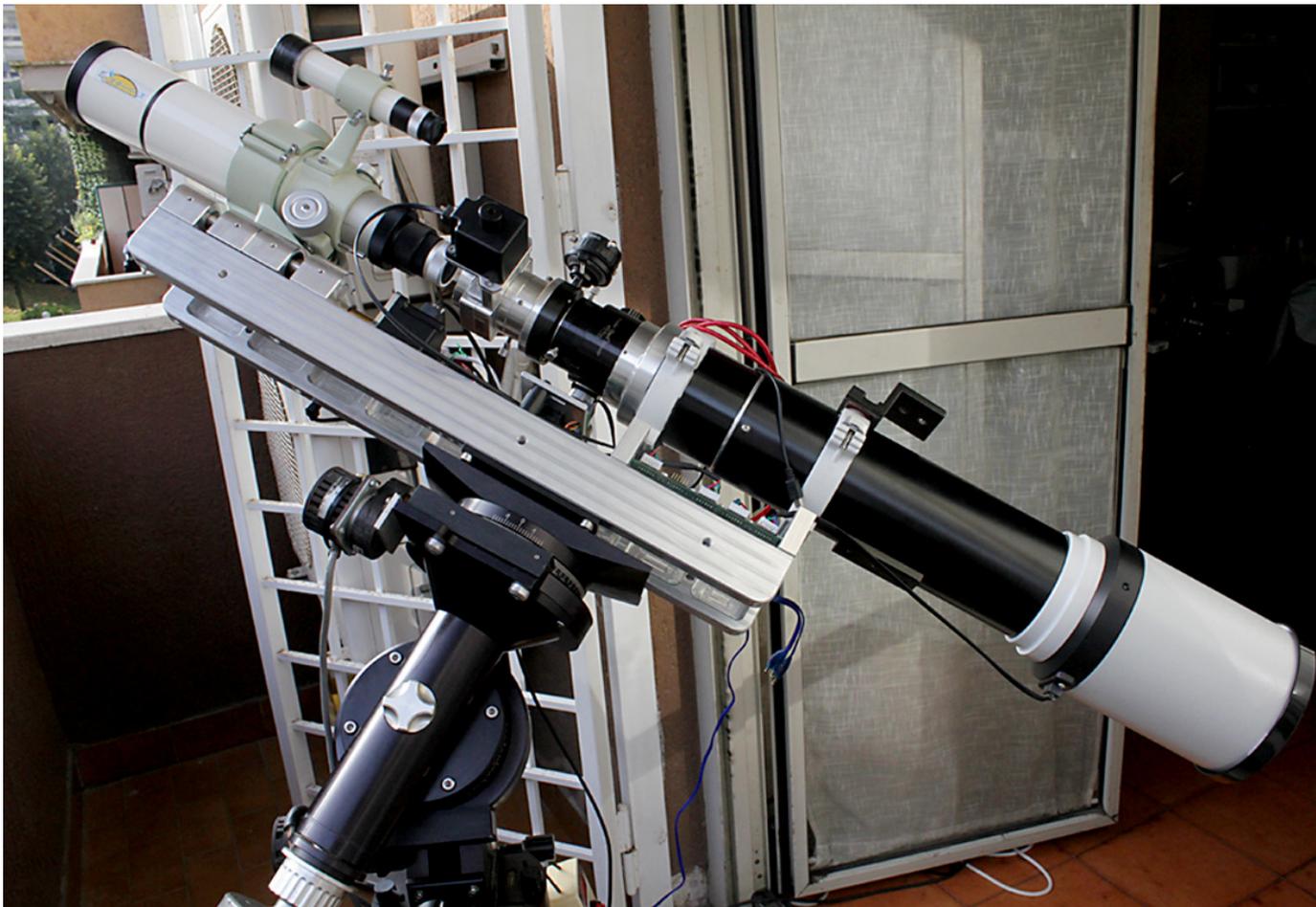


An image of the POSS2

3- Solarscan

The Solarscan project, which was successfully completed 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.

It satisfies the concept of a remote operated SHG using custom designed software to control 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 60C that with its ratio of f5.9 was close to that of f7.5 of the usual SW ED80, also present in this instrument as optics of the spectroscope; the grating is, as always, a Edmund holographic one of 2400 l/mm. Of course this instrument, built with professional skill and tolerances, provides a high level of performance, 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 using the Zeeman effect.



Solarscan on my Losmandy G11 equatorial mount



SolarScan on an Avalon Instruments M1 equatorial mount

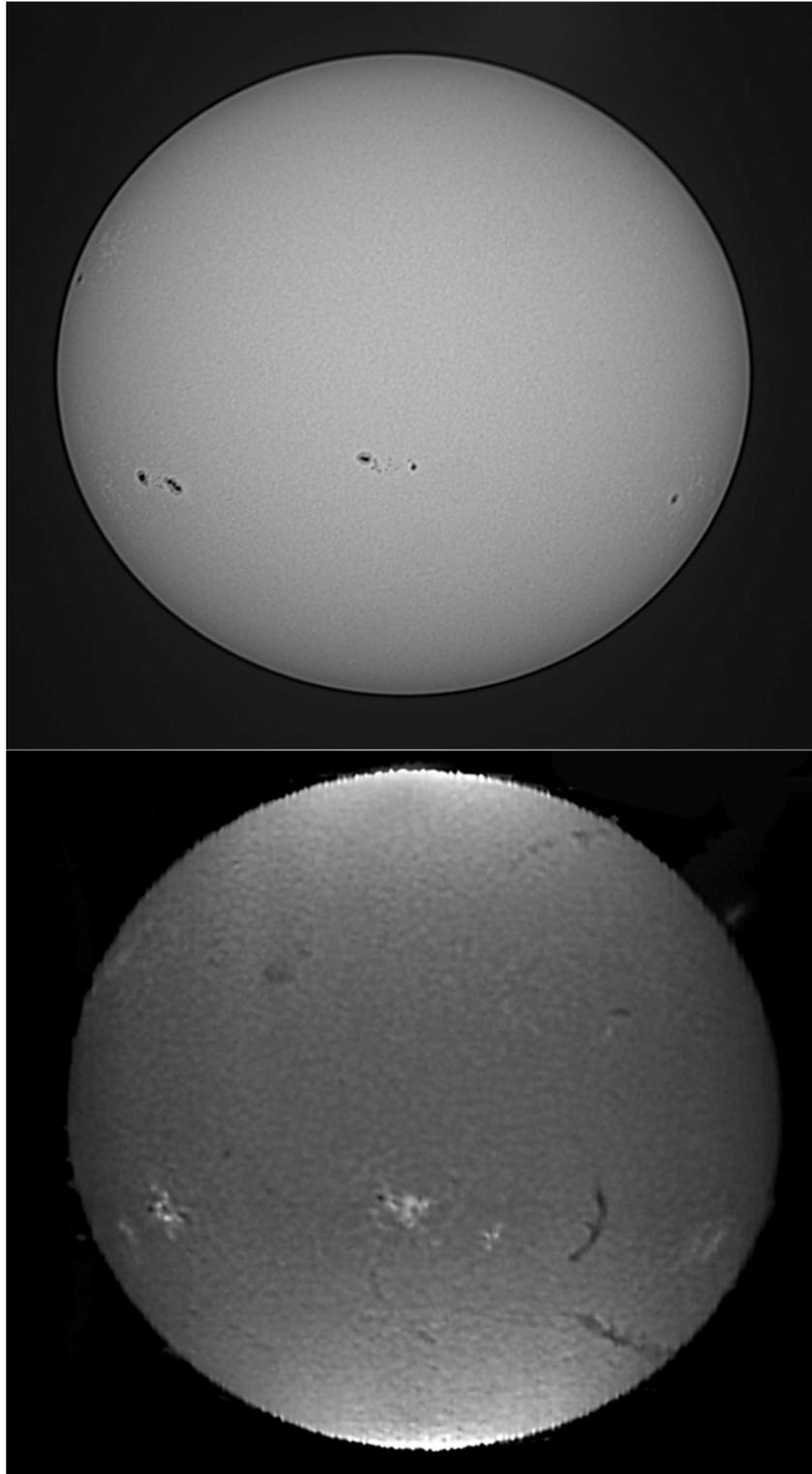
The weight, which has grown to 15kg, and the length to over 110cm due to the sophisticated and robust mechanics, required the use of mounts of high quality and load capacity such as Losmandy G11 and Avalon M1.

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 economic cost of construction, with two achromatic 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 l/mm Thorlabs grating at the cost of 170€. Ultimately the instrument had cost me, everything included, about 400€ (about \$455). The image below shows the HIRSS2 in a white light solar telescope configuration/ SHG, thanks to a flip mirror and an Astrosolar filter. With the filter mounted and the flip mirror lowered, it images the Sun in white light, while removing the filter and by raising the flip mirror, a spectroheliogram can be 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 still acceptable. It is now used by myself exclusively for testing and for some interesting experiments. Last but not least, the achromat 80/400 refractor has been replaced with a good 60/415 vintage scope with less weight and dimensions and similar performance.



HIRSS2 shown in white light mode

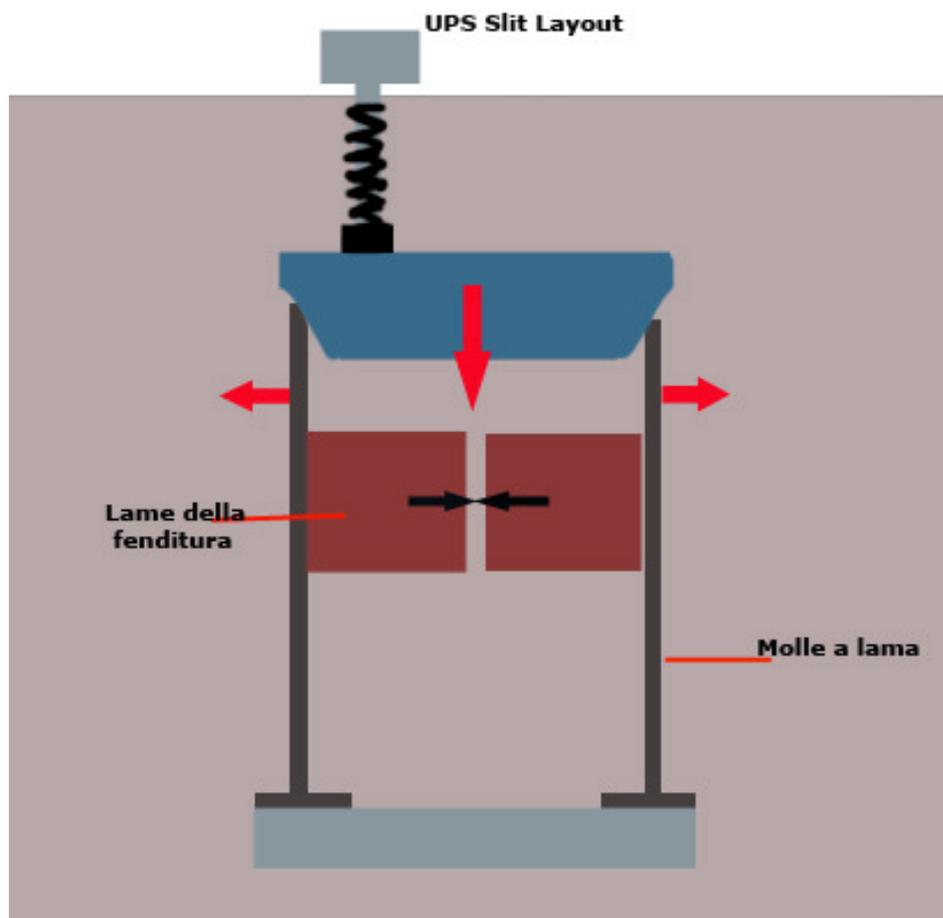


The imaging of solar disk in WL and $H\alpha$ with the HIRSS2

5-UPS

UPS (Ultra Portable SHG) is the smallest and most manageable of my DIY SHGs, and 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 25mm and only 1200 l/mm. The optics of the spectroscope, 36mm aperture and 300mm focal length, comes from military surplus and are absolutely excellent, while the optics of the telescope is made up of an equally excellent 60mm and 420mm focal length Stein Optics vintage refractor. The particular strength of this instrument is the use of a unique slit, which makes use of components from a professional slit, adapted for astronomical use. Its characteristic, difficult to find at reasonable prices, is that of the simultaneous closing of the jaws to 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.



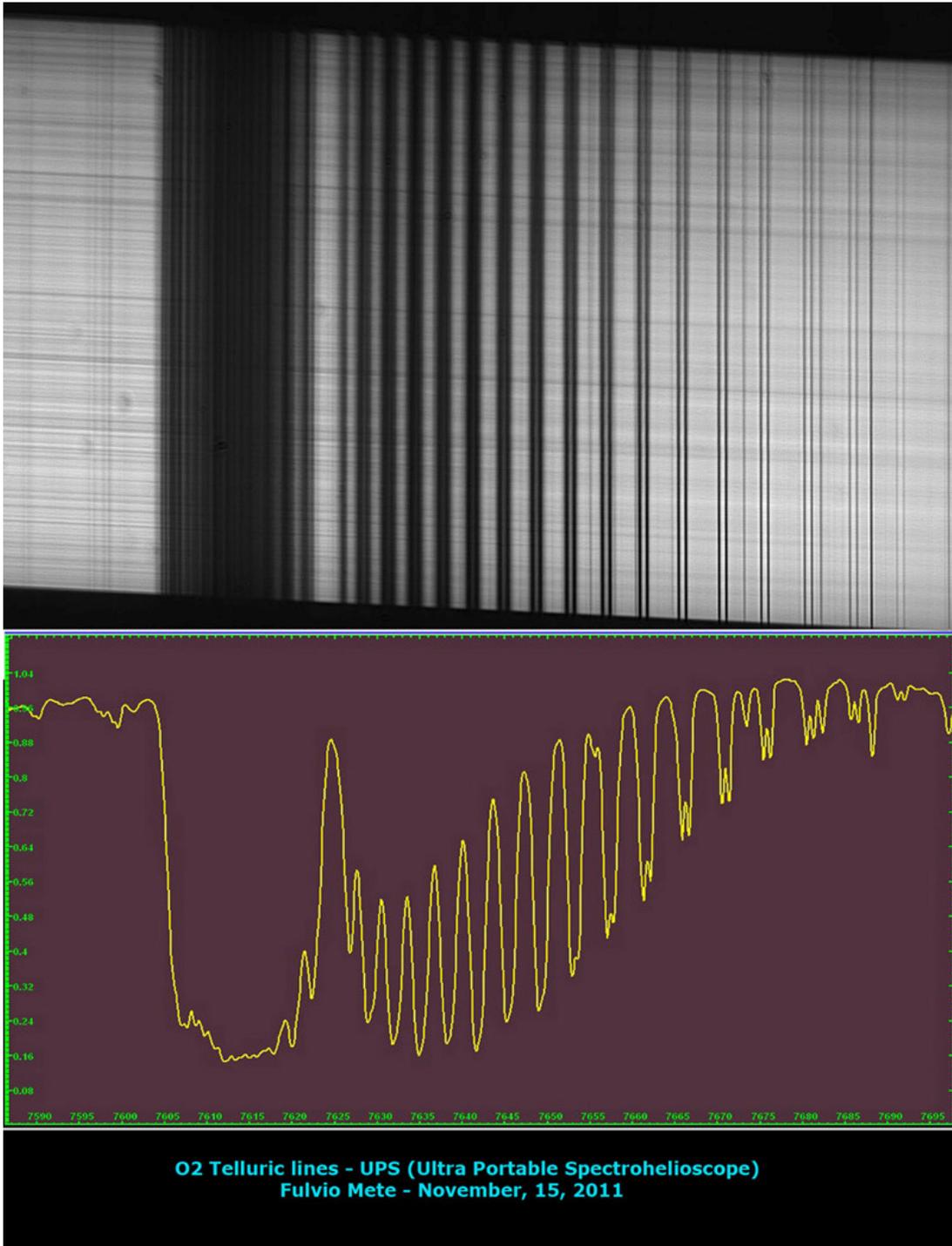


UPS layout

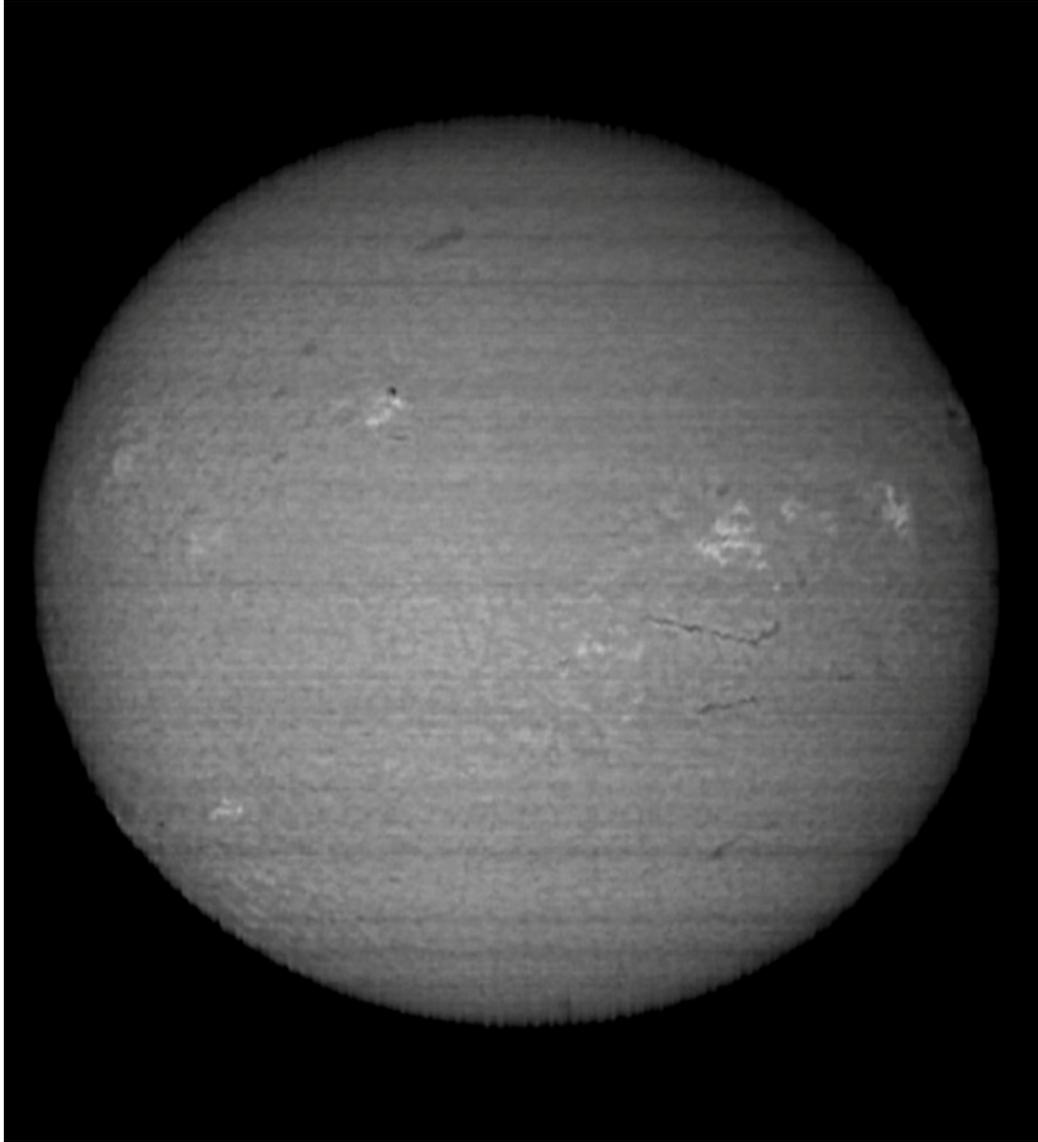
This is a small instrument only 70cm in length and weighs only 3.5kg, capable, however, of a respectable performance. You can see, in the center, the box with the slit mentioned above.



UPS on the Losmandy G11 mount on my balcony.



The good resolution provided by the instrument on the telluric lines of O₂ belonging to the Earth's atmosphere.



A spectroheliogram in H α light by UPS

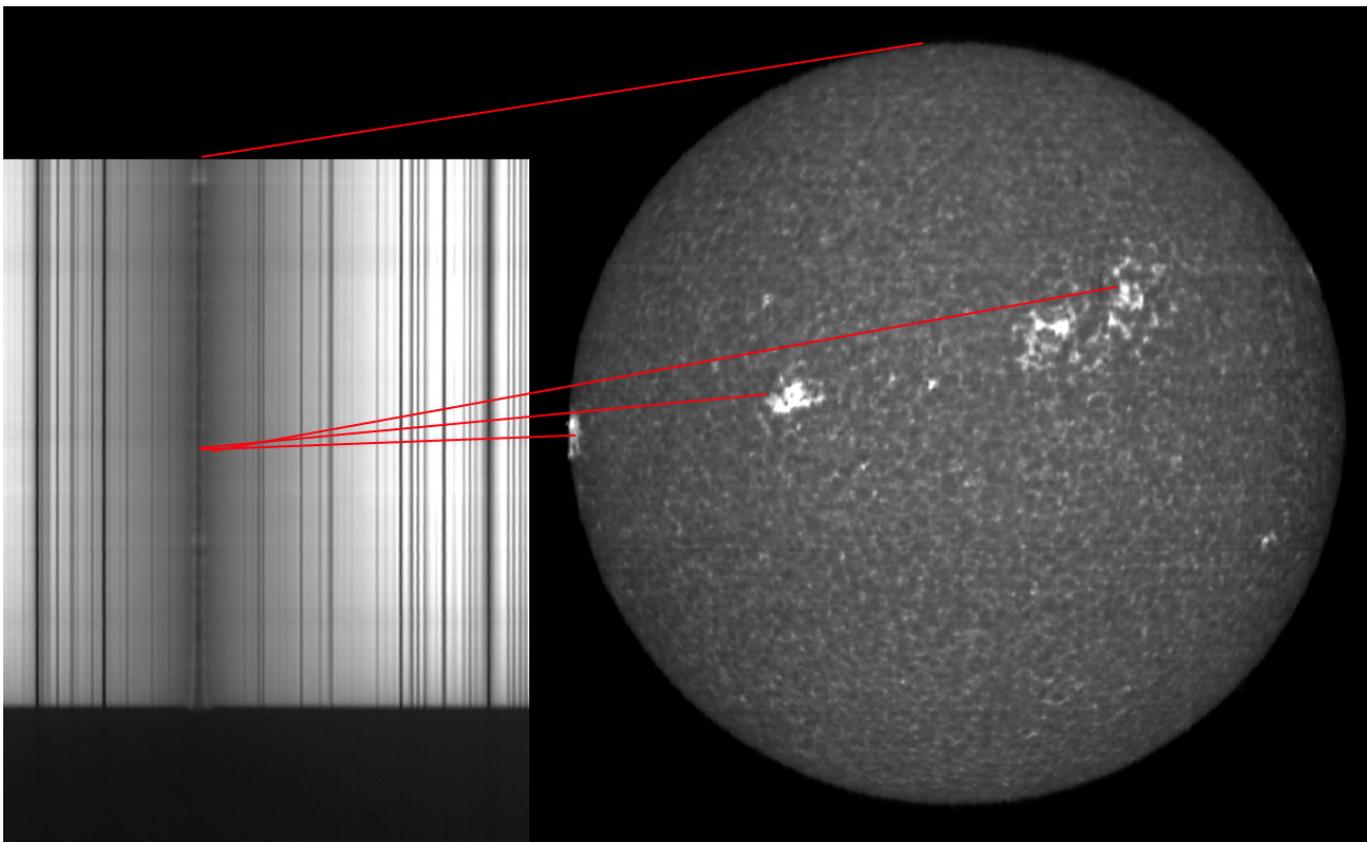
Summary of operations to be performed in digital spectroscopy

1- Focusing

The focusing of a SHG in a 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:

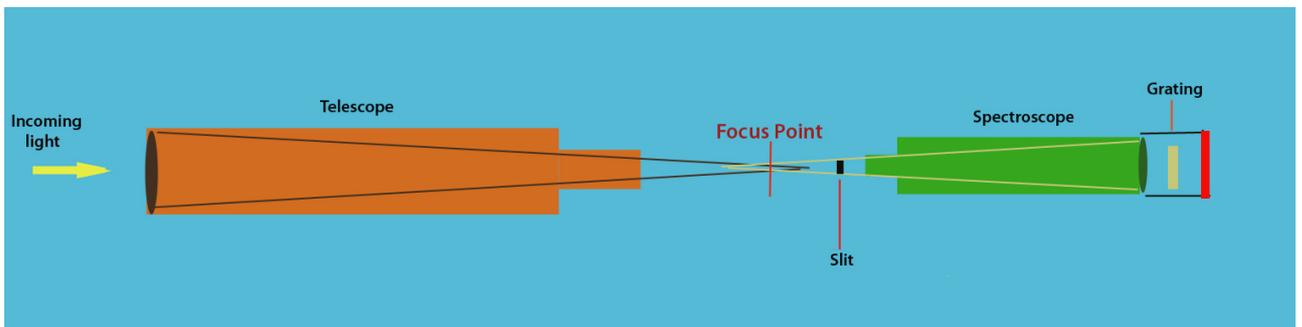
First of all, to understand better, it is necessary clarify a fundamental point: how the image of the spectrum translates into that of the solar disk after software synthesizing operations. In practice, the upper and lower edges of the spectrum correspond to the edge of the solar disk in the final image, 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 visually using an eyepiece, until we get a precise, sharp, spectral image. Once the camera has been inserted into the eyepiece holder, the telescope focusing system is 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 use 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 of the telescope, until the spectrum appears as

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

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 infinity) 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 370mm from the 70/400 telescope and 560mm from the lens of the SW 80/600 refractor.

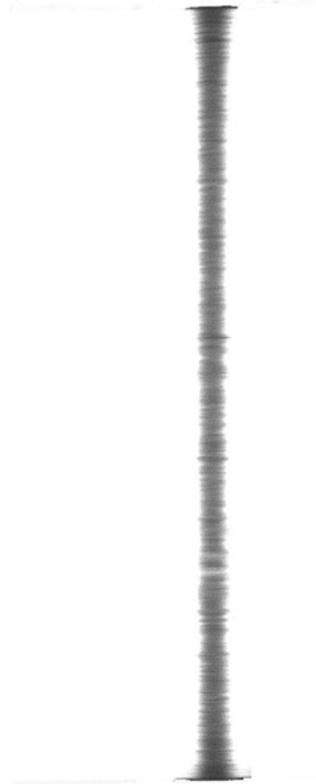
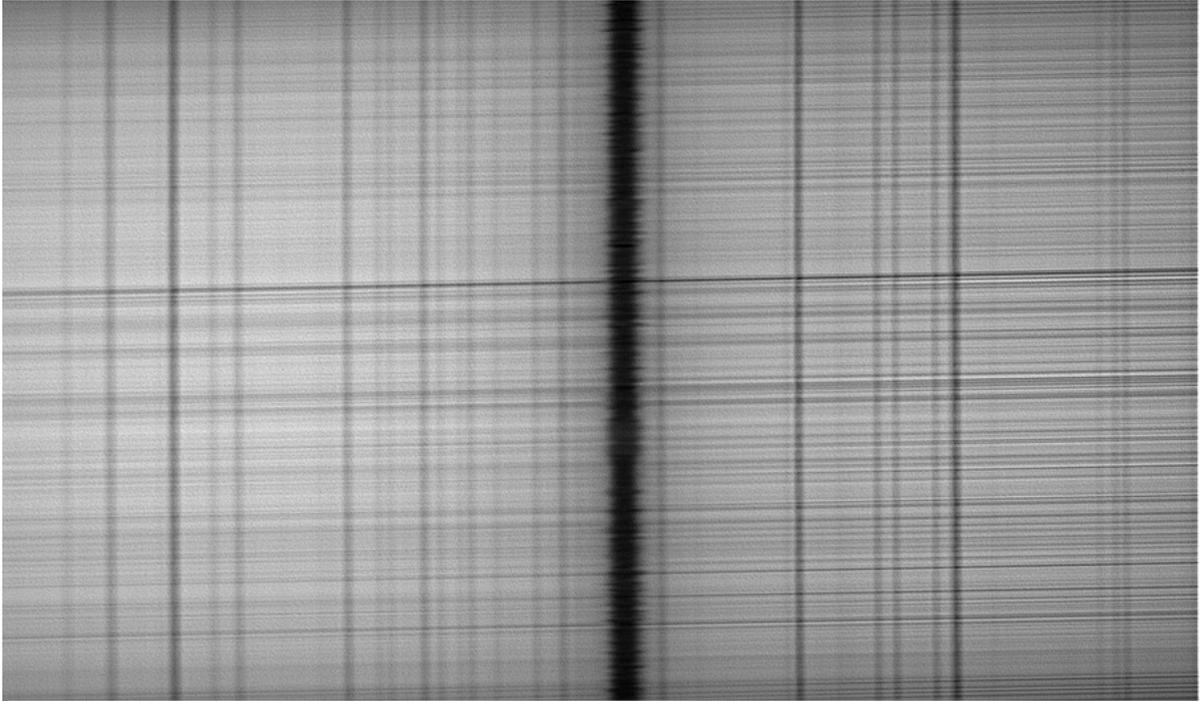


A very common mistake, which has happened several times to the author, was forgetting to put the jaws of the slit to the usual 15-30 μ m opening, causing the lines of the spectrum to be blurred and still out of focus, as long as you use the focuser of the spectroscope, so you will need to close the slit to see them clearly and well 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 H α line 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 α , 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, on which the final focus will be carried out.



Changing the exposure to show the chromospheric detail in the line when focused.

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 SHG 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 at other times, are in my opinion, preferable. Obviously the season and the height of the sun above the horizon are of great importance; the best results are, based on my experience, in late spring and early autumn.

Location

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.

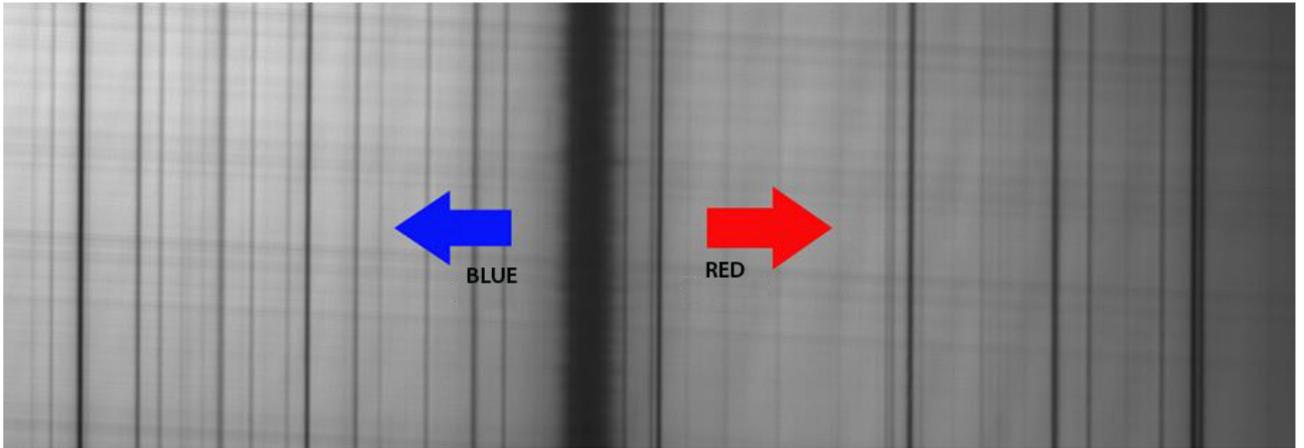
The acquisition

Once the SHG is pointed to the Sun so that the solar disk projected from the telescope optics appears on the slit, insert the camera into the eyepiece holder with the long side of the sensor parallel to the RA axis, identify the line of interest lying 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, i.e. with the blue on the left and the red on the right of the image on the monitor, as in the figure

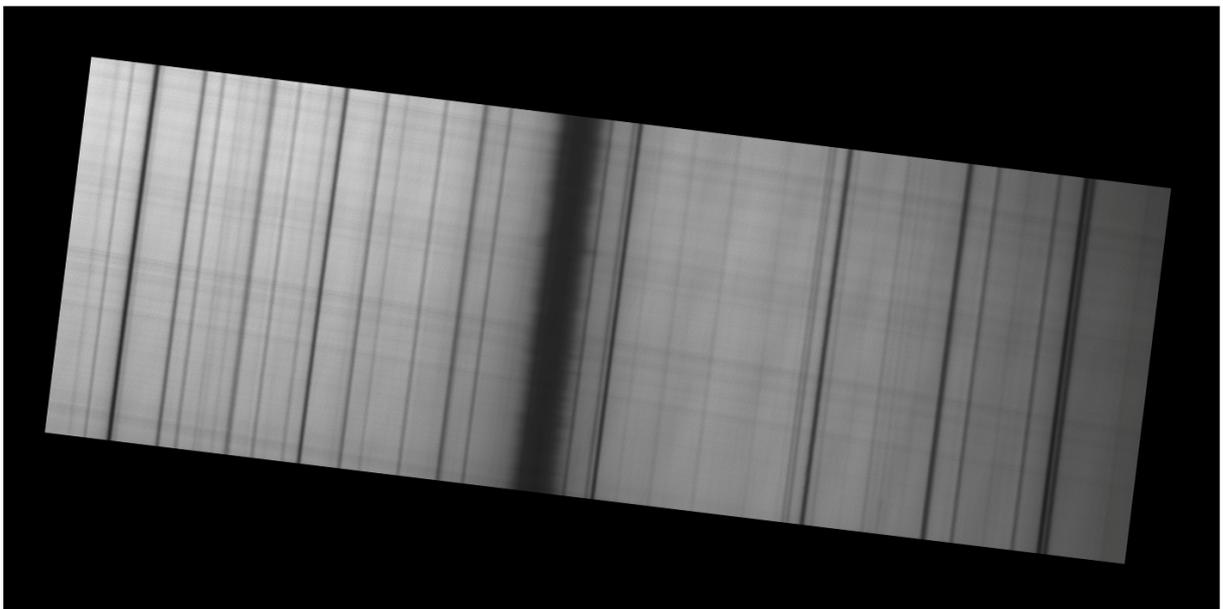
below. Online catalogs are useful for checking orientation, among which, in addition to that of Moore, the following is very useful:
http://bass2000.obspm.fr/solar_spect.php



The correct orientation of the H α spectrum

b) The "Tilt" of the spectrum

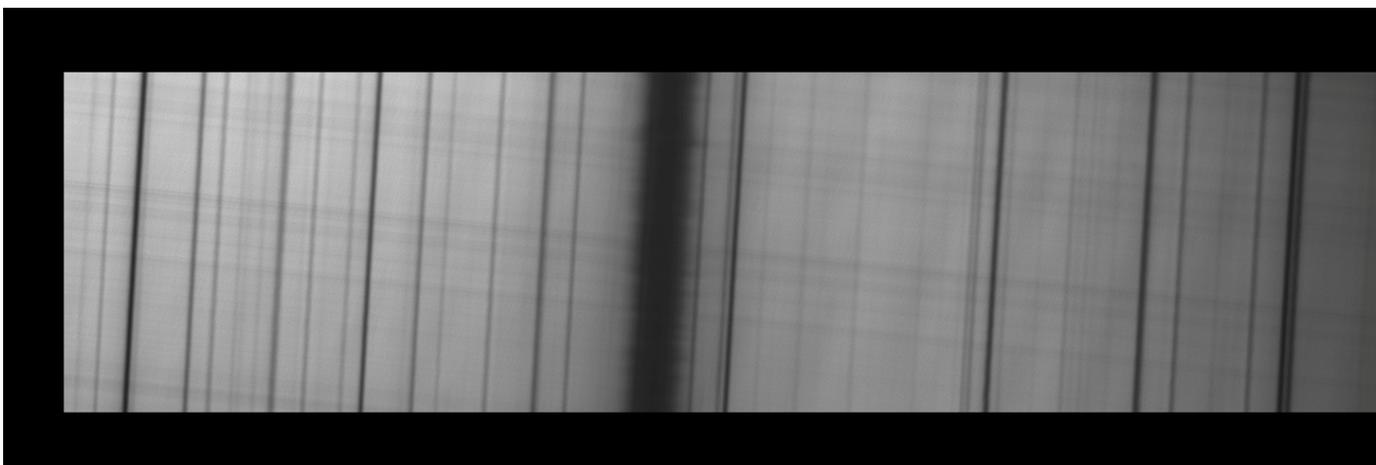
It may happen that the camera is not correctly oriented with respect to the spectrum and it doesn't appear straight on the monitor as in the figure that follows; do not worry, just turn the camera slightly to the left or right to straighten it up.



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, this 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, Vspec and SLiM, allow the correction of 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 SLiM.

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.

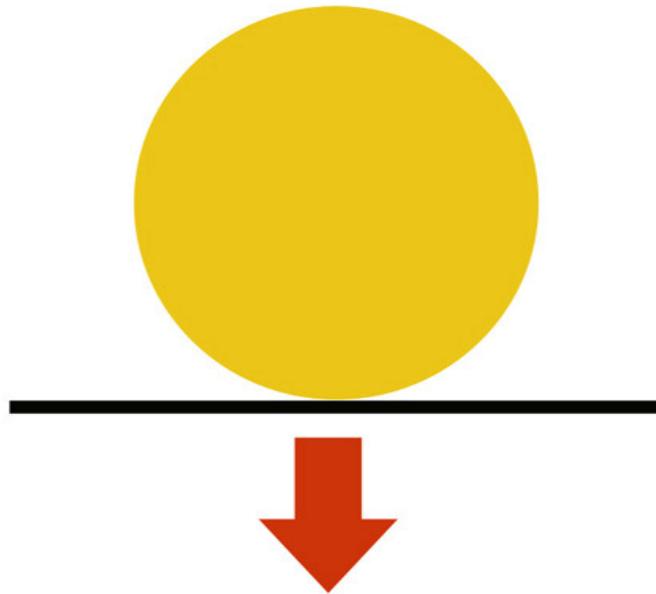


Immediately before the acquisition, the spectrum of the line (in these examples the $H\alpha$) after selecting the ROI, will appear roughly as shown:



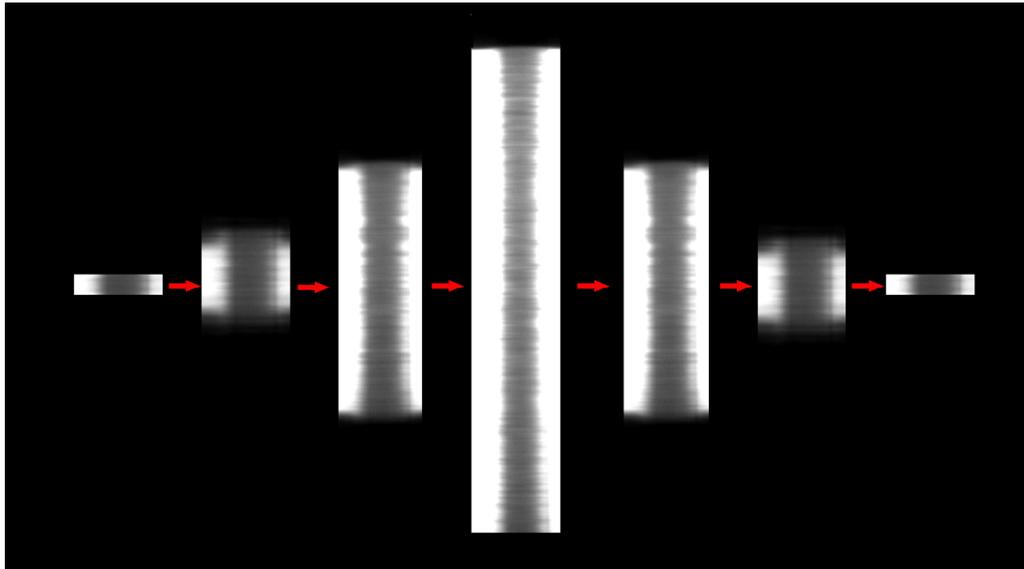
After having possibly corrected the anomalies of the spectrum, focused on the chromospheric details of the overexposed line, and selected the line with the ROI as shown in the image above, you'll bring the solar disk tangent to the upper edge of the slit using the fast motions of the mount and pressing the "W" (West) button of the hand controller (in the case of the FS2 controller this is the case but it should also be similar with other motor drives); the spectrum image will shrink and disappear from the PC screen. Then, you start 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 around the line, which greatly decreases the size of files to be downloaded; the frame rate will depend on the camera and the power of the PC. I normally use the DMK 41 with a frame rate of 7.5 or 15fps and with the DMK 51, 7.5 or

12fps, with good results. At the same time as starting the video you must stop the RA tracking motion of the equatorial mount, letting the solar disk slide slowly onto the slit, from east to west.



As this happens, you will observe that the spectrum grows, reaching the maximum size, then shrinks until it becomes a thin line disappearing from the screen. At that point, after another 3-4sec you can stop the video and eventually turn on again the tracking motor 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.

The image that follows is an example of how the selected line appears (in this 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 120sec (plus a few additional seconds for the black part of the image), and the image size will depend, as we said, on the frame rate used.

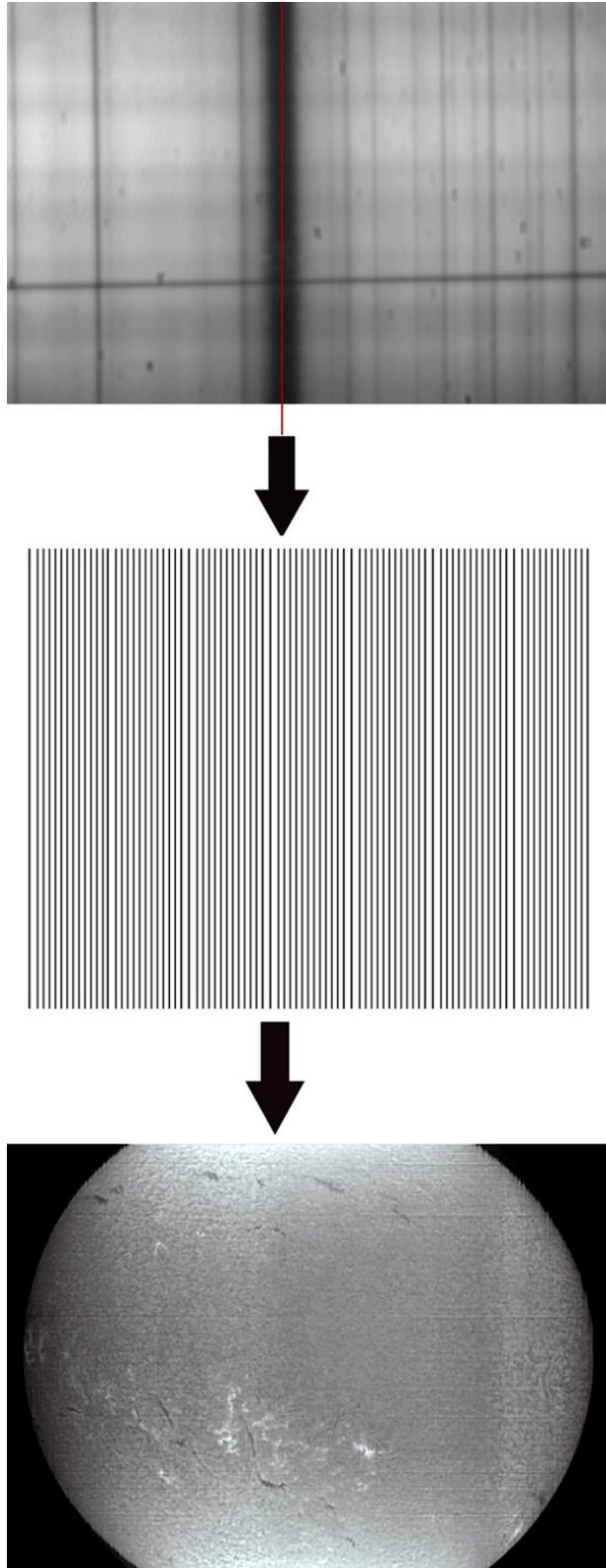
Digitization and image construction starting from the spectrum

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 SHG. In practice, once you have chosen the pixel column corresponding to a point of the spectrum, usually the center or the edges of the line of interest, all the different processing 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 there are 1200 total frames of the video obtained with the scan, we will have an image 1200 pixels wide on the X axis and as many pixels as those native to the camera chip on the Y axis.

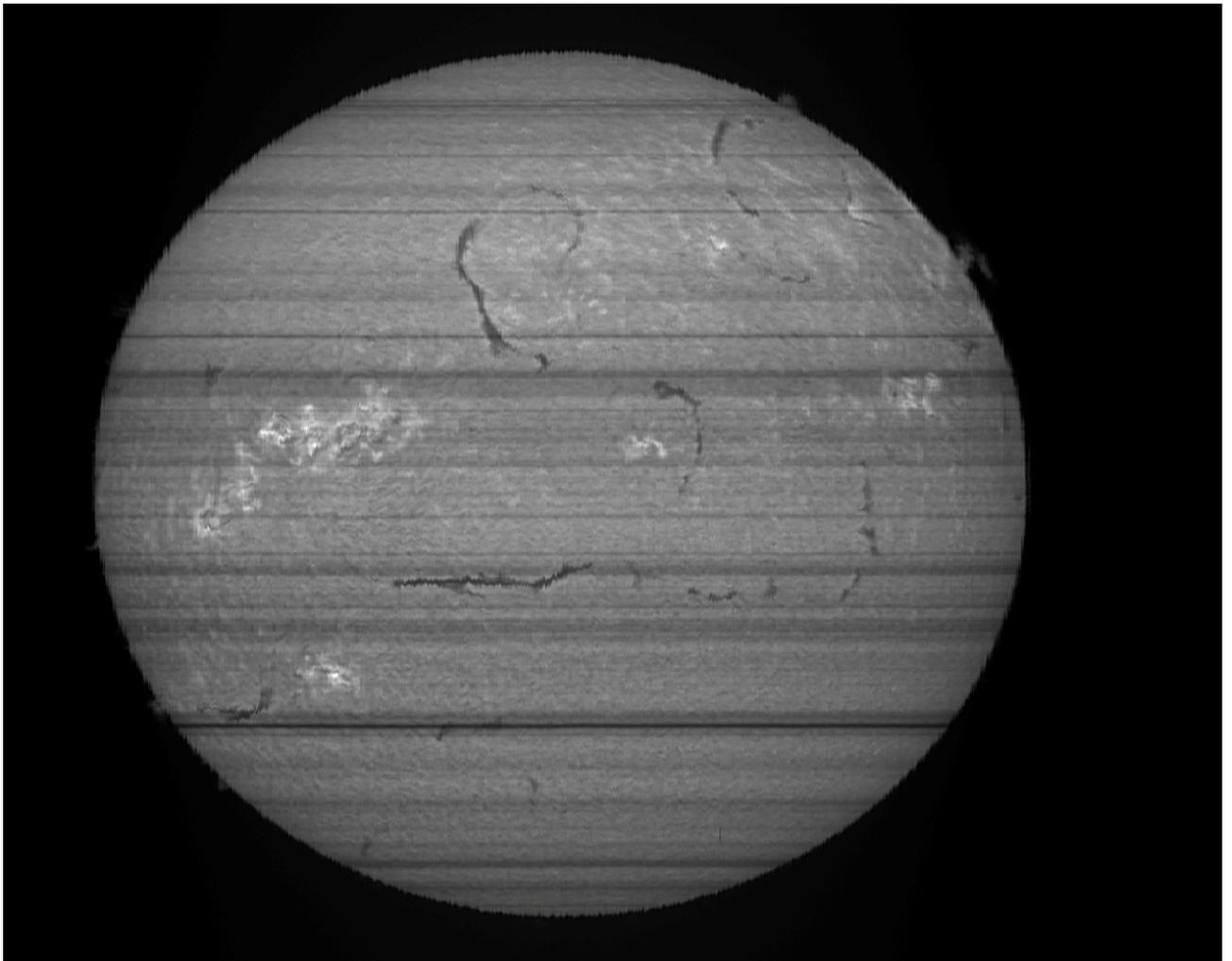
This procedure therefore replicates the conventional type SHG, allowing us to associate each pixel of the image of the spectrum along the X axis to a given wavelength of very small dimensions (with VHIRSS and a DMK camera with pixels of 4.65 microns, it is equal to about 0.029\AA in violet and 0.019\AA in deep red) in the corresponding solar image. While the format of the Y axis of the image is that native of the camera used, that along the X axis is given from the frame rate chosen and the duration of the scan. If, for example, the native image format is 960×1280 pixels, the images that will be obtained will have a resolution of $960 \times (T_0 \times \text{fps})$ where T_0 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 $T_0 = 160$ sec and $\text{fps} = 7.5$, the image format of the X axis will be $160 \times 7.5 = 1200$ pixel. We will have therefore, in the

example a solar image of 960 x 1200 pixel. This last consideration leads us to reflect on the importance of the camera used, 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 slit gap, which, as we said, decisively influences the resolution of the spectrum and therefore the quality of the solar image. If you close the slit to the minimum possible gap 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 more sophisticated solution, but not too difficult to achieve, is that of modifying the slits mentioned previously by working their blades, 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 the digital SHG, as it is able to supply the final image of the solar disk in the line of interest, according to the methods described above.

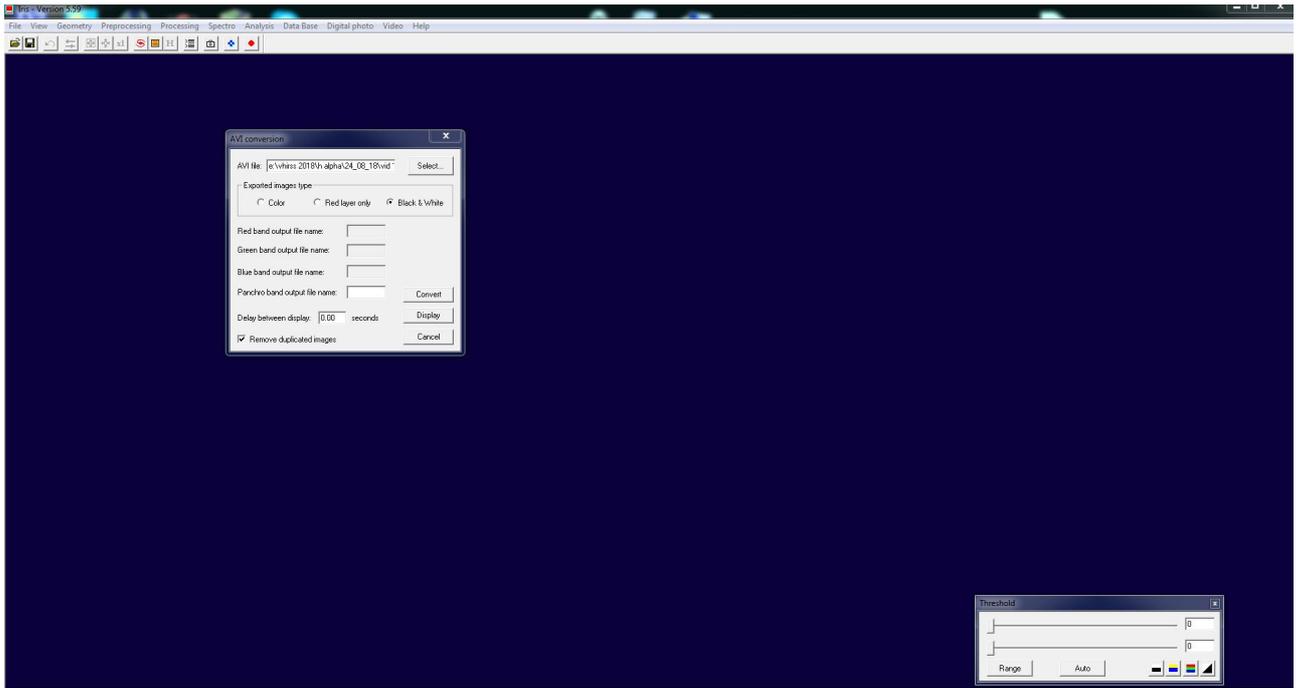
1 - SpecHelio Bas

The French amateur astronomer Daniel Deforneau was the first to have the idea of introducing, with a SHG based on a traditional spectroscope, a digital camera to allow amateur spectroheliography. His ability also extended to the computer software required, 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.

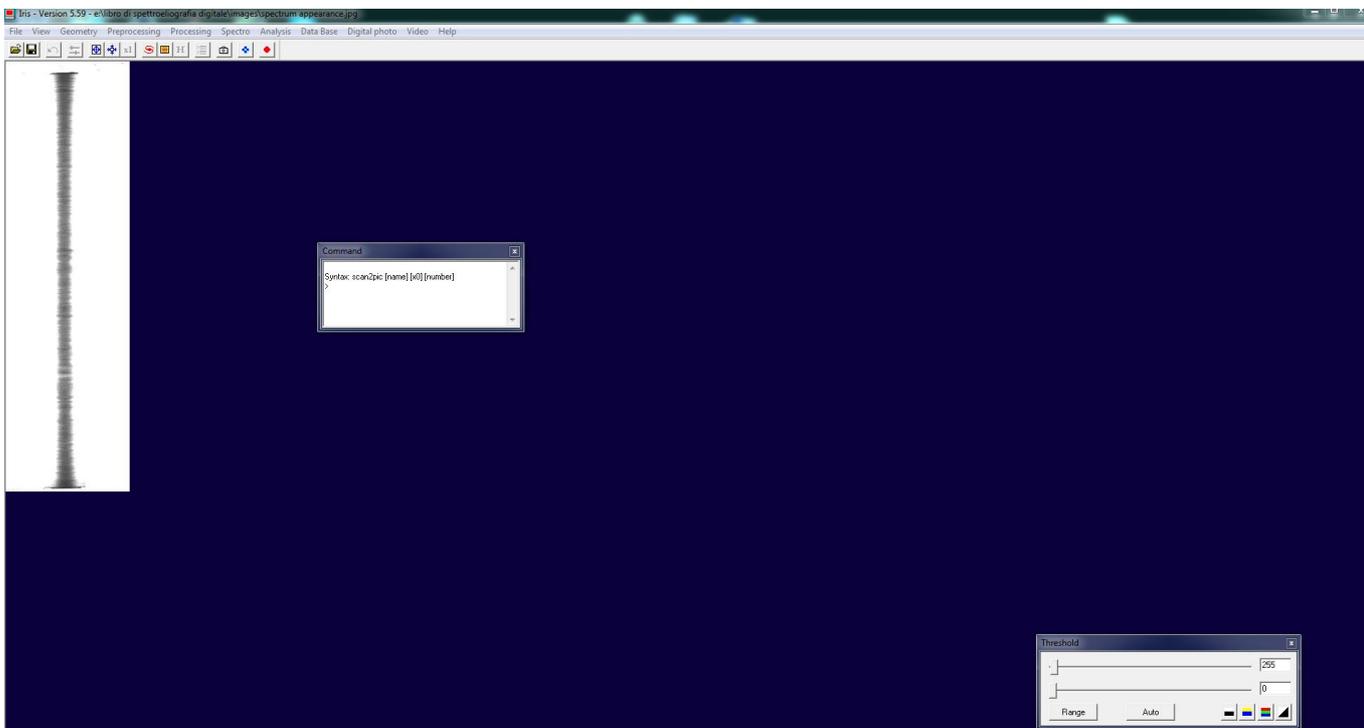
<http://astrosurf.com/cieldelabrie/sphelio/program/>

2 - IRIS

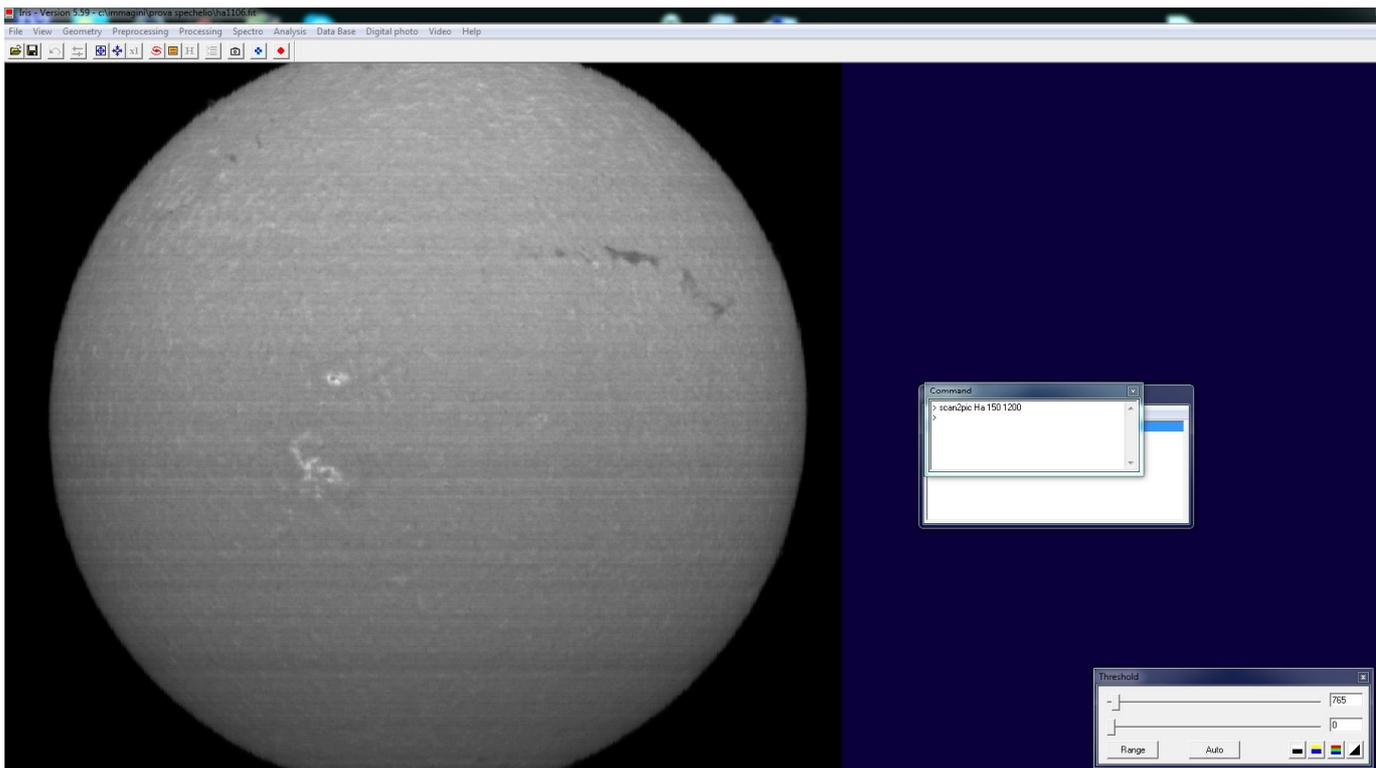
The famous and very popular C.Buil program allows, with some routines and specific commands, the conversion of AVI files into monochromatic fits. It is advisable to convert it into an ad hoc folder on disk C (e.g. C/SpecHelio) selecting it as the working directory and moving the AVI file into it.



The Fits files obtained from the conversion generally correspond to the number of frames generated by the video, except for any lost during acquisition. Assuming that there are 1200 files, 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. 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 column 150 for all the 1200 Fits files, obtaining the mosaic of the final image corresponding to the selected pixel column.



This command does not seem to like long file names, so it is advisable to use a short name working directory (e.g. 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 – SLiM (**S**pectral **L**ine **M**erge)

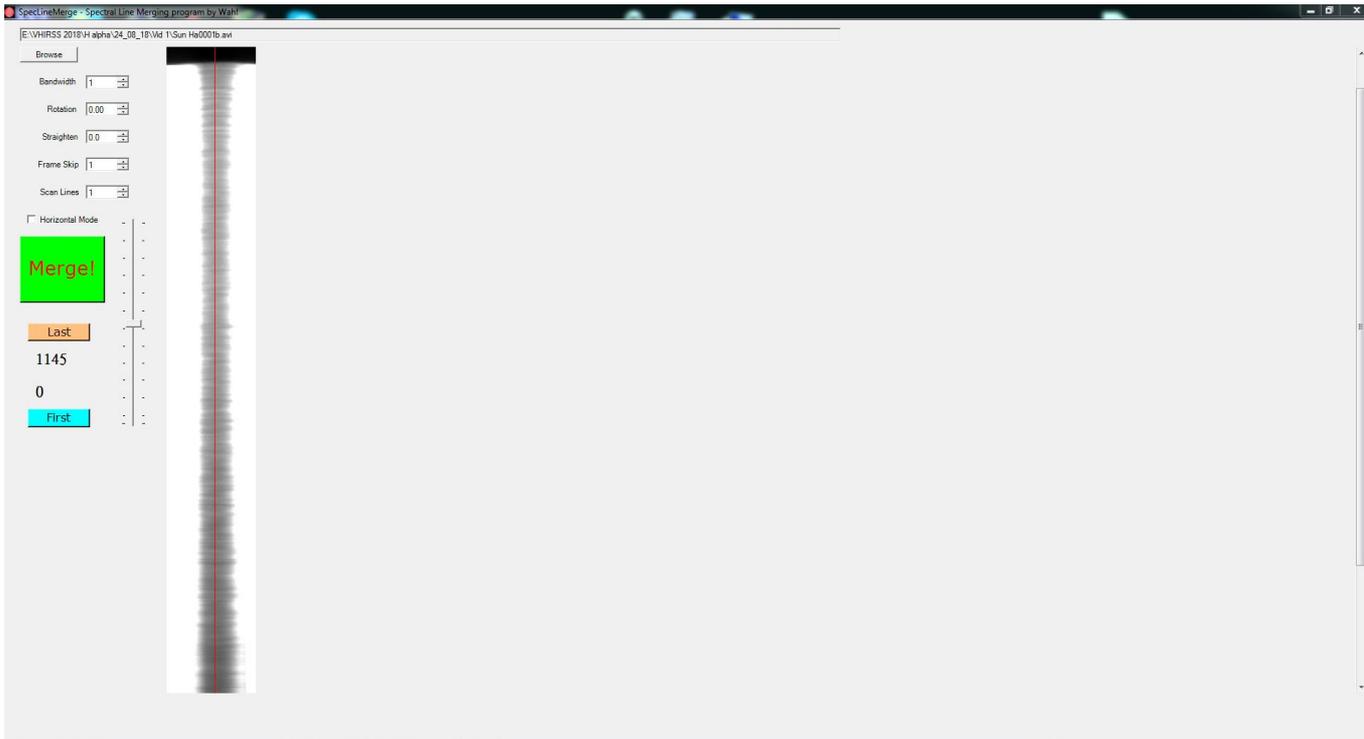
The Chinese amateur astronomer Wah-Heung Yuen has created a specific program for digital spectroheliography which handles AVI and SER files. It has many interesting features, despite its extremely simple and "user friendly" interface.

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

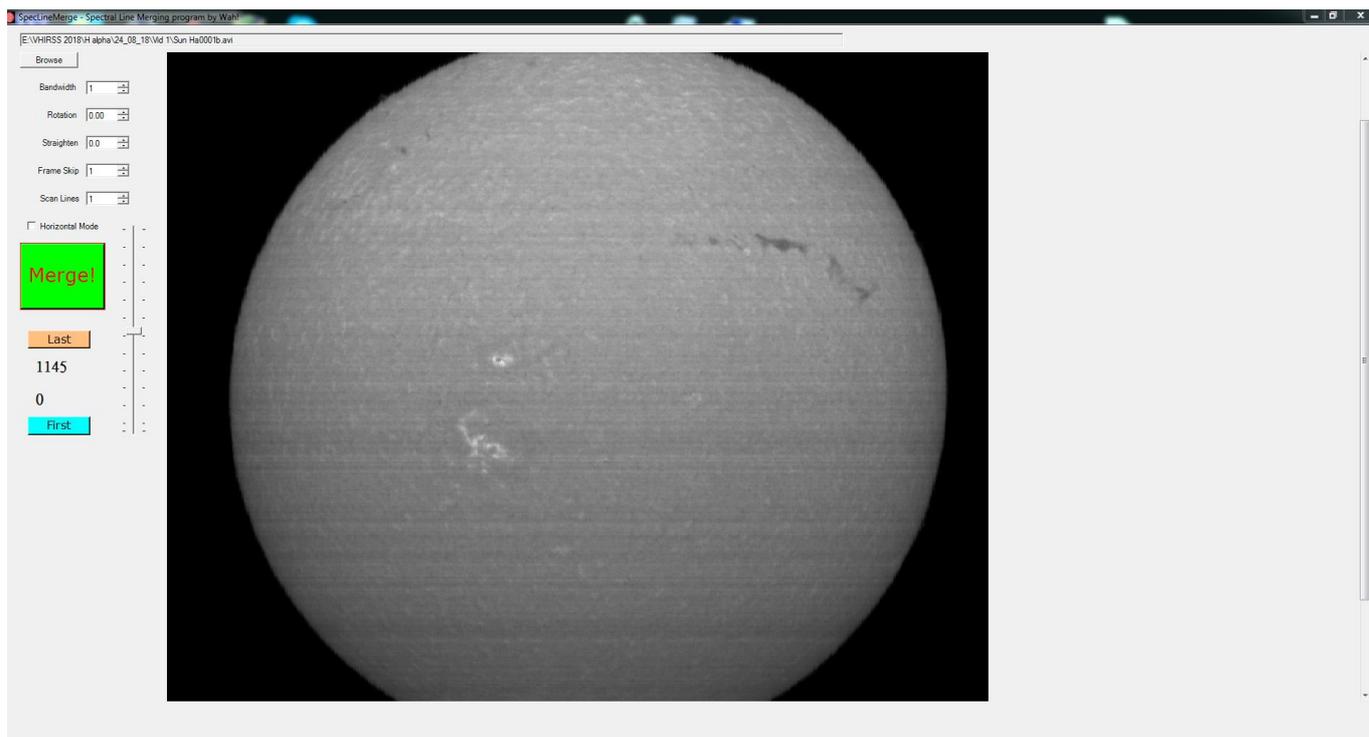
The latest version can be downloaded from the Solarchat forum:

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

However, the program requires a pre-processing of AVI files (cropping). This can be achieved by choosing a suitable ROI during acquisition or using the well-known freeware program Virtual Dub (VB). In practice, you need to load the file into VD and 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 SLiM.



The SLiM 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 (see figure below). However, unlike IRIS, the software can select a band wider than a single pixel, i.e. the conversion of several pixels contiguous to that chosen to obtaining a series of images with benefits in the final sampling. The program also allows the rotation of the line and the possible correction for smile (curvature).



SLiM is therefore a simple and complete software, with a minimal 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, which is 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, to which I have also collaborated, for the extraction and treatment of spectroheliography images. The program is currently at version 1.9.9 beta. For download go to:

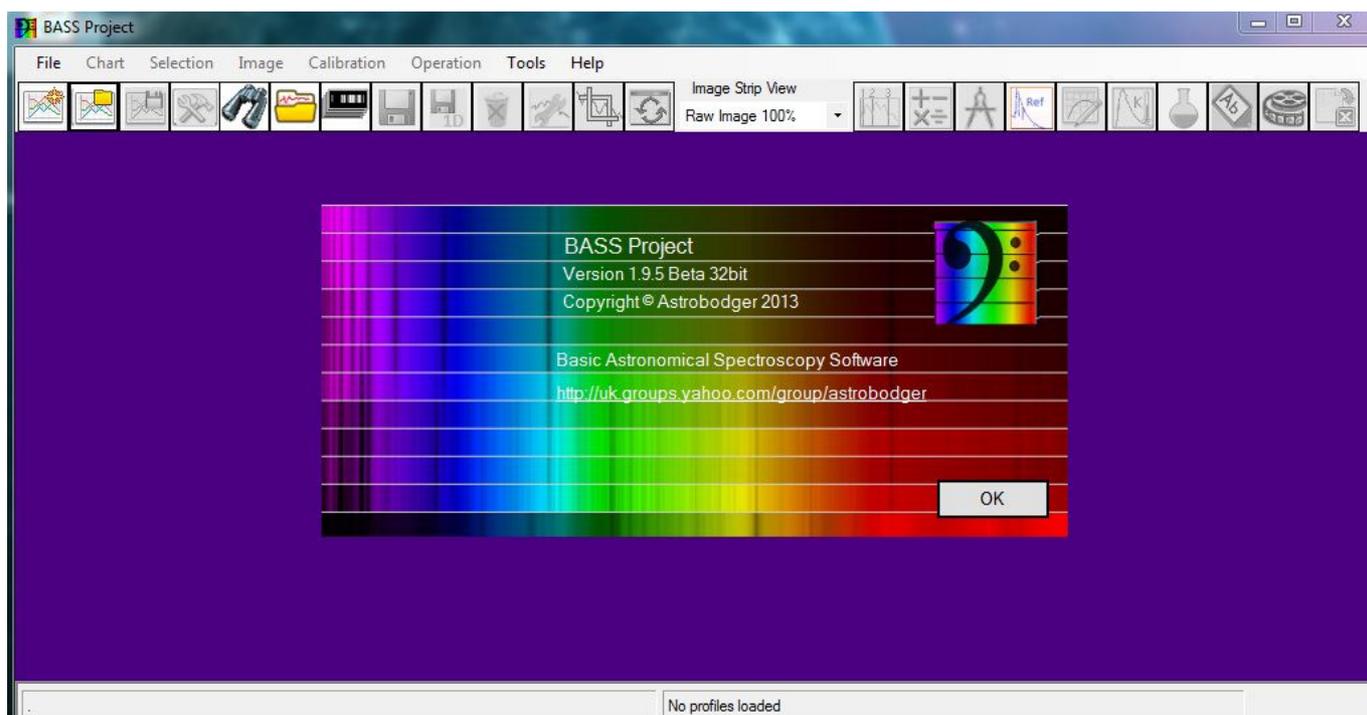
<https://groups.io/g/BassSpectro/wiki/13559>

(32 bit)

<https://www.dropbox.com/s/onvoy3mw3pu9l2h/BASSProject199b3.exe?dl=0>

(64 bit)

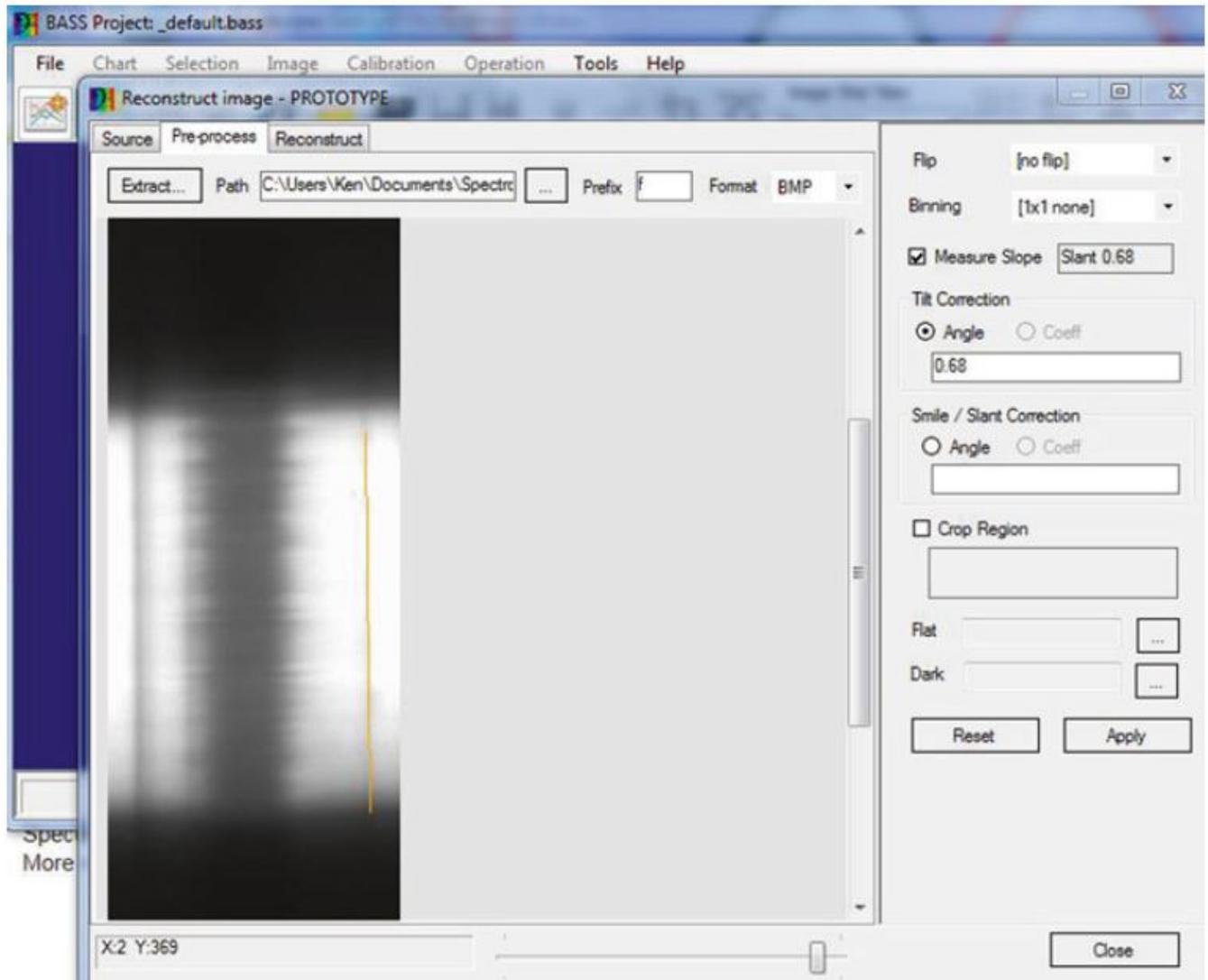
<https://www.dropbox.com/s/zc3y89mmq6qmk8k/BASSProject199b3-64.exe?dl=0>



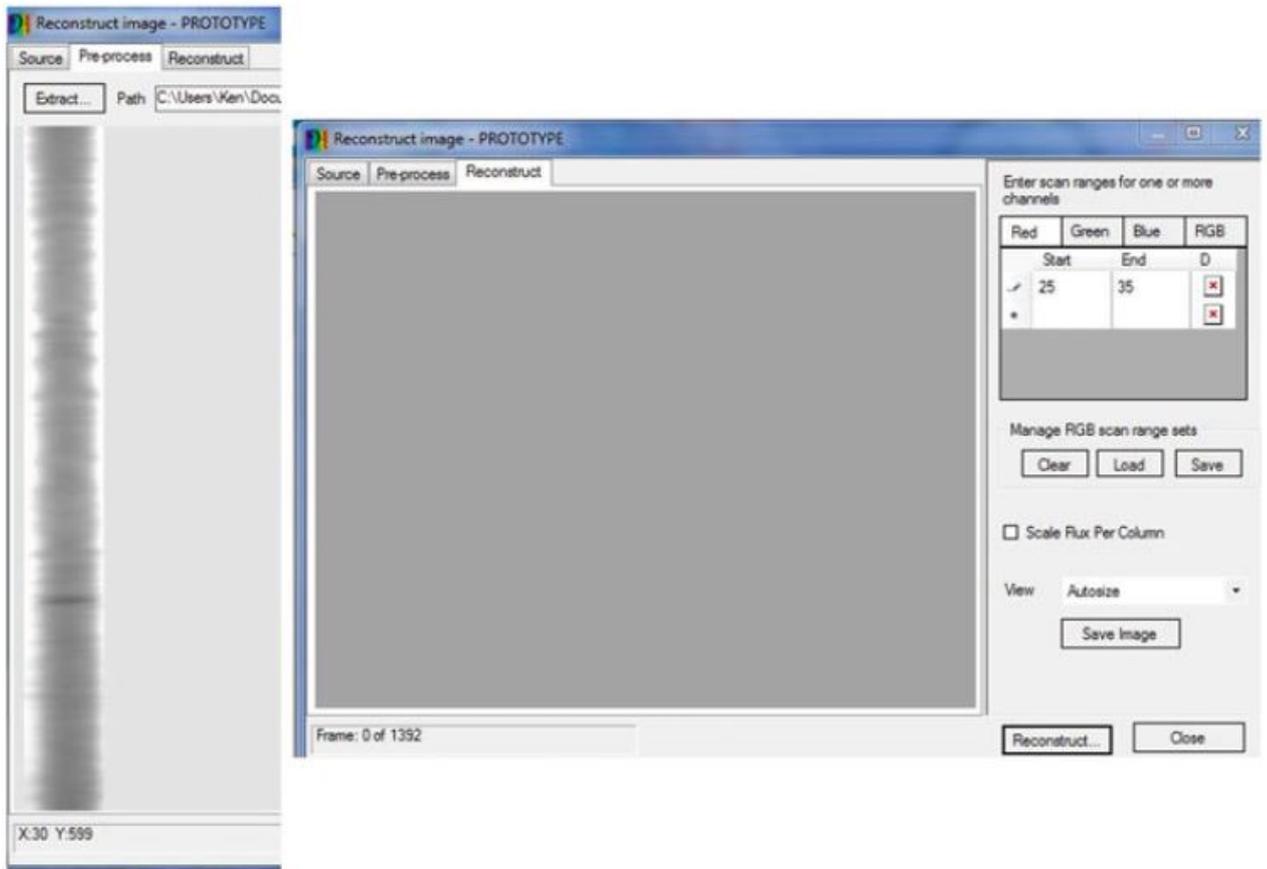
The operating procedure is as follows:

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

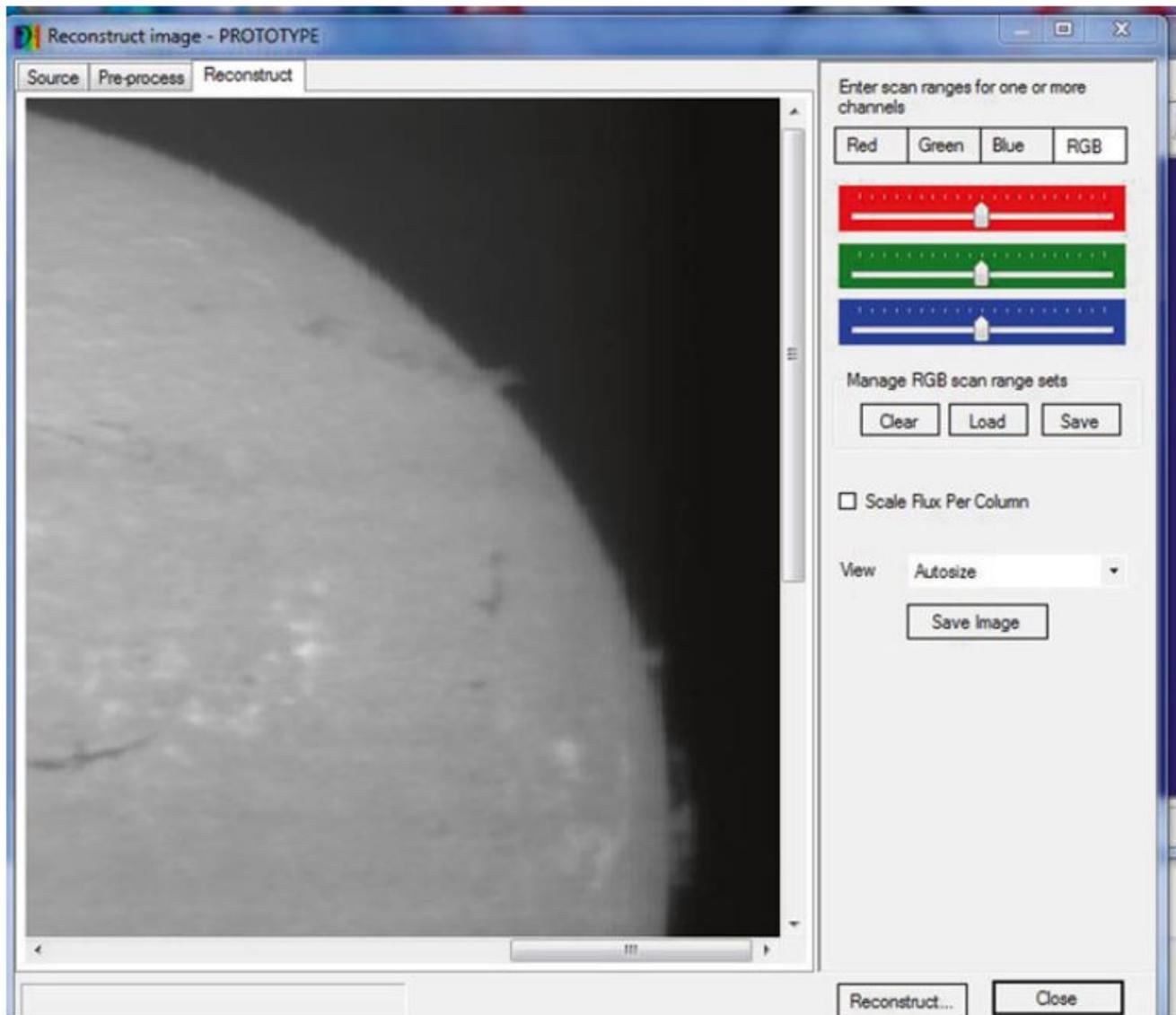
Using the slider, load a frame in which you can clearly see the line in absorption of interest, and use the slider to go to a frame that shows visible the transversalium (to correct the tilt), and another line near the one of interest to correct the slant if necessary, then press the "Apply" button. 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 (e.g. 30).



Then go to the "Reconstruct" menu (see 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 column in the reconstruction, while writing 25-35 will use 10 pixels and the final image will be better sampled.

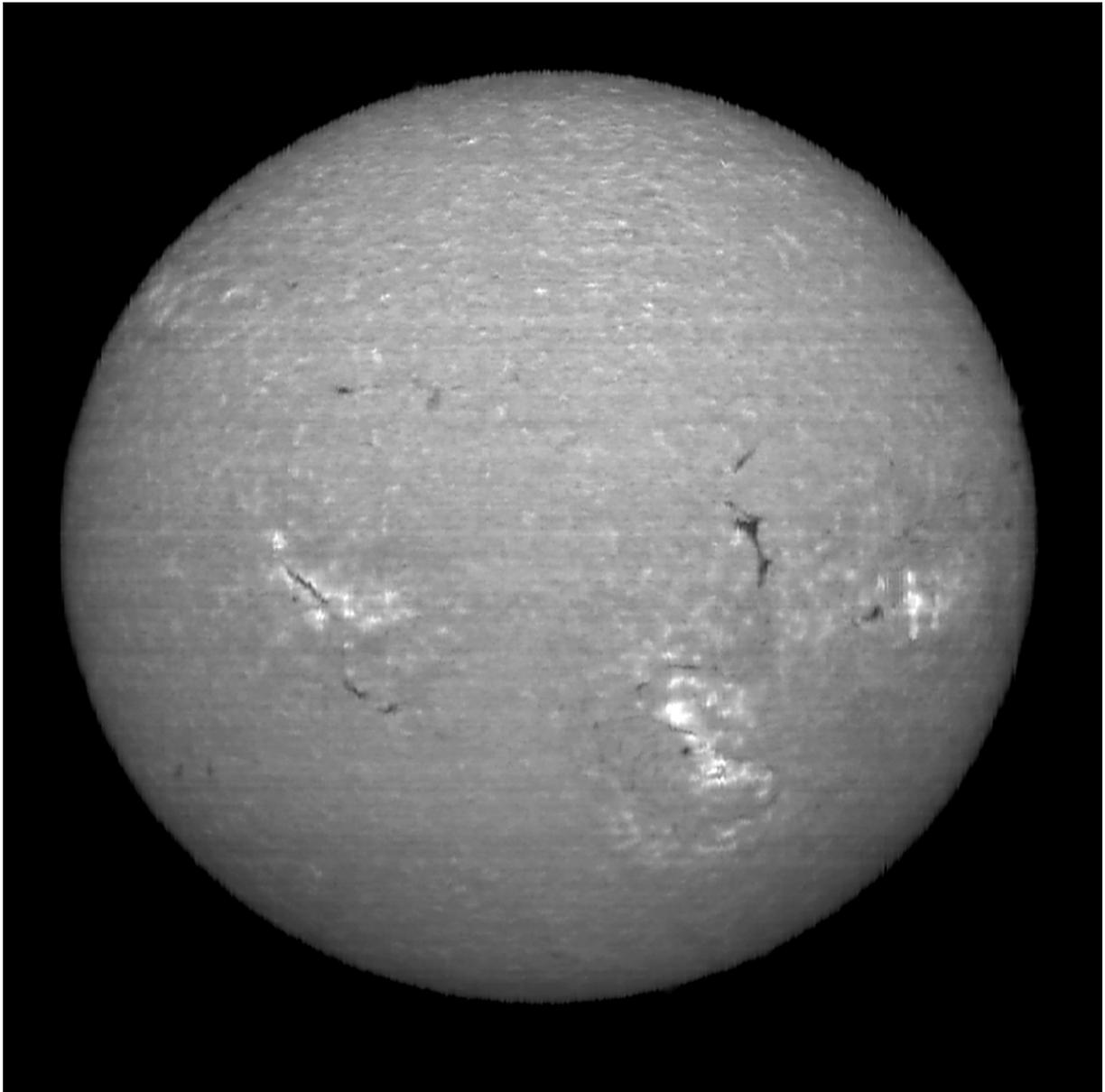


I must say that the functionality of the routine, at first glance a bit complex, is very good and produces good images: the only flaw is, in my opinion, the processing time in a medium power computer maybe a little long, superior to those of IRIS (which nevertheless allows the reconstruction on a single pixel) and, even more so, of SLiM 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 H α image obtained by the author 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 it constitutes an excellent and complete spectroscopy software, which the author often uses in addition to Visual Spec for the treatment and processing of stellar and deep sky spectra.



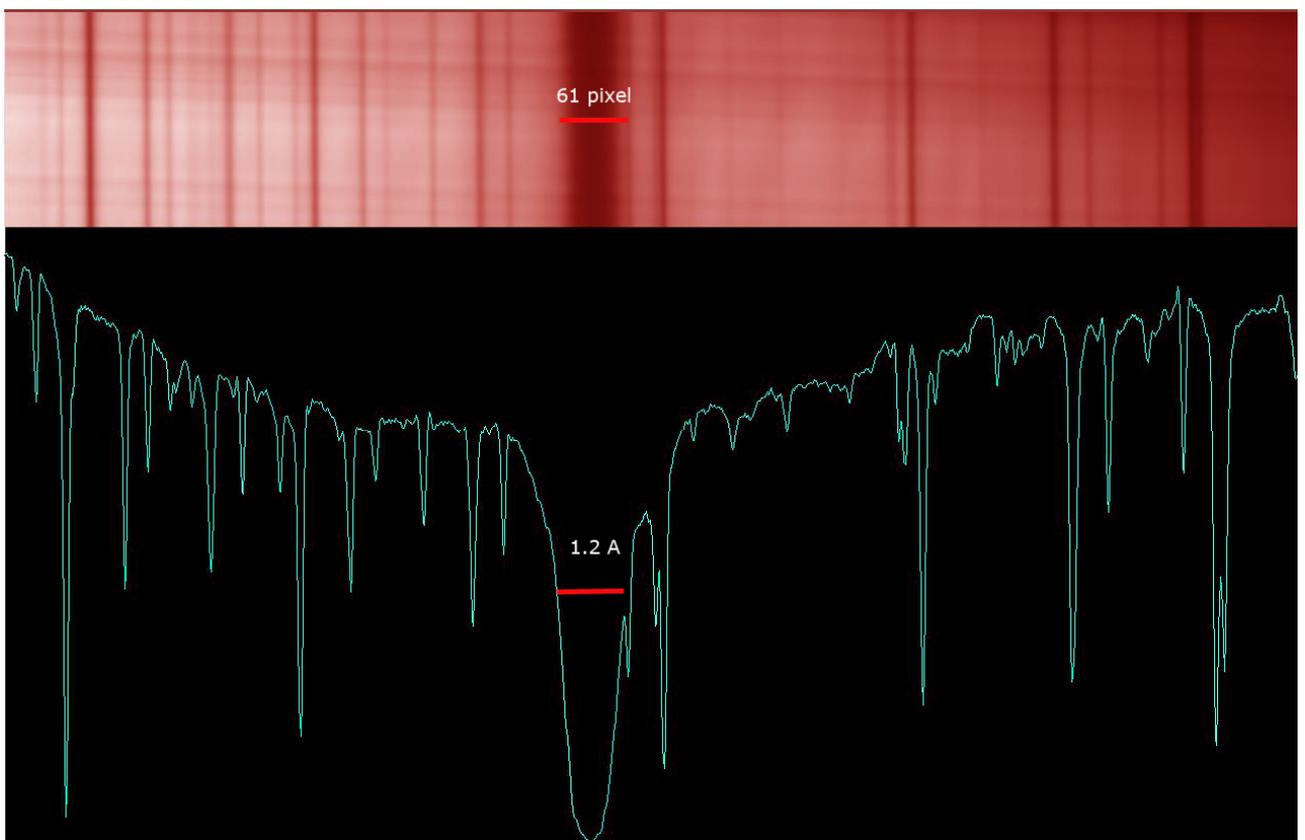
Results obtained in digital spectroheliography with a Littrow SHG

Let us now examine some results obtainable in full-disk solar imaging with a DIY Littrow-type SHG 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 ask is of the type: "but what can a SHG really be used for, given that the images in H α and CaII K light of the commercial filters are very beautiful and detailed, and aesthetically superior to those of the SHG? ".

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

SHGs such as VHIRRS or Solarscan reach without any problem on average a resolution somewhere between 0.03 and 0.019 \AA /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 the resolution of image equals the dispersion of the spectroscop. In practice therefore, hypothesizing the average resolution of 0.025 \AA , this is 40 times that of a 1 \AA filter and 20 times one of 0.5 \AA . But the thing does not end there: the very high level of dispersion per pixel causes the H α line, e.g. at 0.0195 \AA / pixel appears 61 pixels wide on the screen of a PC, as shown in the figure, with a bandwidth well 51 times narrower than a 1 \AA filter and with a resolution level of final image 51 times higher!



This has the important consequence that it is therefore possible to position the one pixel image acquisition column at 30 pixels from the center of the

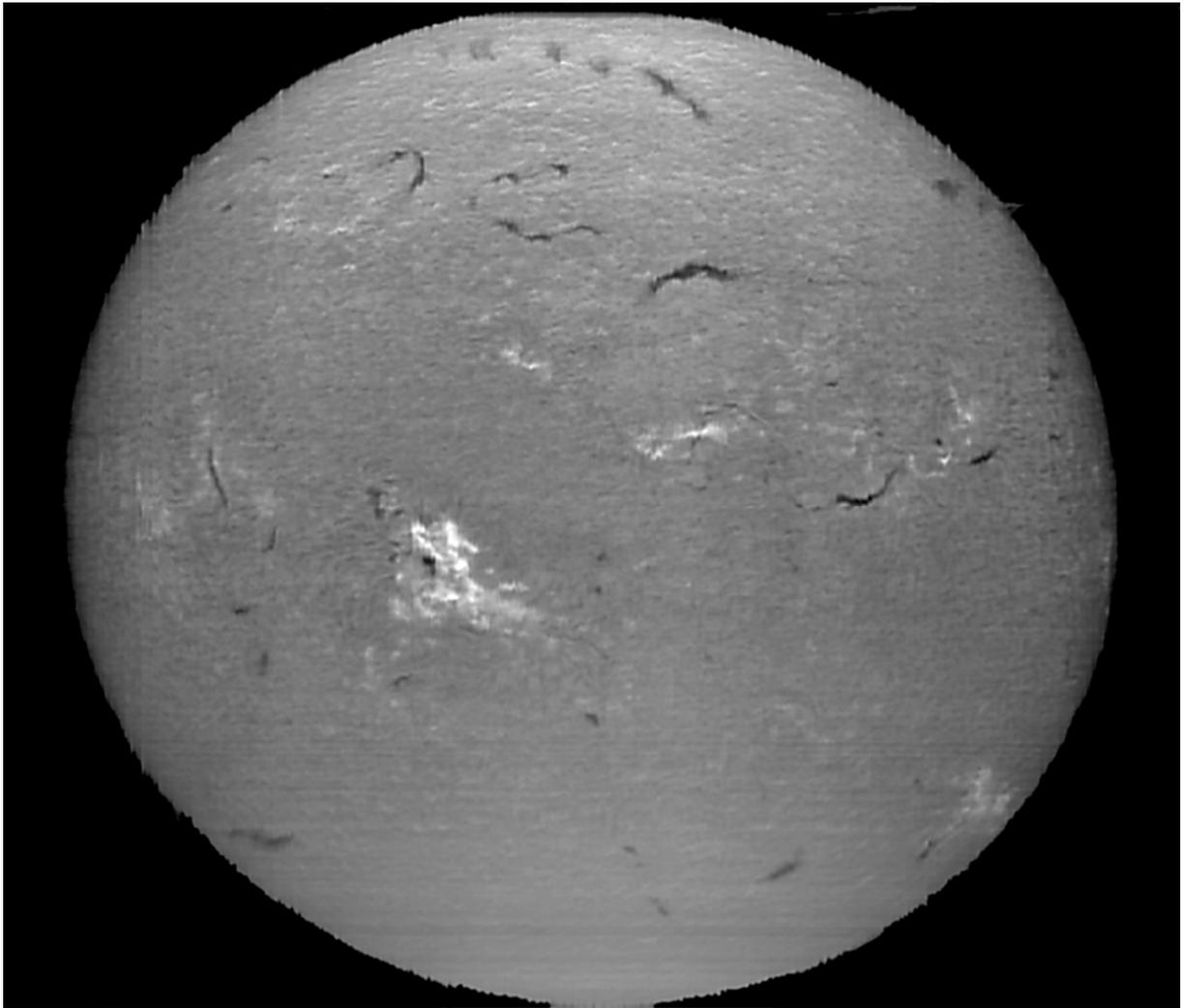
very center of the line, thus obtaining as many as 61 images of the H α line from the center to the wings. One in the center, 30 towards the blue and 30 towards the red. Similarly for the CaII K, CaII H lines and so on. This allows us to go from the lower chromosphere, at the borders of the photosphere, up to the highest part of it, thus operating a real tomography of the chromosphere, which is impossible with commercial filters.

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

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

H α 6562.8Å

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 number of visible details.

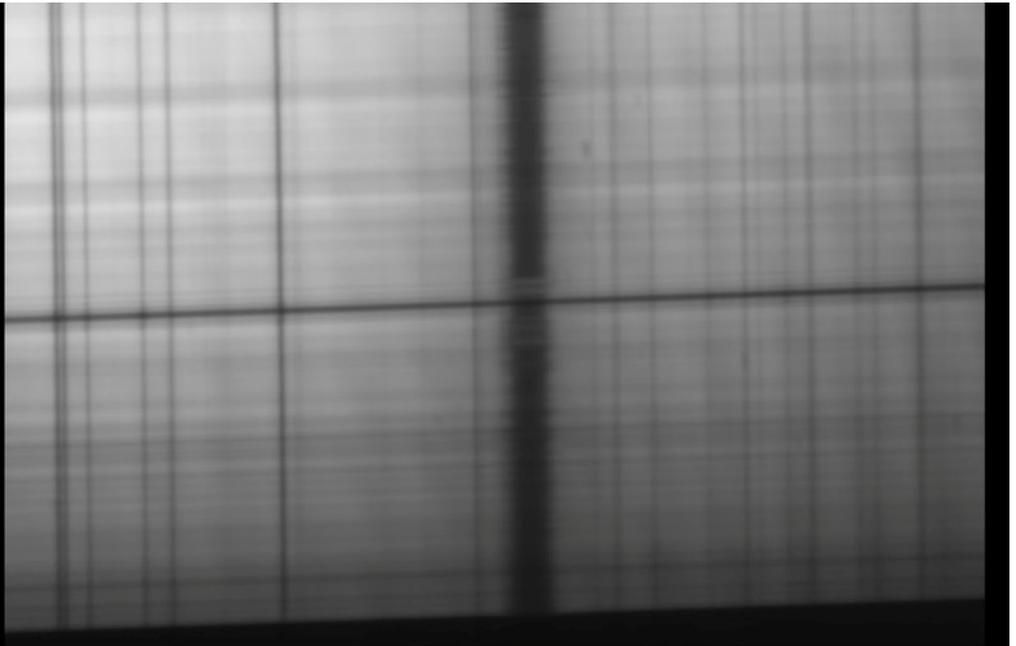


This image can be considered an example of the difference between spectroheliograms and traditional amateur H α imaging. The detail visible in the spectroheliograms are clearly higher than those of the H α filter, where the image quality is lower.

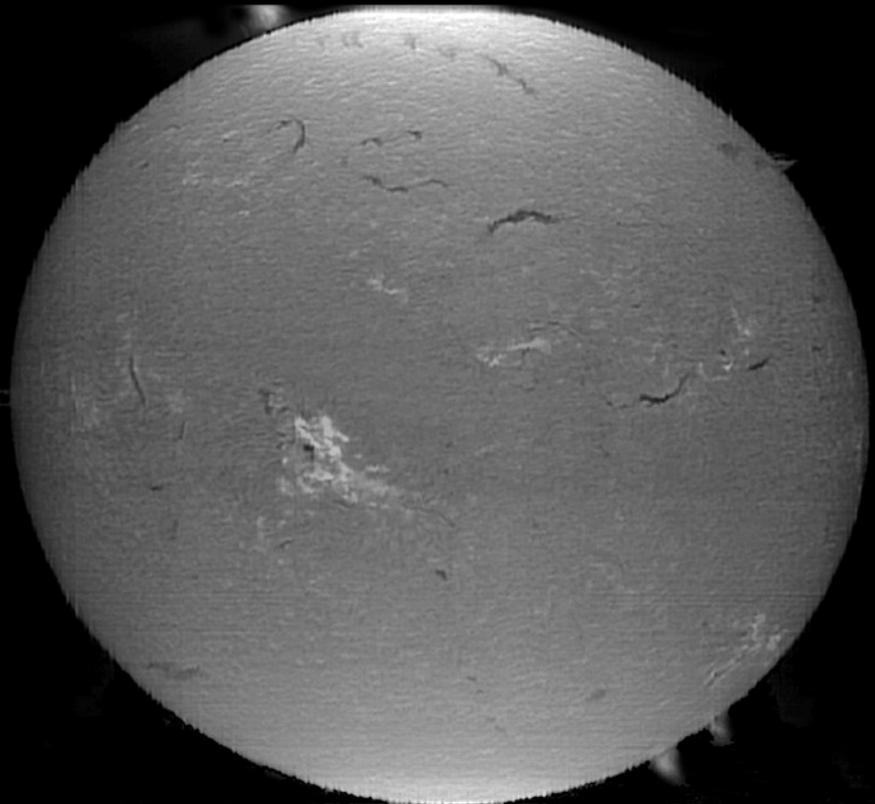
This implies that from a purely aesthetic point of view, imaging with narrow band solar filters is a winner, while from the scientific point of view the spectroheliogram is superior.

Below the same image with better observable prominences.

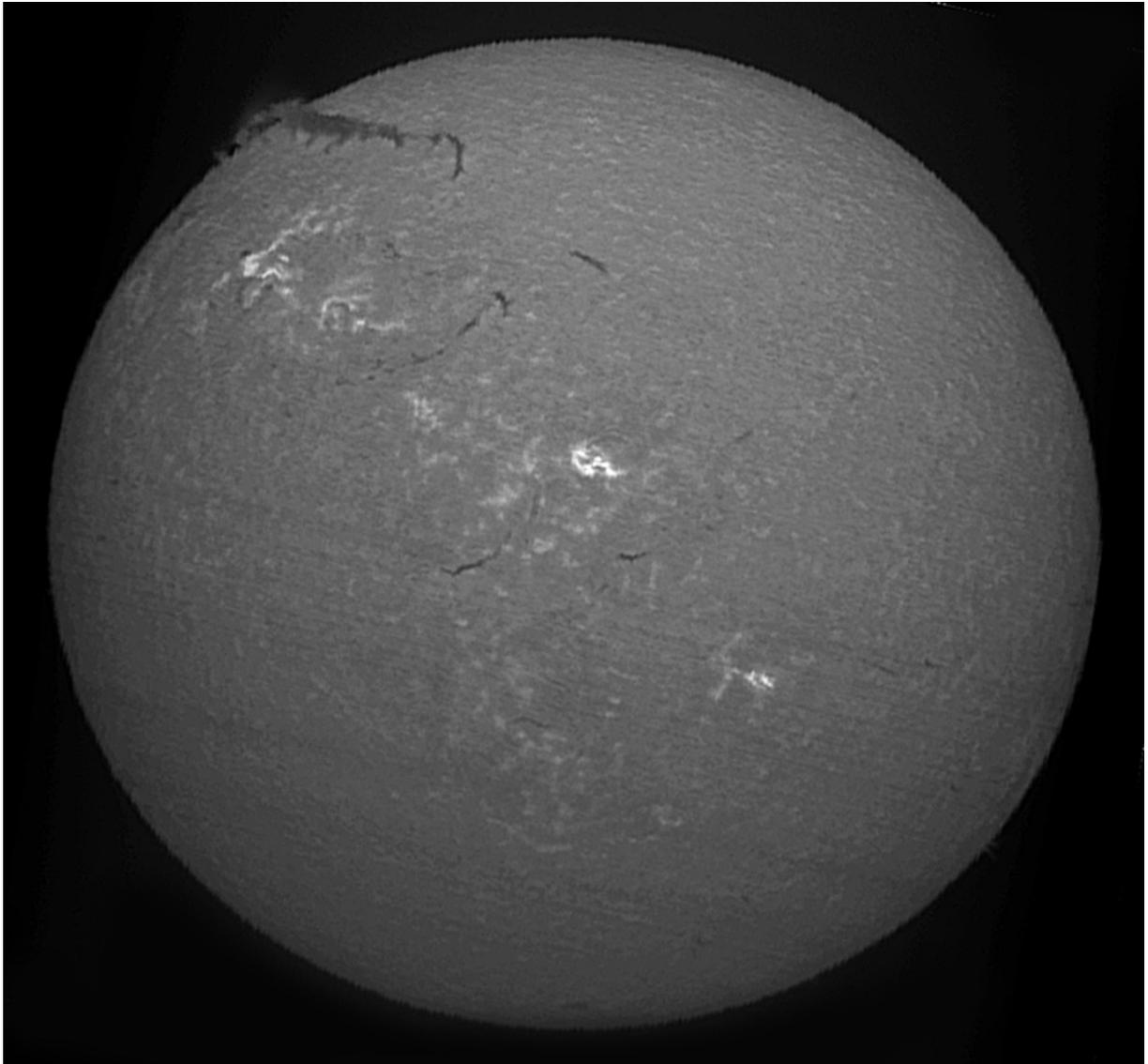
AR 1476 →



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

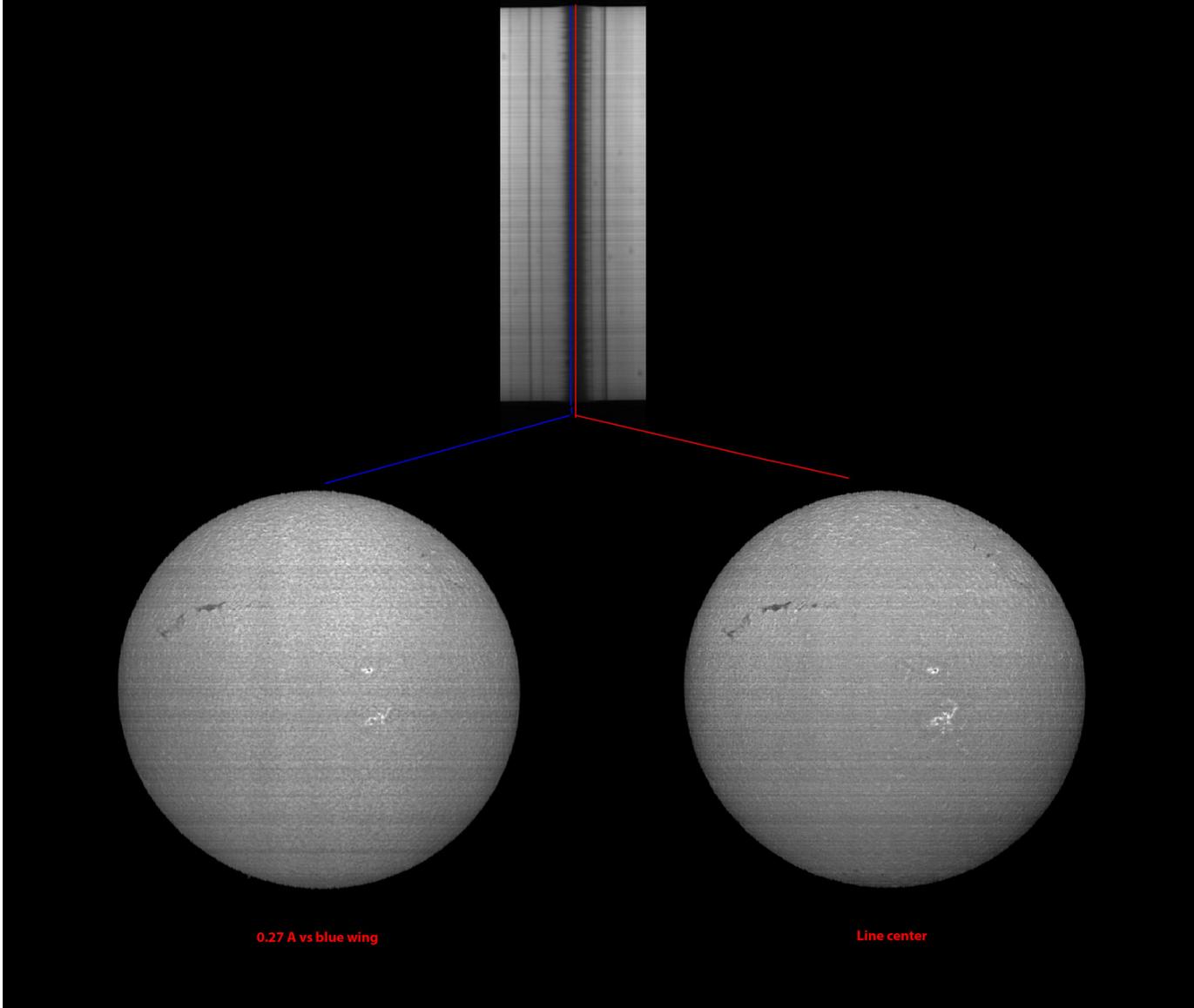


Below, a characteristic image of the sun with a gigantic prominence that extends from the disk, where is visible as a filament at the edge (filaprom), vaguely resembling a centipede.

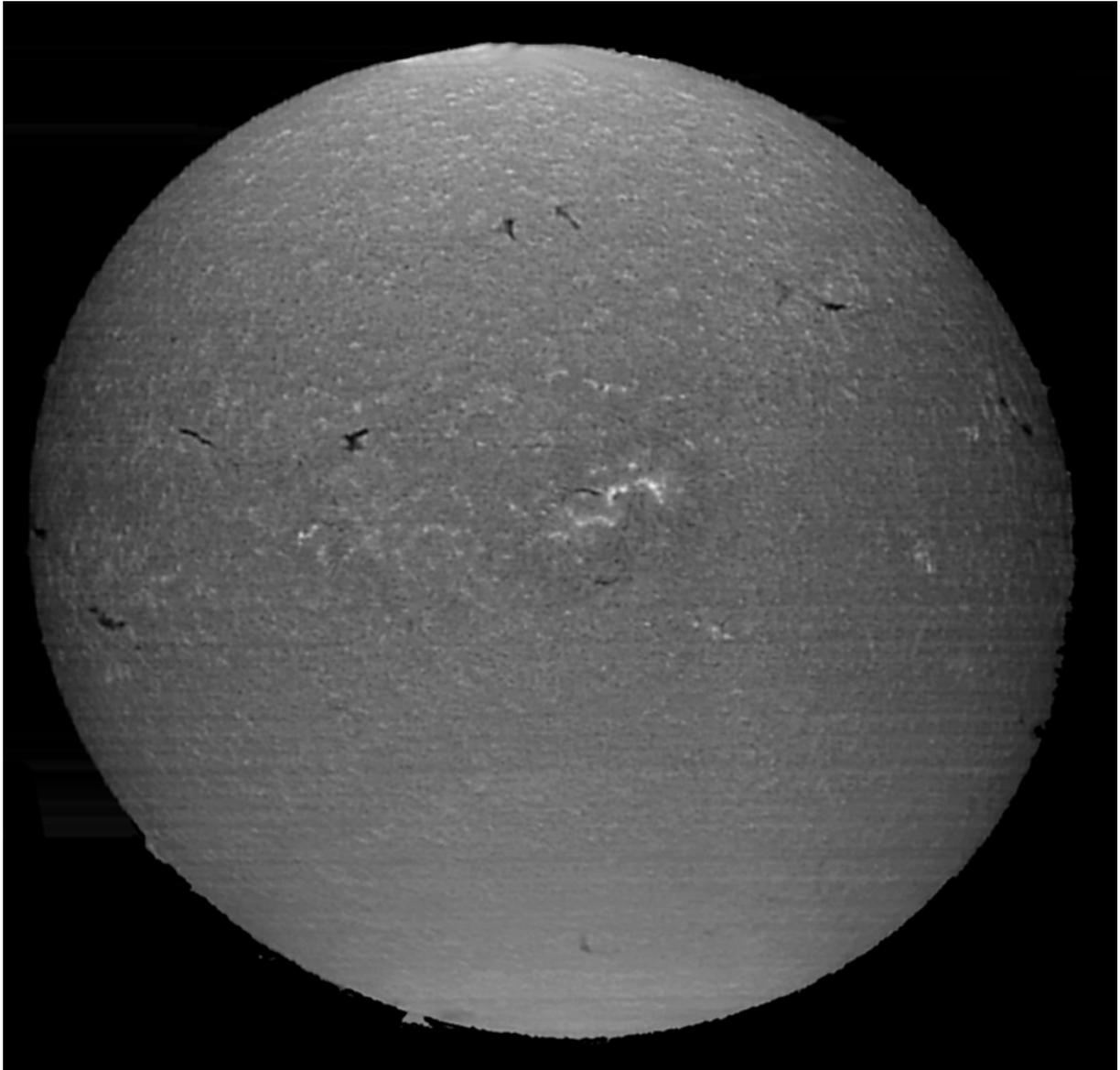


The image below shows the change in the appearance of the solar disk in $H\alpha$ light with spectroheliograms taken in the blue wing (6562.53 \AA) just 0.27 \AA away from the center of the line, and another in the very center of the line (6562.80 \AA). The difference is only about a quarter of \AA , but it is already enough to see the changes in the visibility of the chromospheric details passing from the wing to the center of the line. This shows the changes going from the continuum towards the wings and then towards the center line. We pass from the borders of the photosphere and the low chromosphere and then into the high chromosphere.

Sun Image in H α 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

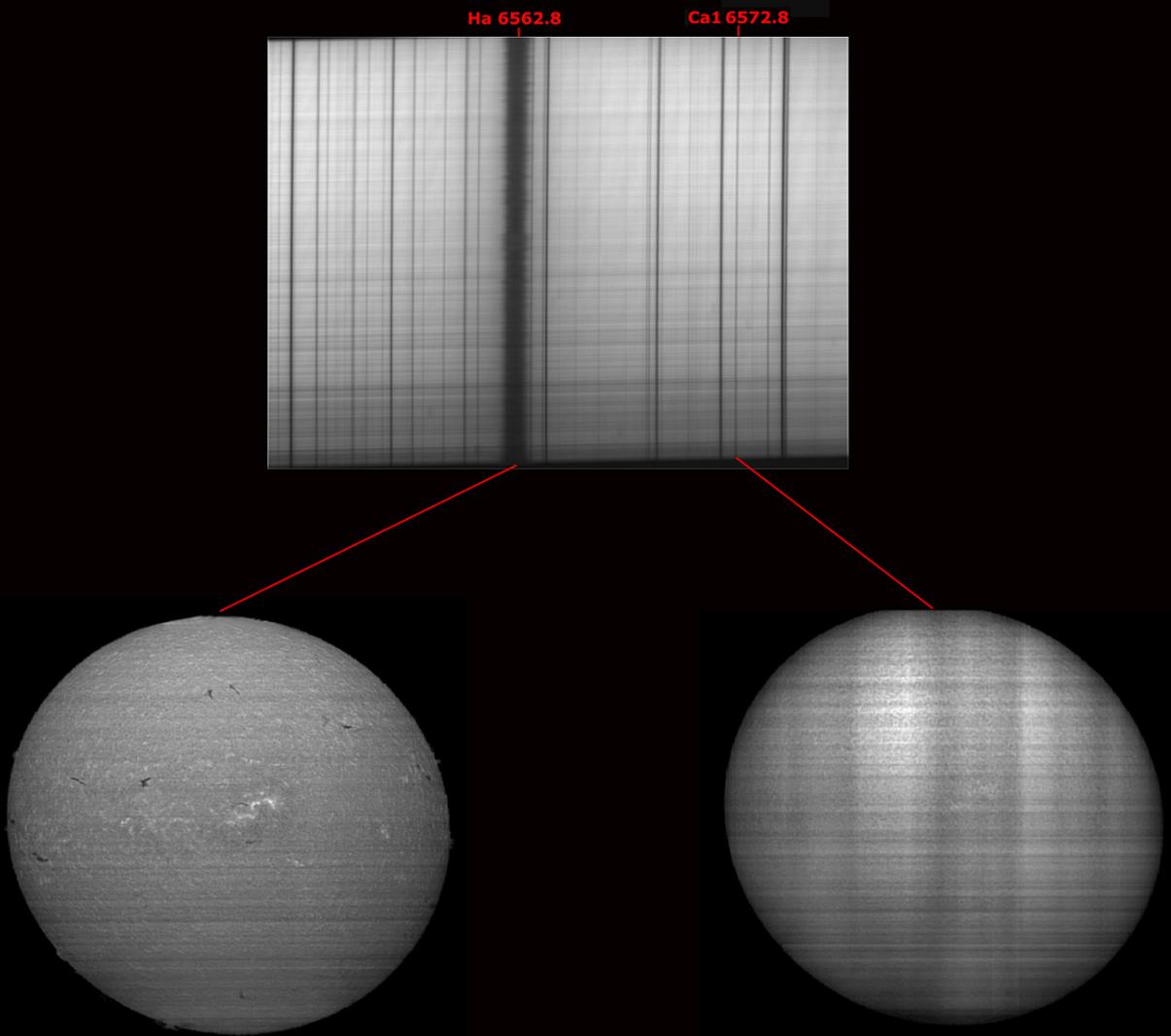


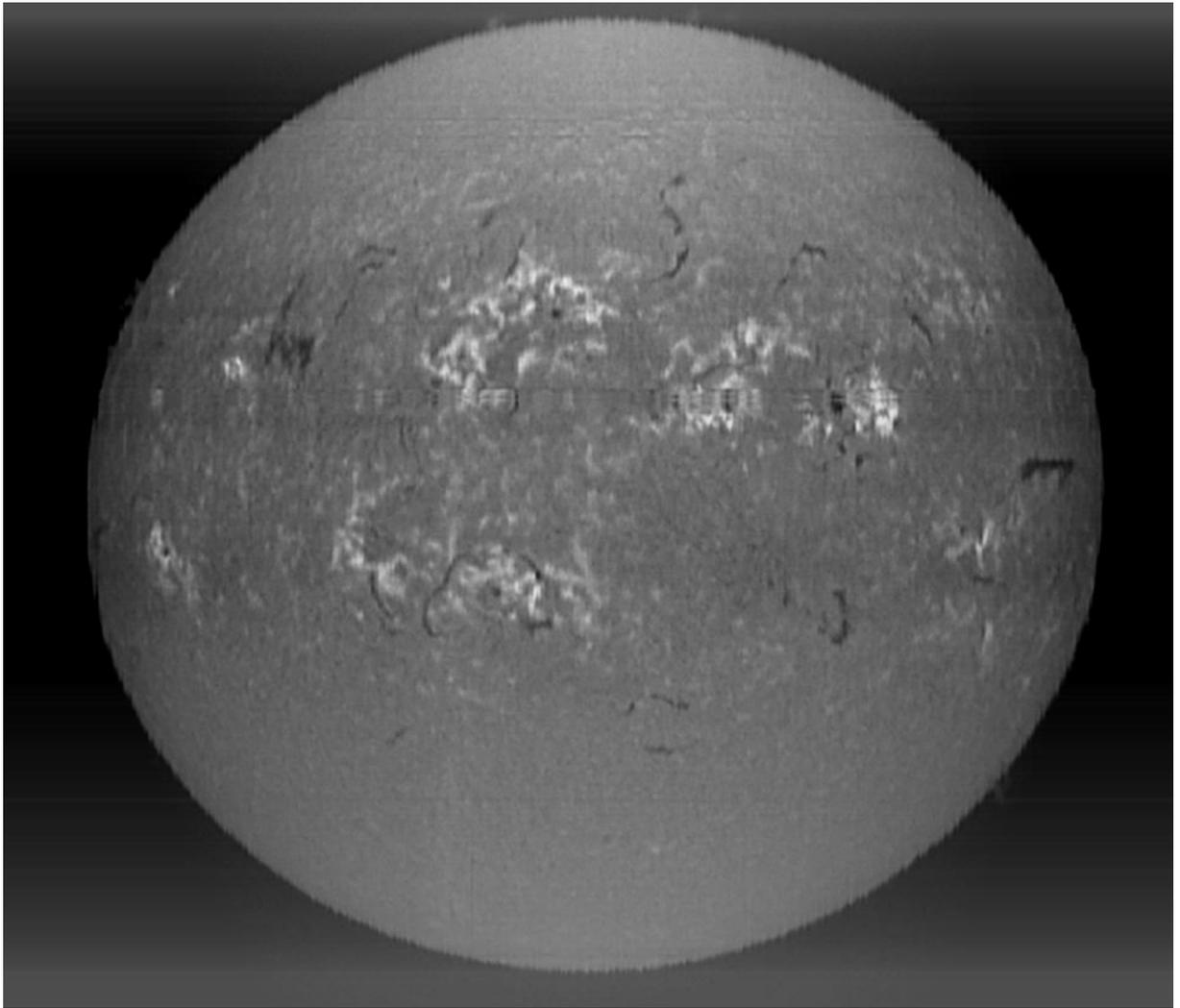
Another H α image by VHIRSS from August 21, 2016, to which a synthetic flat was applied to eliminate transversalism.



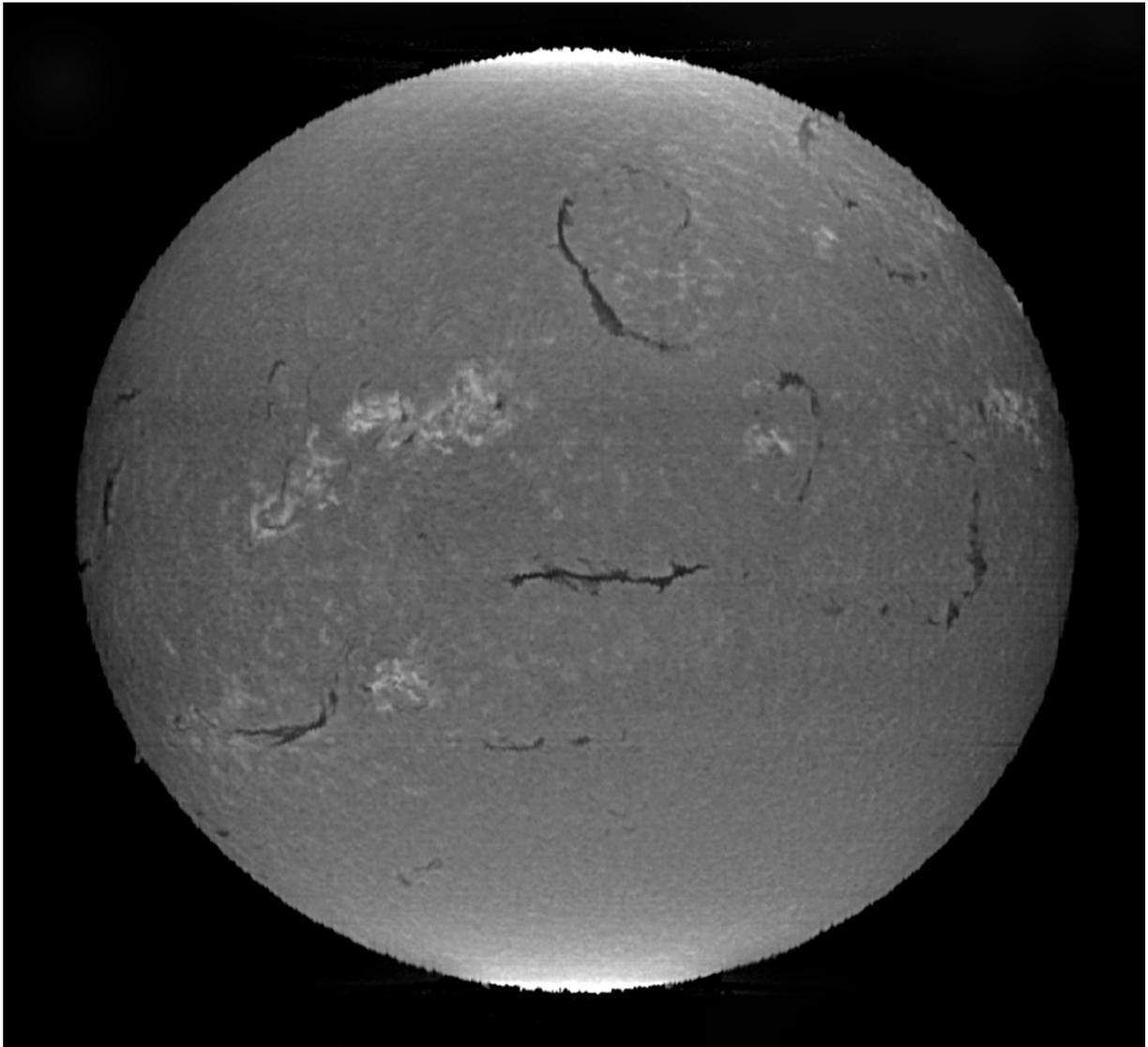
In the composition that follows, the previous $H\alpha$ image was compared with one in neutral Calcium (CaI). The poor sensitivity of this element to the magnetic fields in the active regions is observed, as opposed to what happens for the ionized calcium (CaII).

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





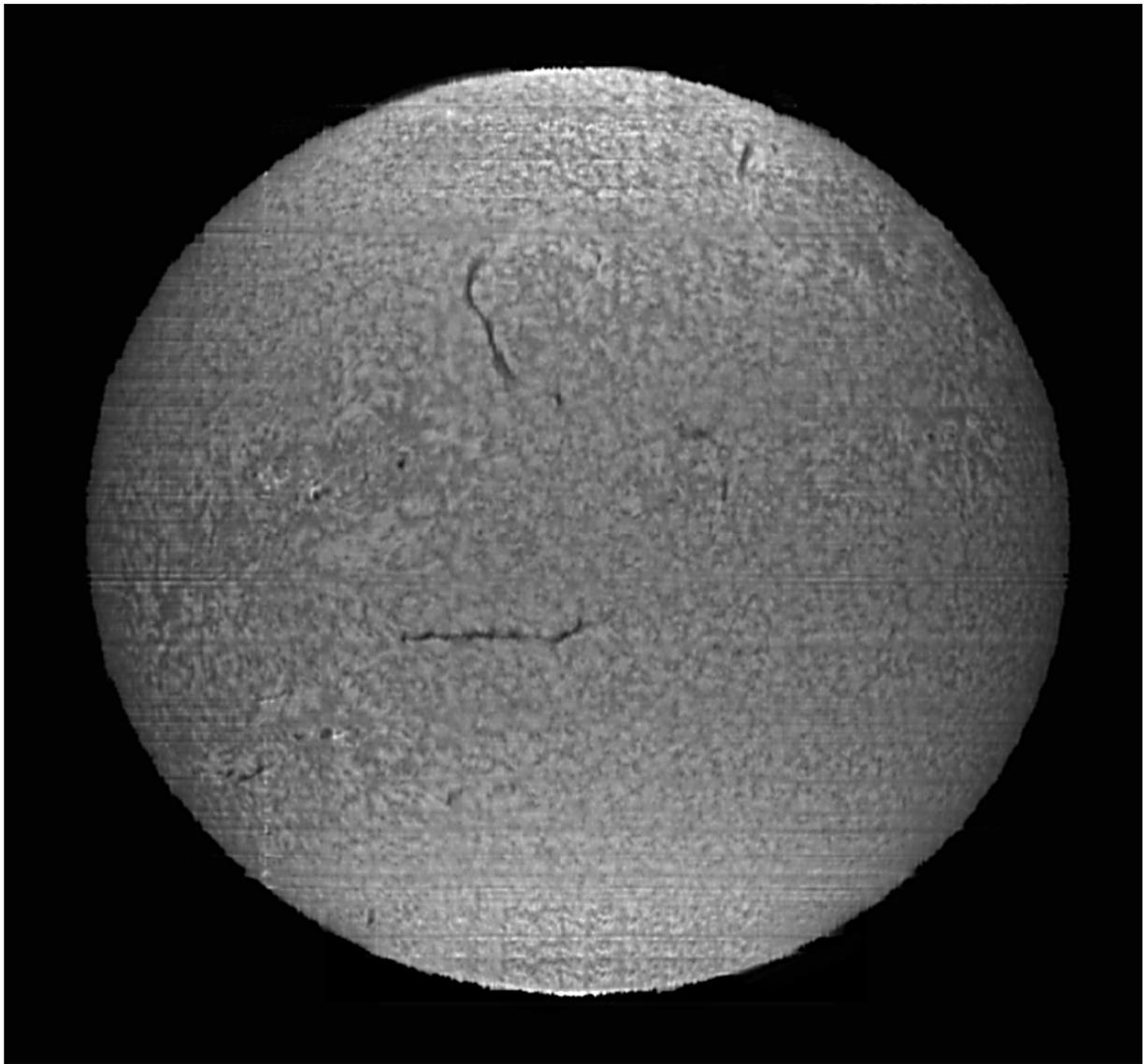
The impressive amount of visible detail: POSS2, scan of July 6, 2014

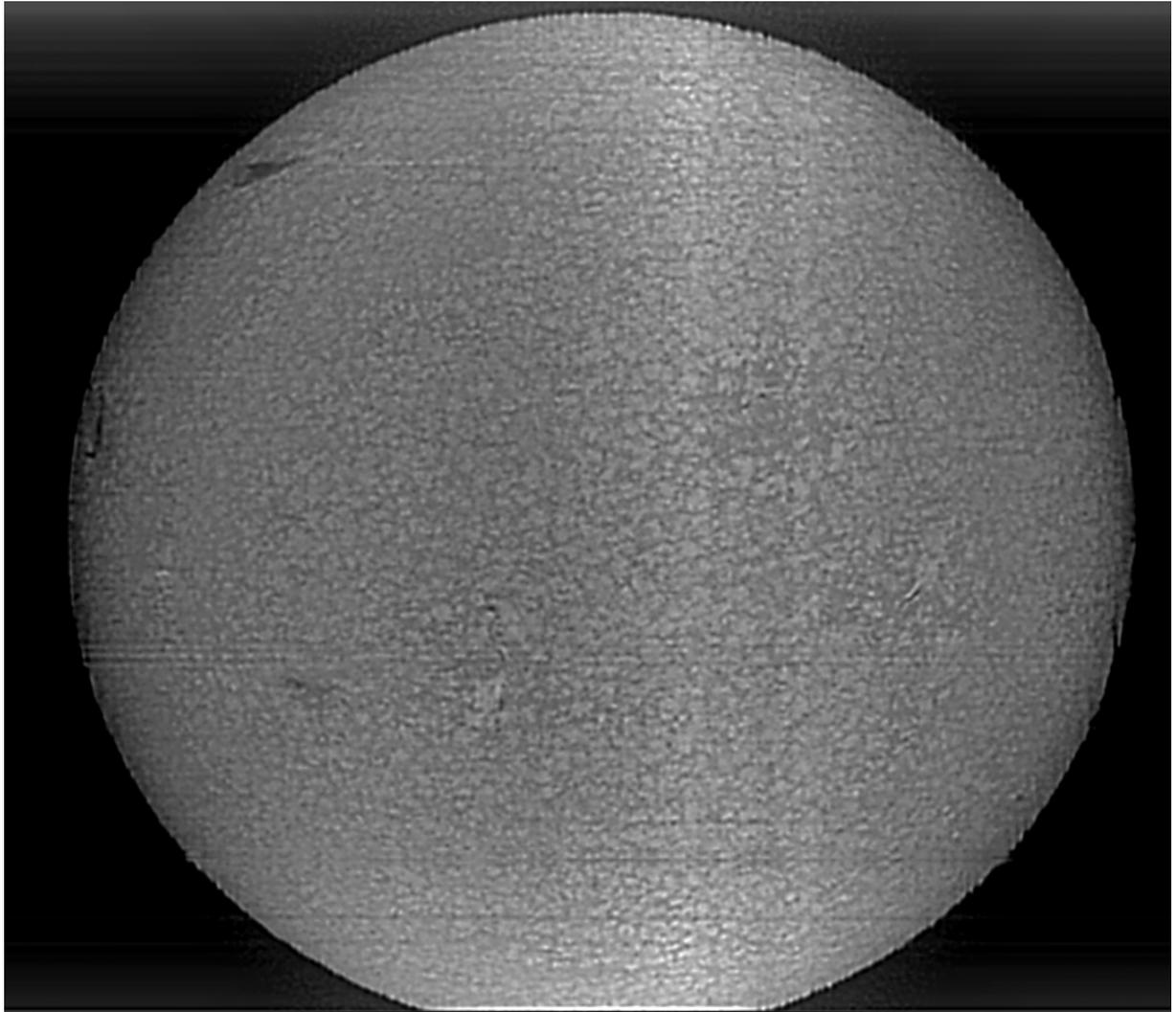


A highly contrasted Solarscan image in $H\alpha$ light of September 27, 2014: the saturated points at the north and south of the image are due to the flattening procedure with Astroart 3.

$H\beta$ at 4861.34Å

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 QE: 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, i.e. 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.



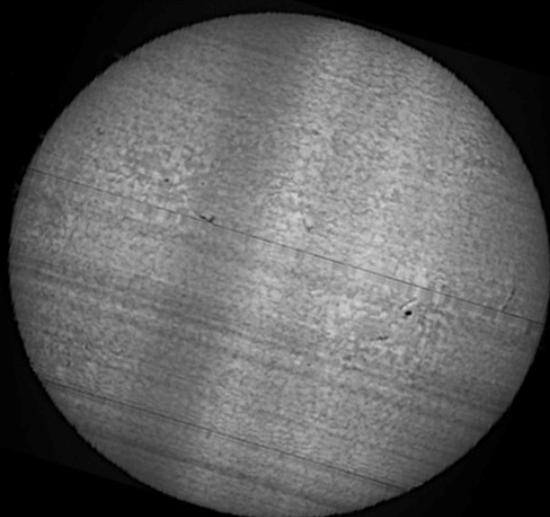
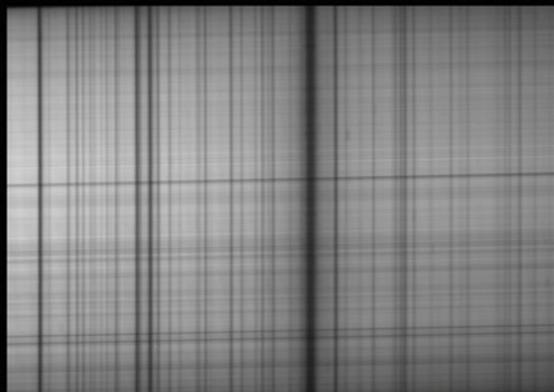


The second feature, which was previously mentioned, is the minor observability of some chromospheric details, such as the plage areas of the active regions, which appear dark rather than bright as in $H\alpha$, and the greater, on the other hand, evidence of supergranulation. Below is a comparison between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

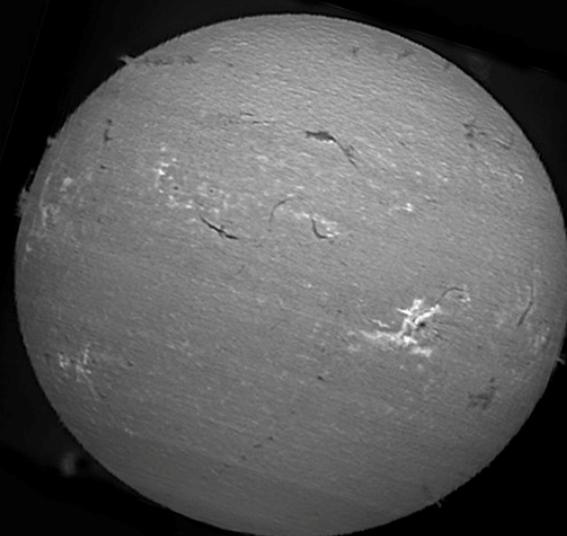
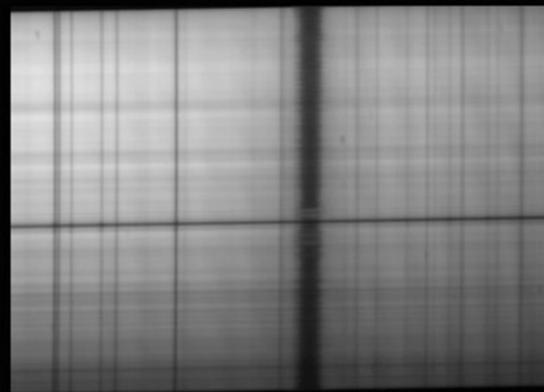
Sun disk Hydrogen beta- Hydrogen alpha comparison

VHIRSS spectroscopie in spectrheliocope mode May 13 2012
Fulvio Mete, Rome, Italy

H beta
4861 A

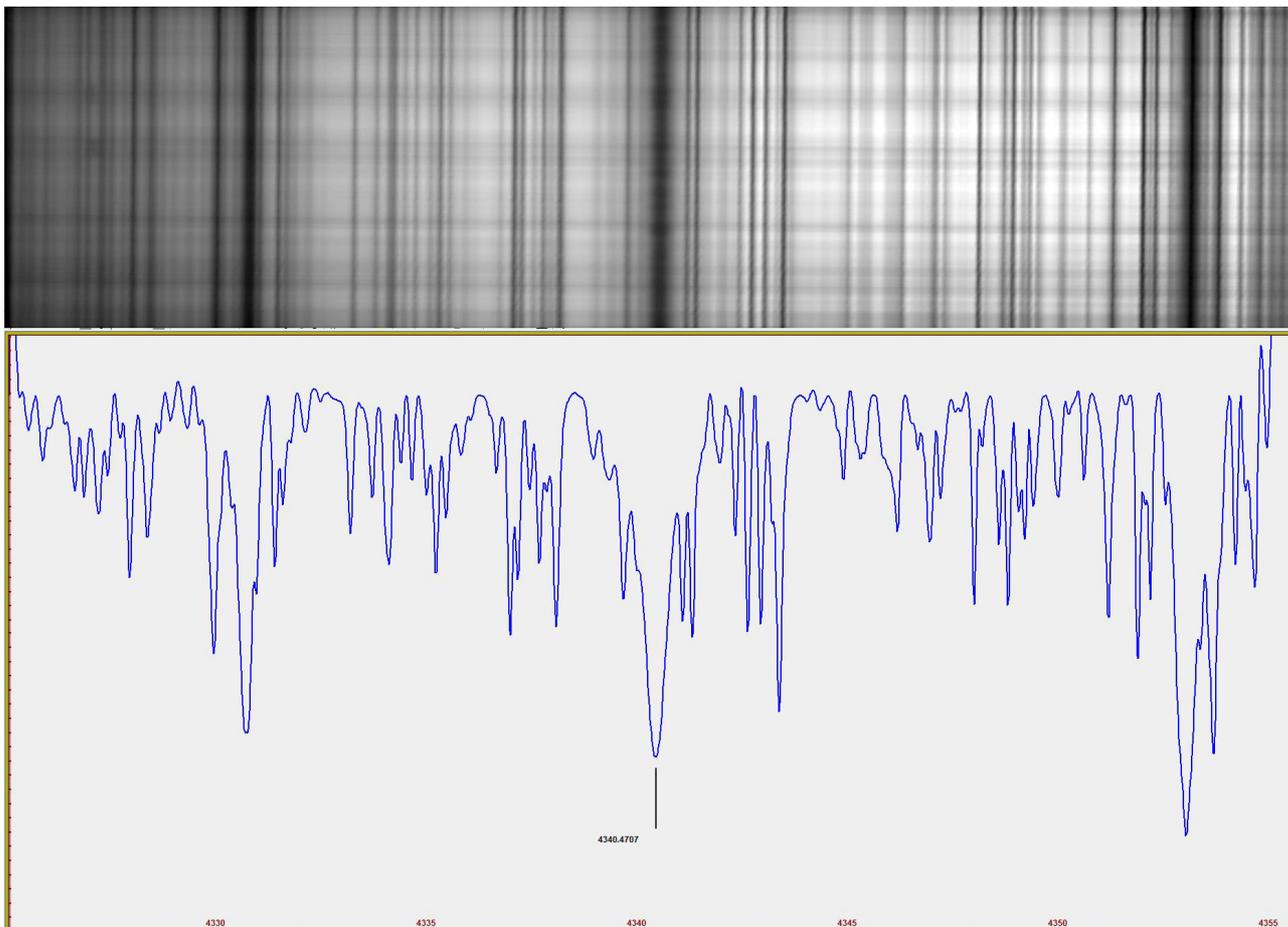


H alpha
6563 A

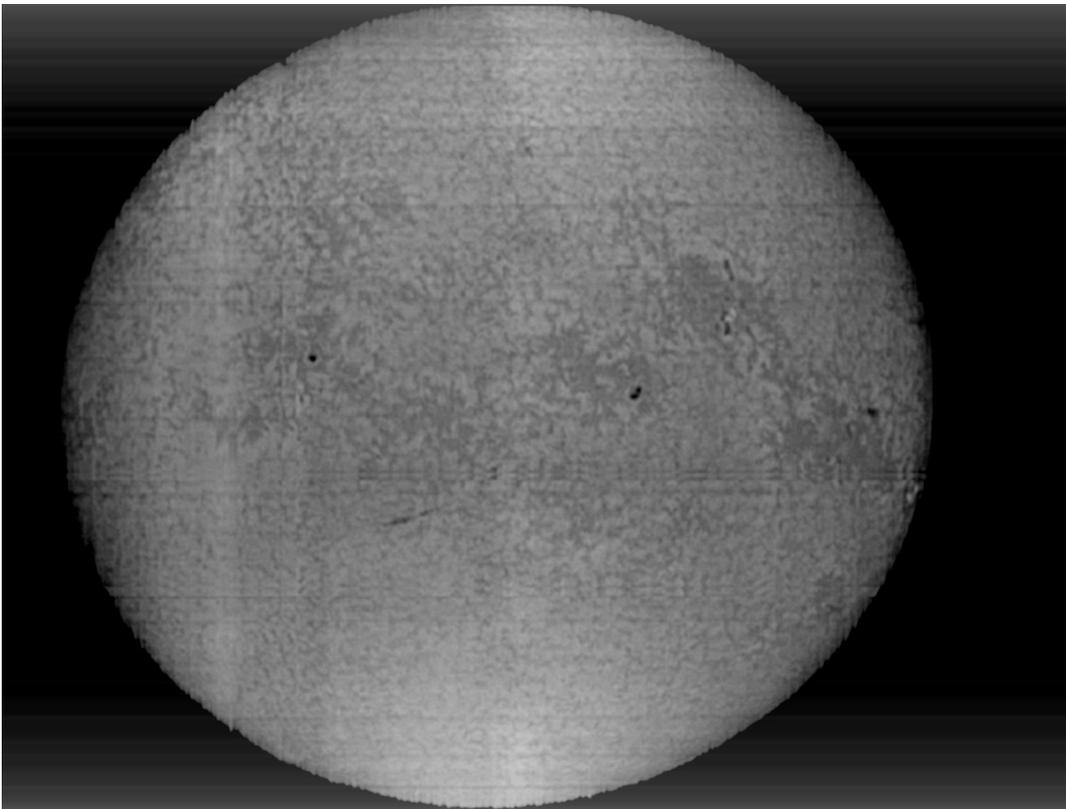
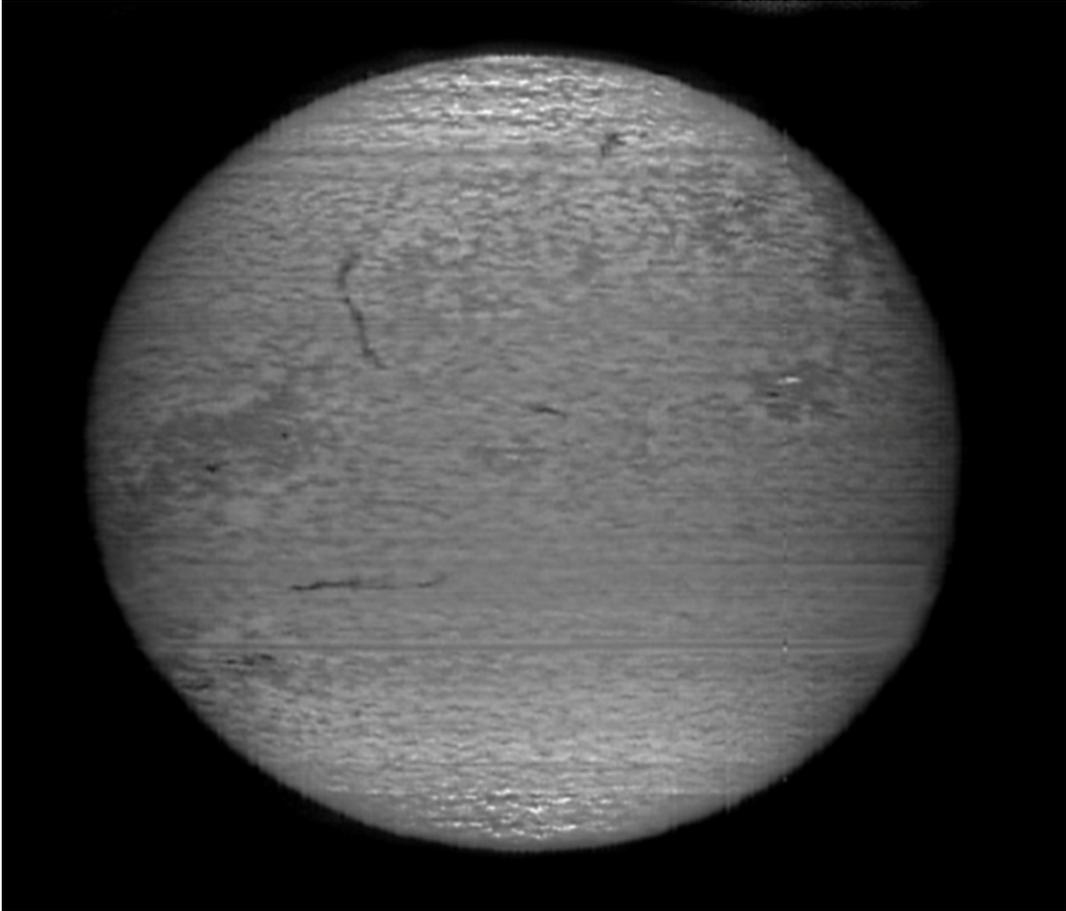


H γ at 4340.47Å

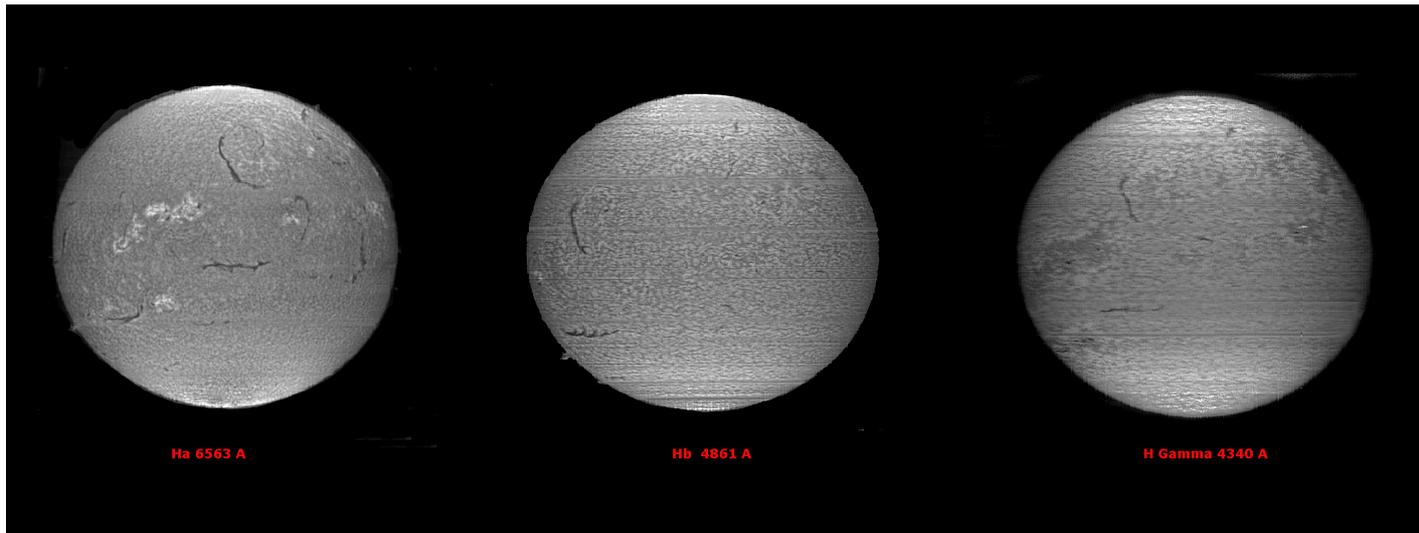
Making spectroheliograms in H γ light is not trivial, due to the relative poor width of the line and its thin optical window in the chromosphere.



The features of minor observability of the plage areas and in general of the active regions in H β light, however, are now more evident in the images of the solar disk in H γ light at 4340.47Å, as observed in the following images, taken with Solarscan and VHIRSS:

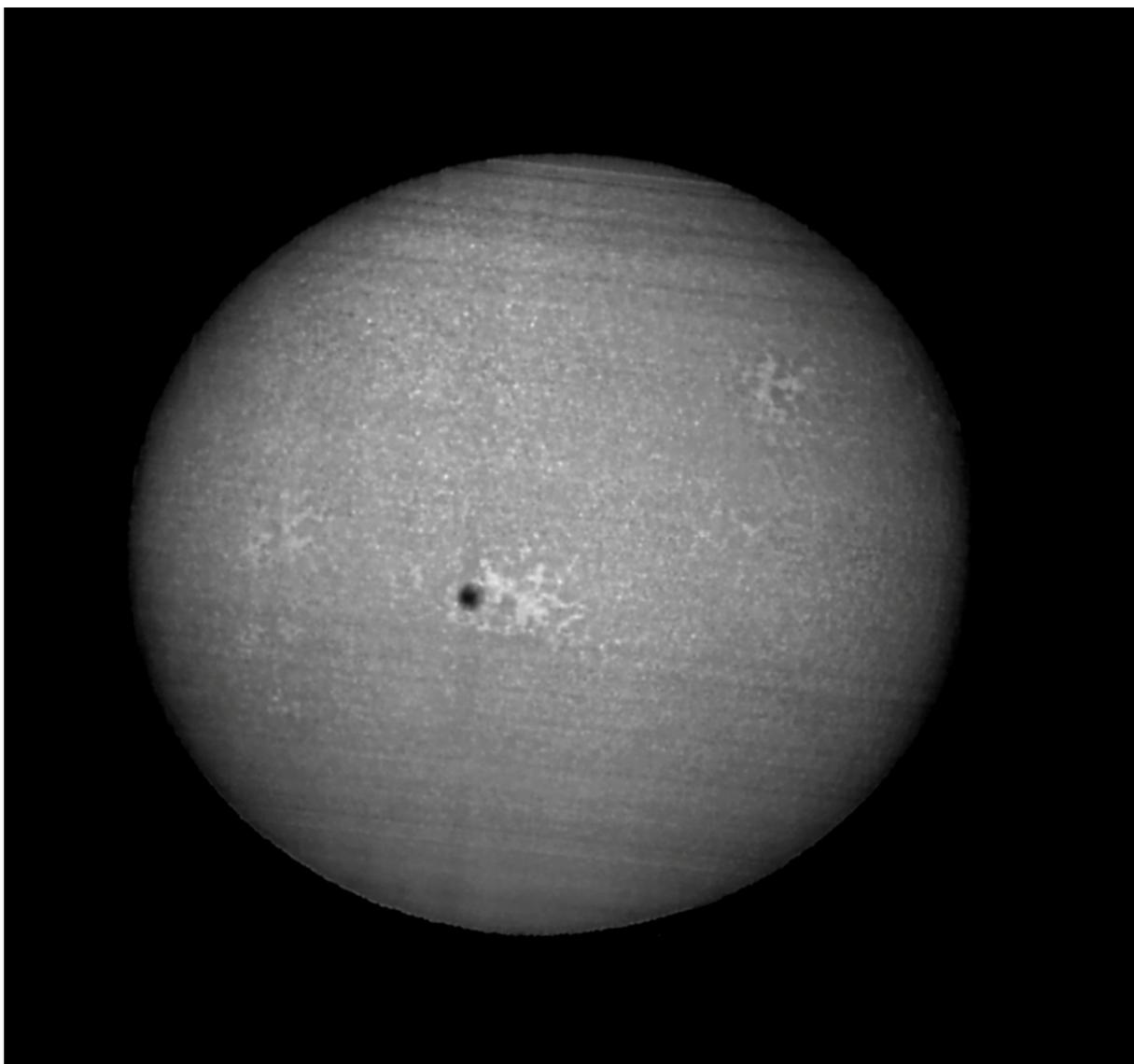


The image of the solar disk in the main lines of the Balmer series of ionized hydrogen, $H\alpha$, $H\beta$, $H\gamma$ confirms the trend described in the appearance of active regions, which pass from the bright white feature of the plage areas in $H\alpha$ to the gray of $H\beta$, and dark gray of $H\gamma$, 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 location of the lines in the chromosphere and the difference of temperature.



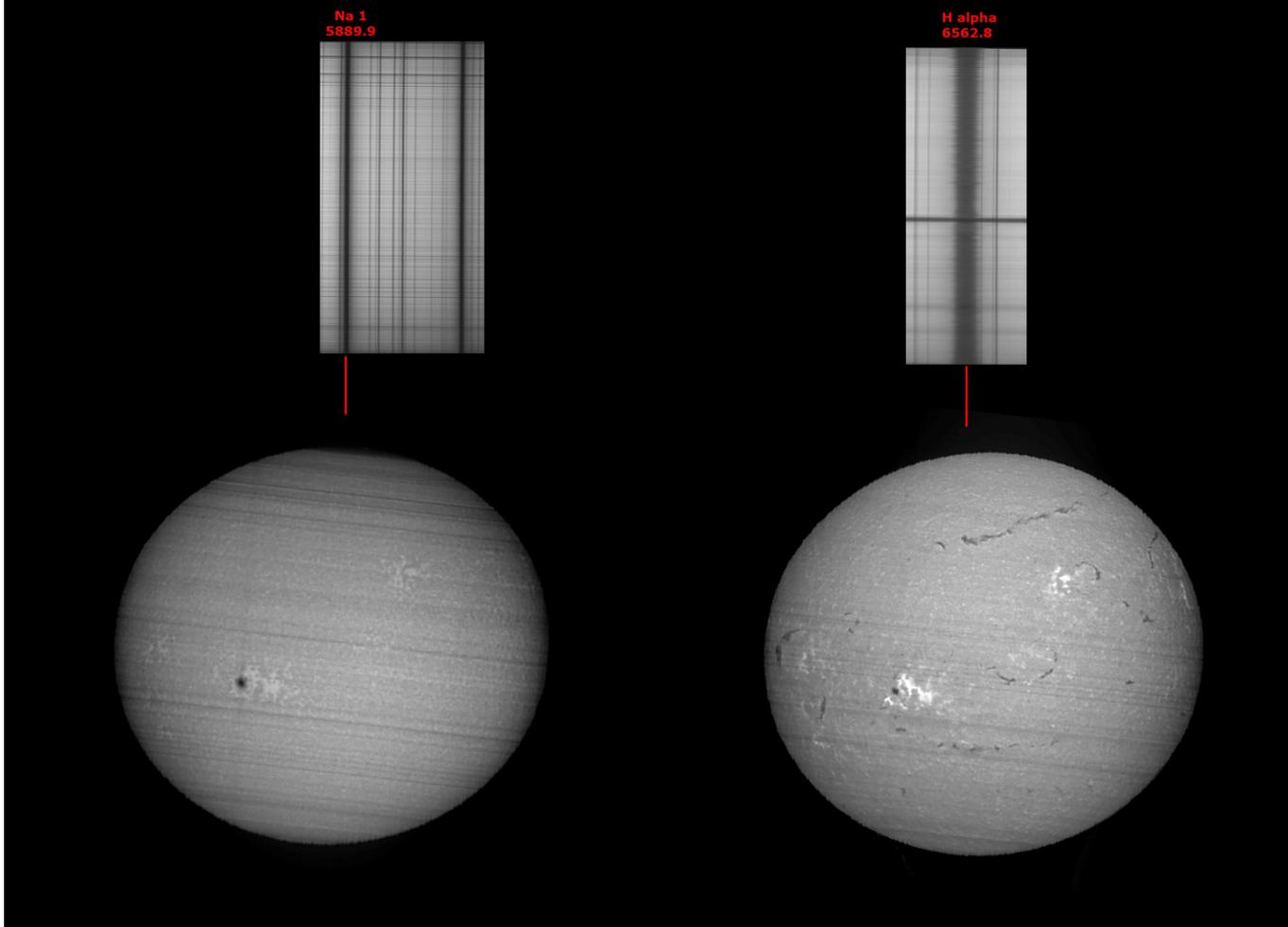
Na D1 and D2 lines at 5889.75 and 5895.94Å

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

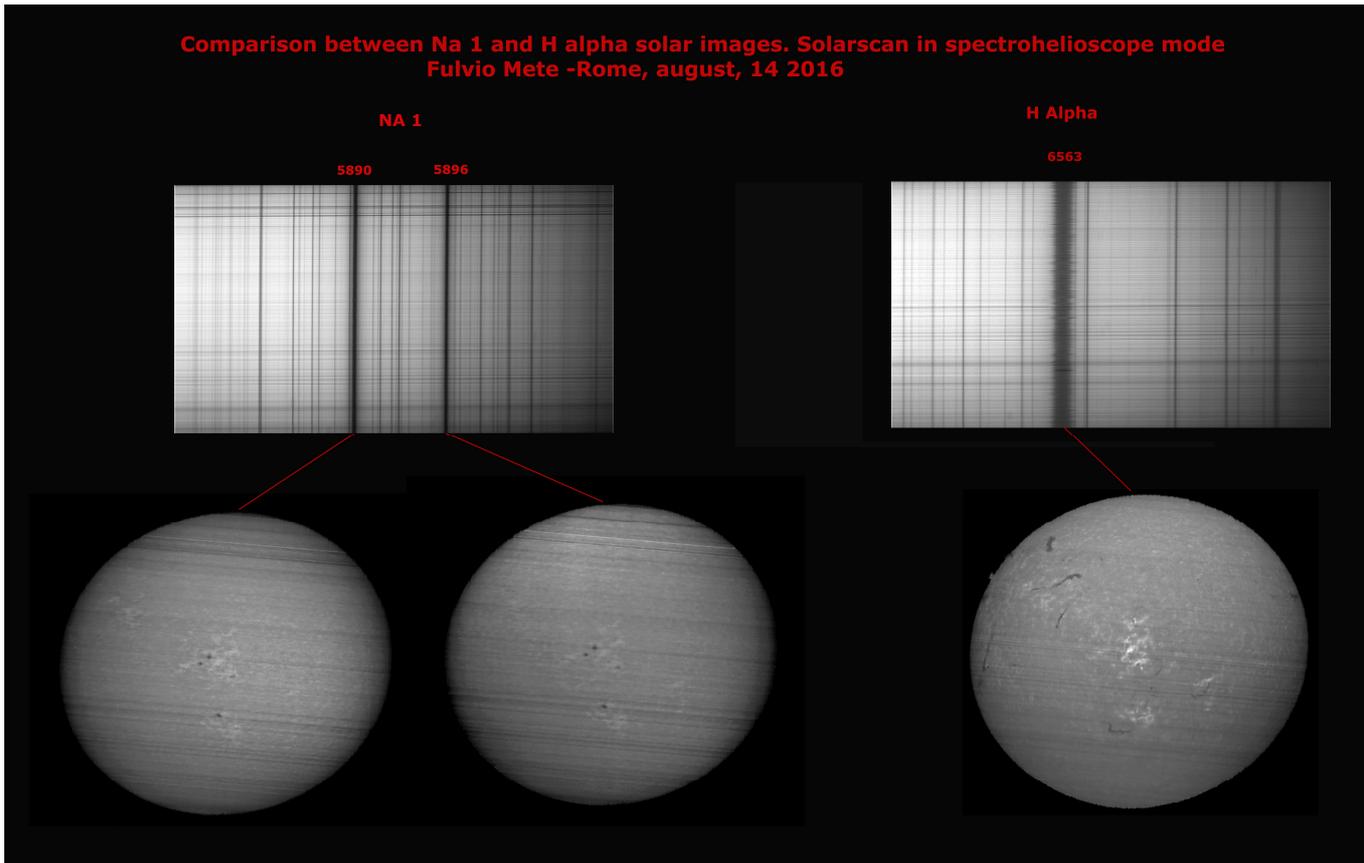


Here is shown a comparison between the above image and a spectroheliogram in $H\alpha$ light carried out on the same day. The plage areas are clearly visible, although less brilliant than in $H\alpha$, while the filaments on the disk are almost absent.

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



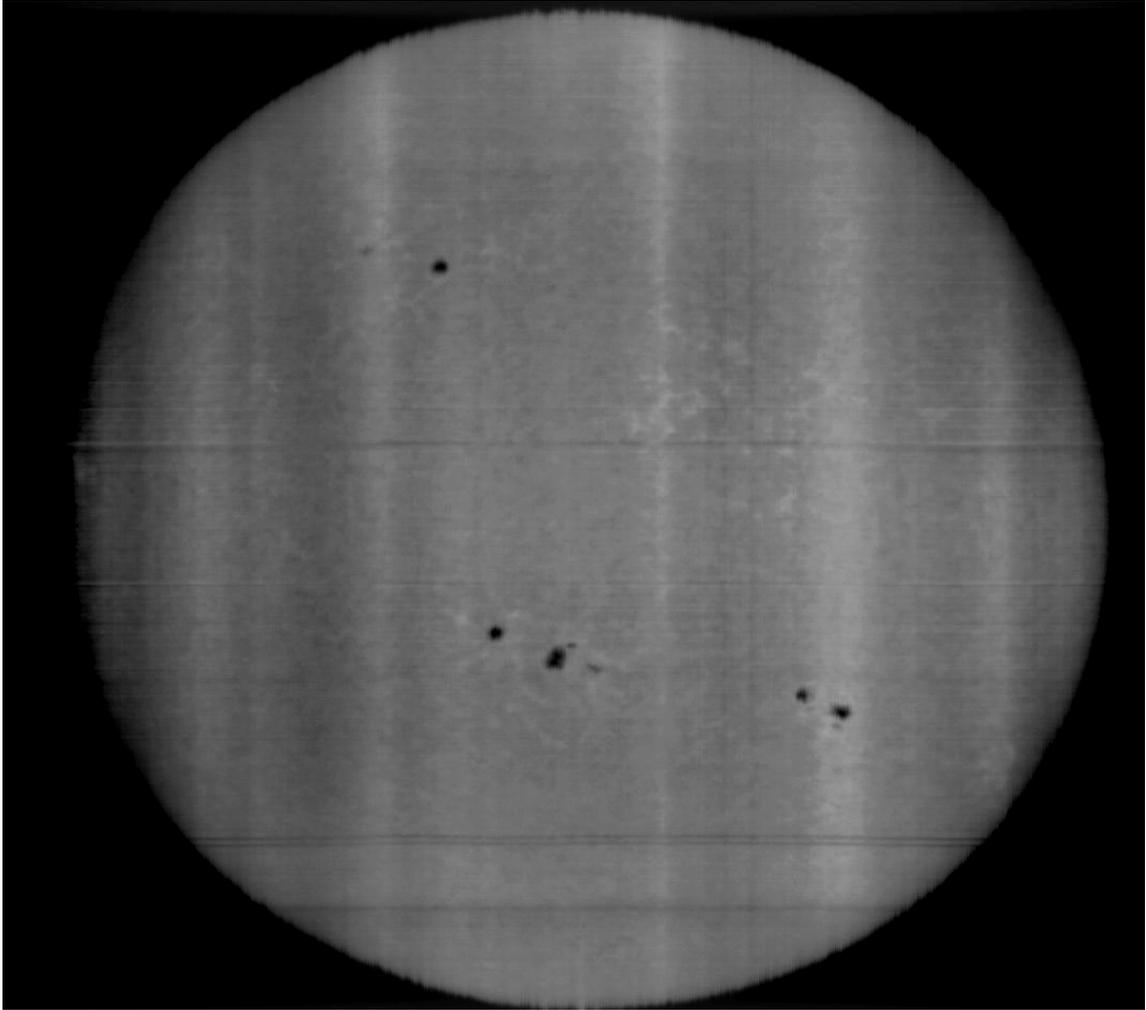
Another interesting observation was that of August 14, 2016, in which a comparison was made between the images, at the chromospheric level, of the solar disk in Sodium Na D1 and D2 light and a H α one.



FE 1 4957.61Å

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

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



The lines of ionized calcium:

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

CaII K at 3933.68Å

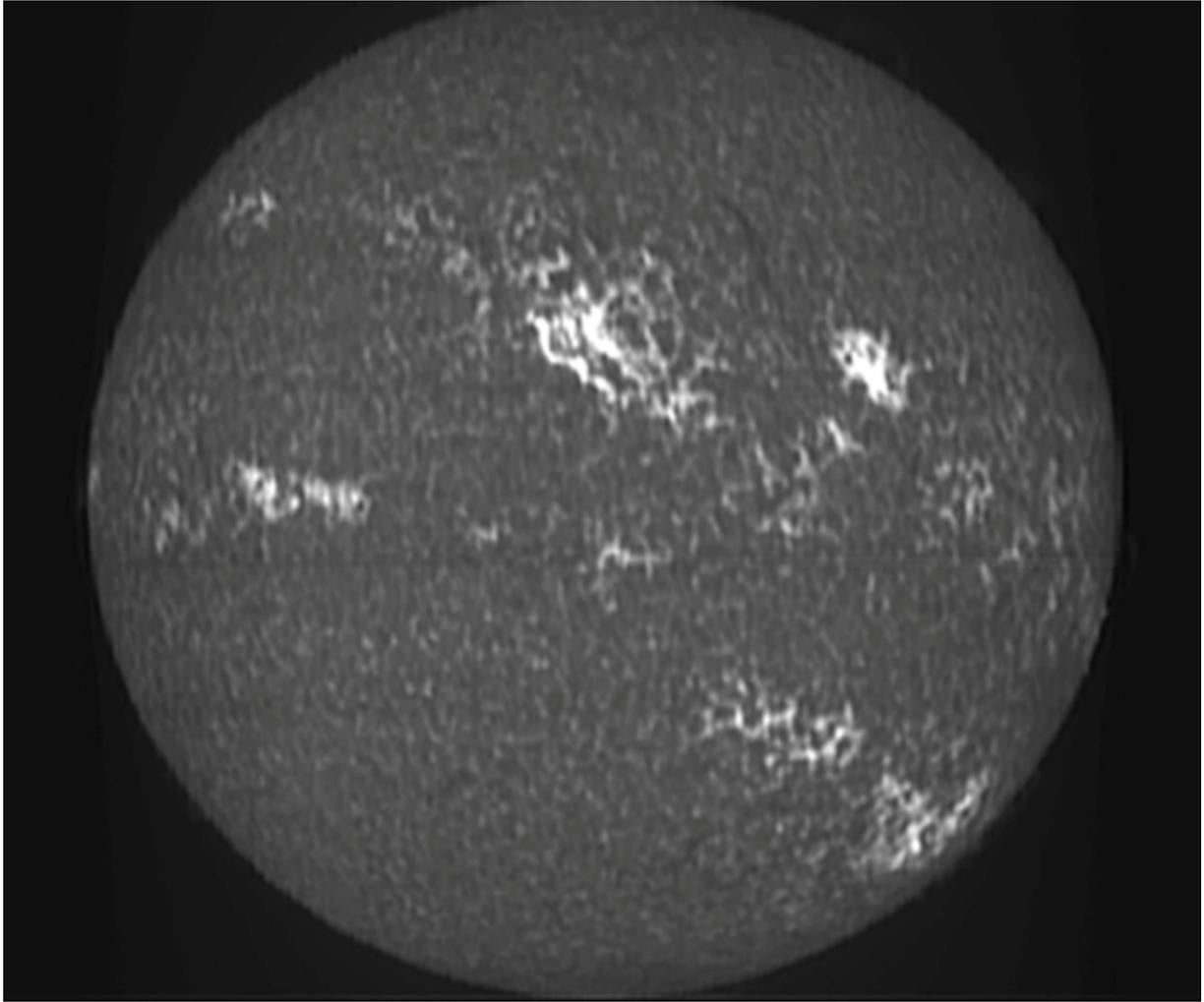
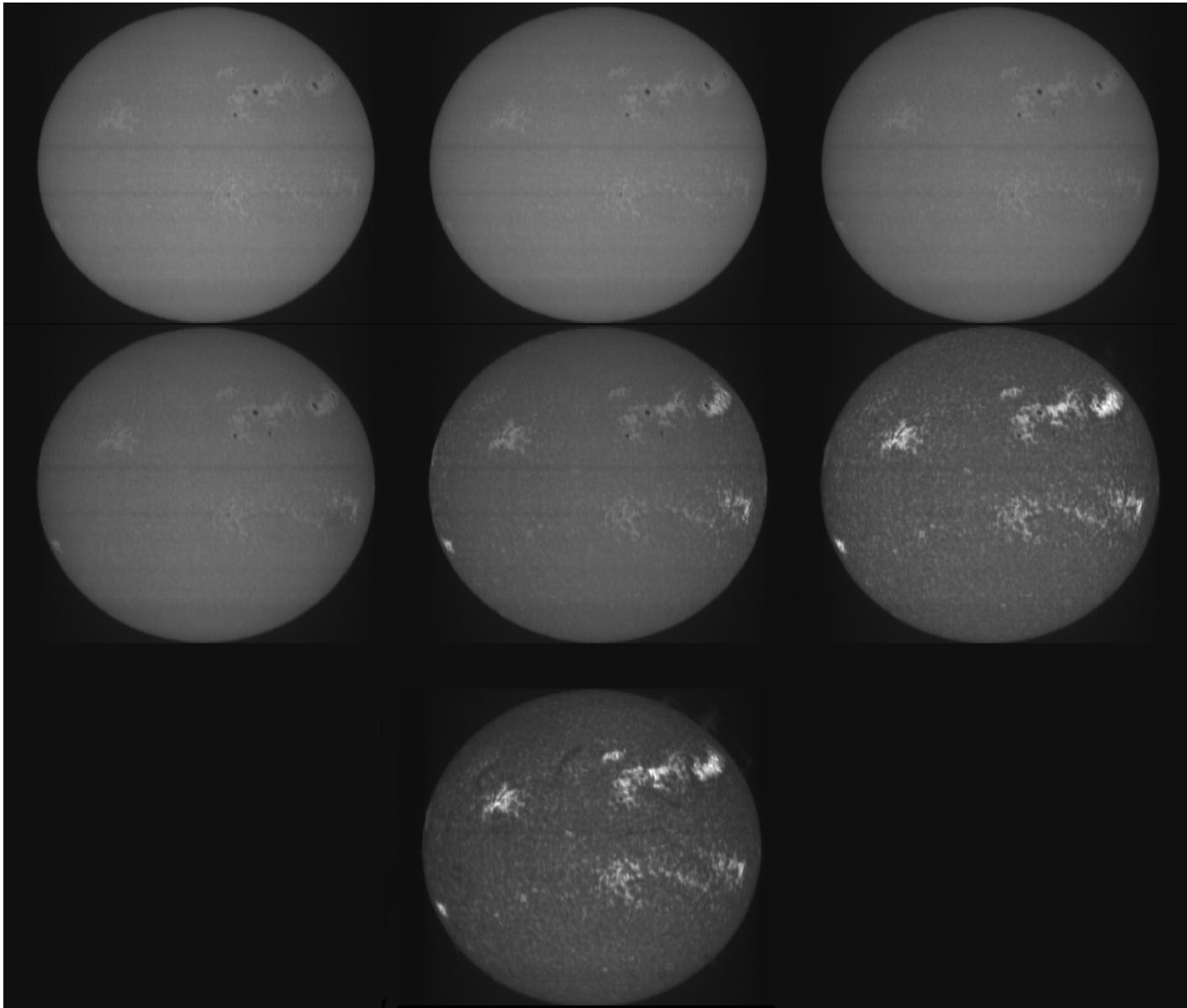


Image of the sun in light CaII (k3) (center of line) taken on July 28 2012 with the VHIRSS.

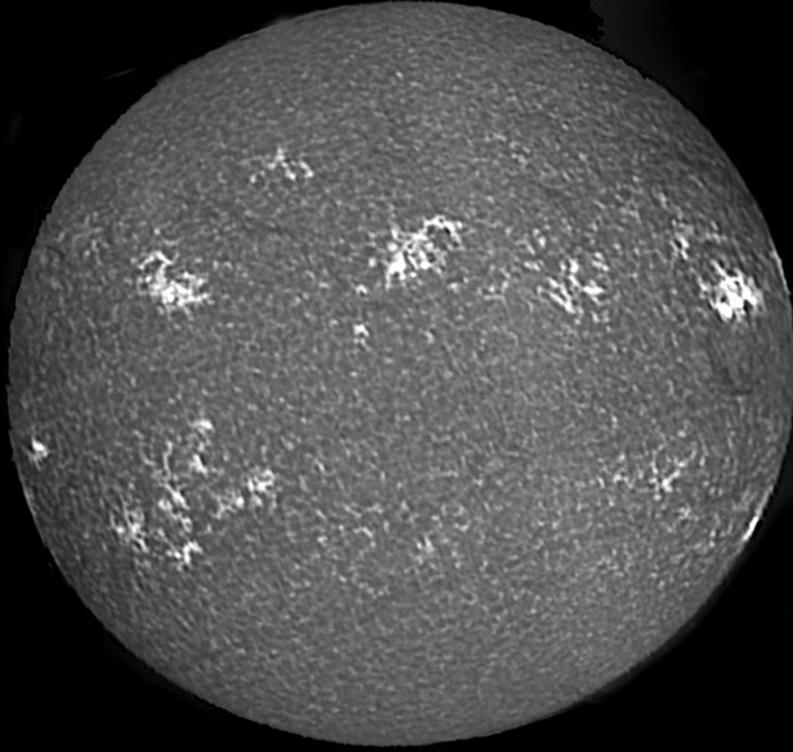
The following image shows the succession of 7 frames, each of 0.029\AA bandpass in the violet wing of the line, spaced out by 0.174\AA , which covers from 3932.61\AA to 3933.68\AA (center line k3). The sequence also includes the image of the stationary point k2v at 3933.32\AA . Considered that the absorption coefficient of a line with respect to the continuum is a function of the height above 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 us to perform a sort of tomography of the height of the chromosphere zone observed, reaching more than 2000km from the photosphere in the very center of the line k3. Each frame would therefore correspond to a zone of the high chromosphere. The dramatic change in the appearance of the chromosphere 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 prominences.



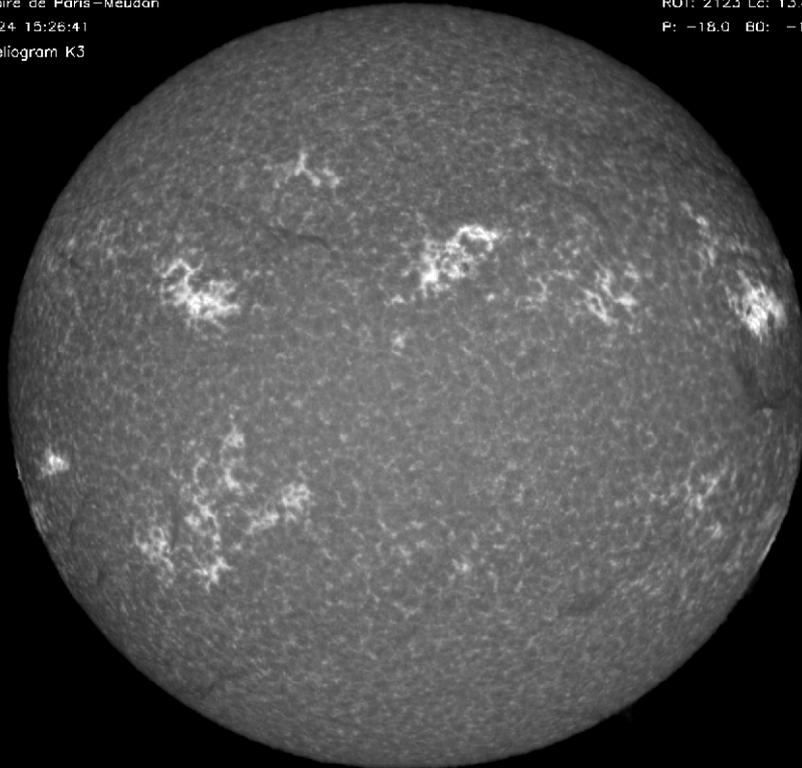
The following image is a comparison between a CaII K solar light image obtained by VHIRSS and one with the Paris-Meudon Observatory SHG, mentioned previously. The difference is less than one might imagine.

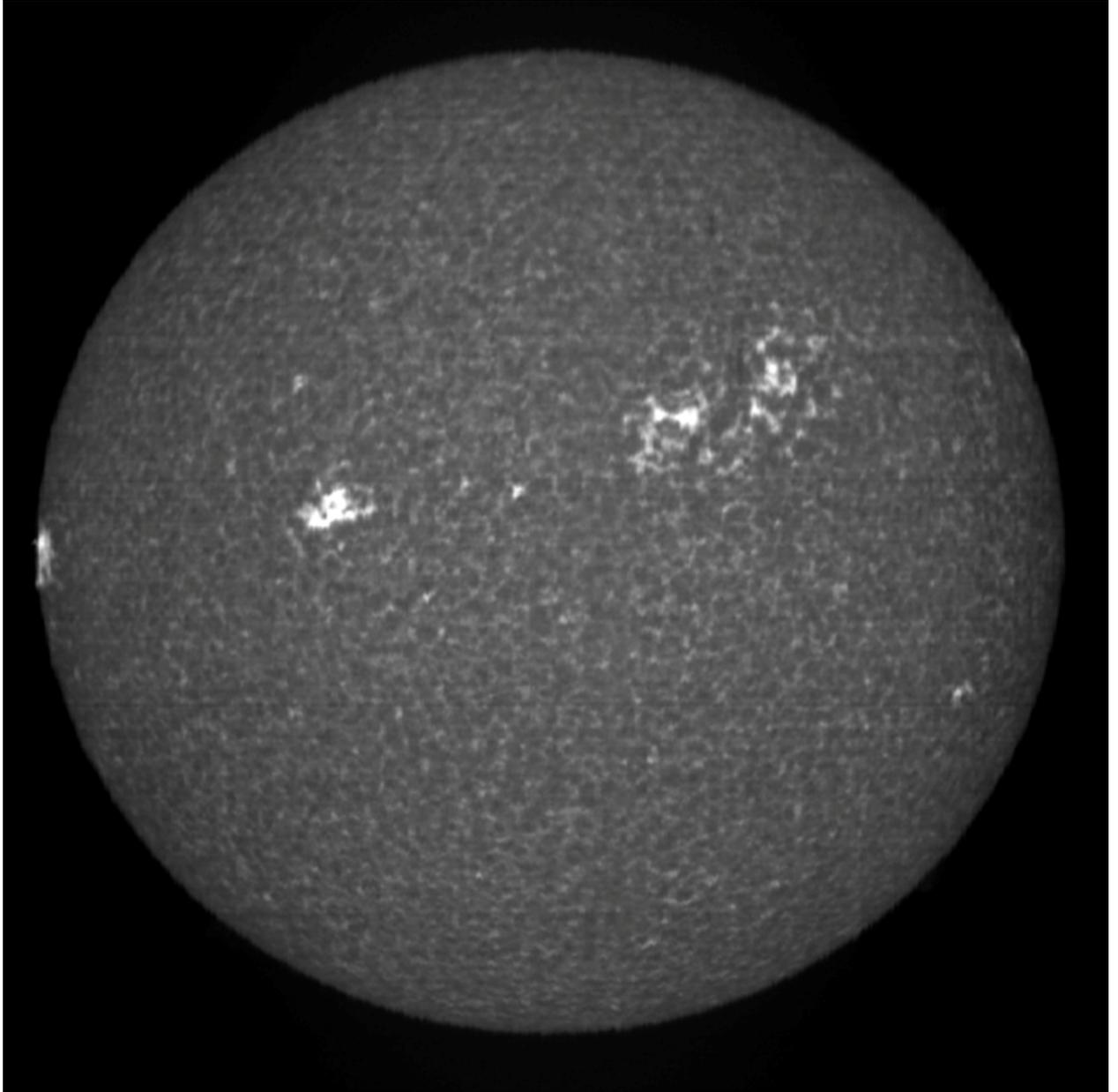
Sun CaII K VHIRSS
24-05-12 Fulvio Mete
Rome Italy



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

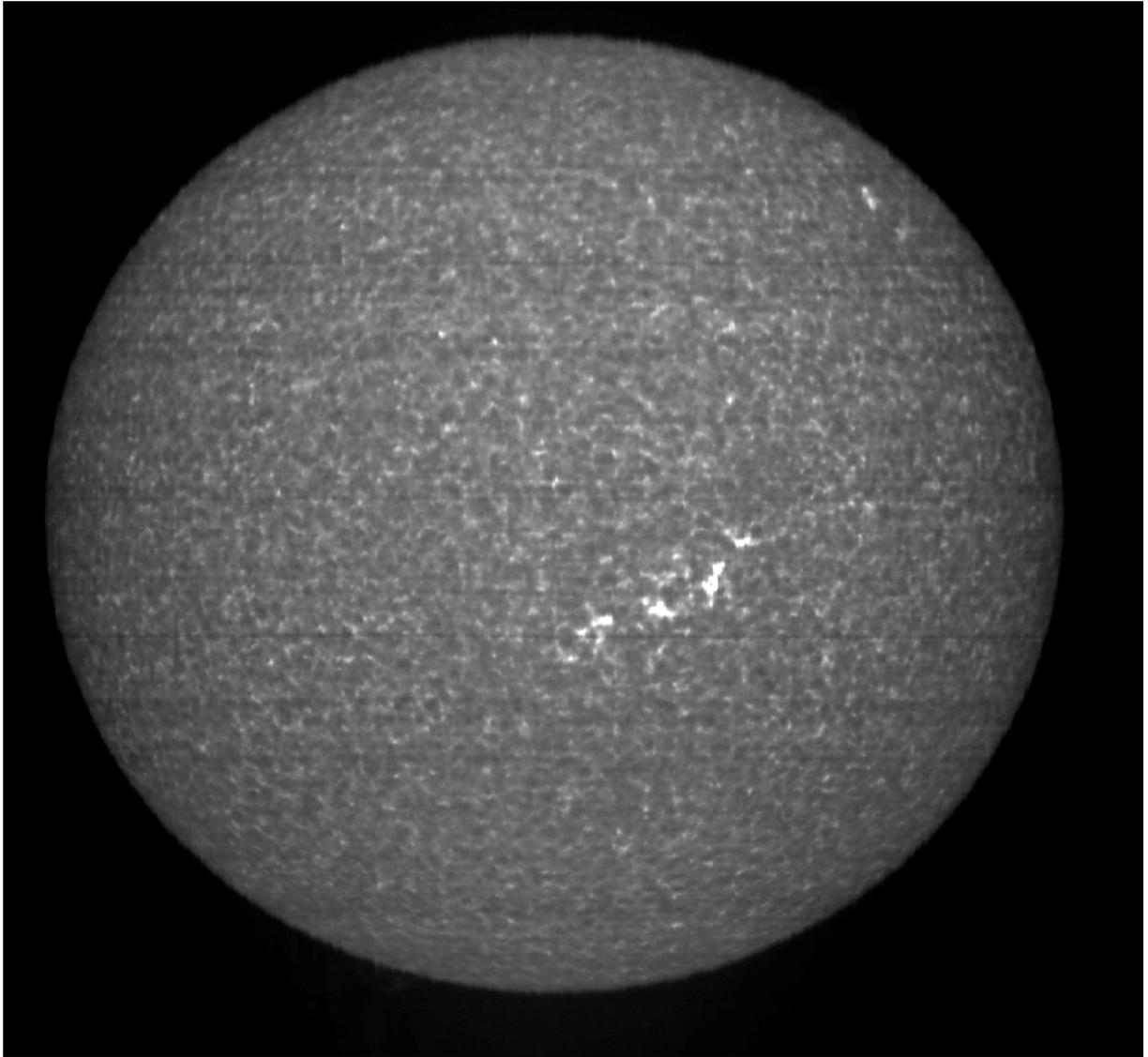
ROT: 212.3 Lc: 13.8
P: -18.0 B0: -1.5



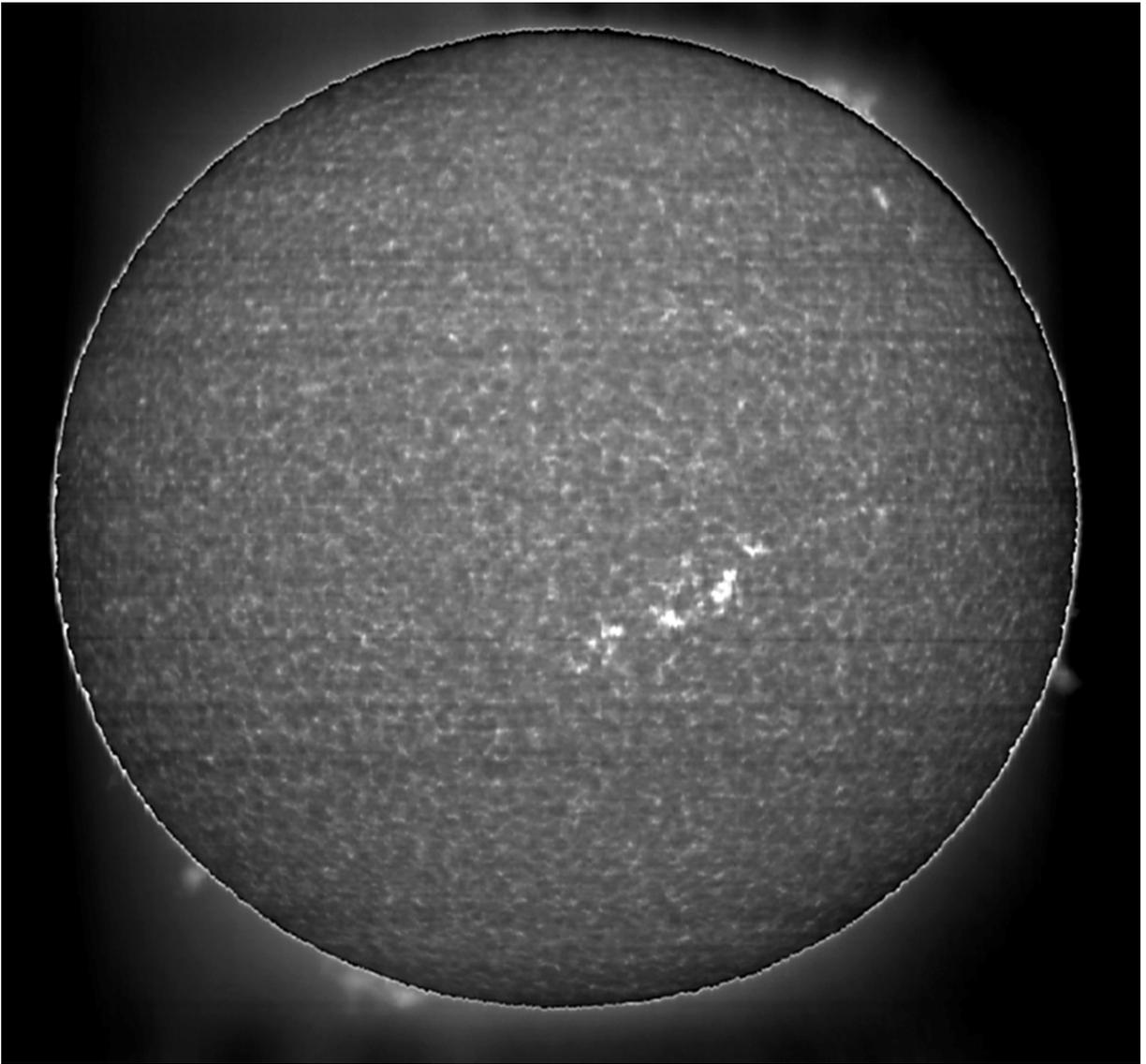


A nice image in CaII (k3) (line center at 3933.68\AA) of June 24 2018 with POSS2, bandwidth 0.037\AA . Note, it is practically impossible to obtain such images of the center of the line with amateur CaK interference filters, their bandwidth being too wide (about 2.2\AA).

Below another detailed image of the solar disk in CaII (k3) light imaged on October 18, 2018 by POSS2 SHG.

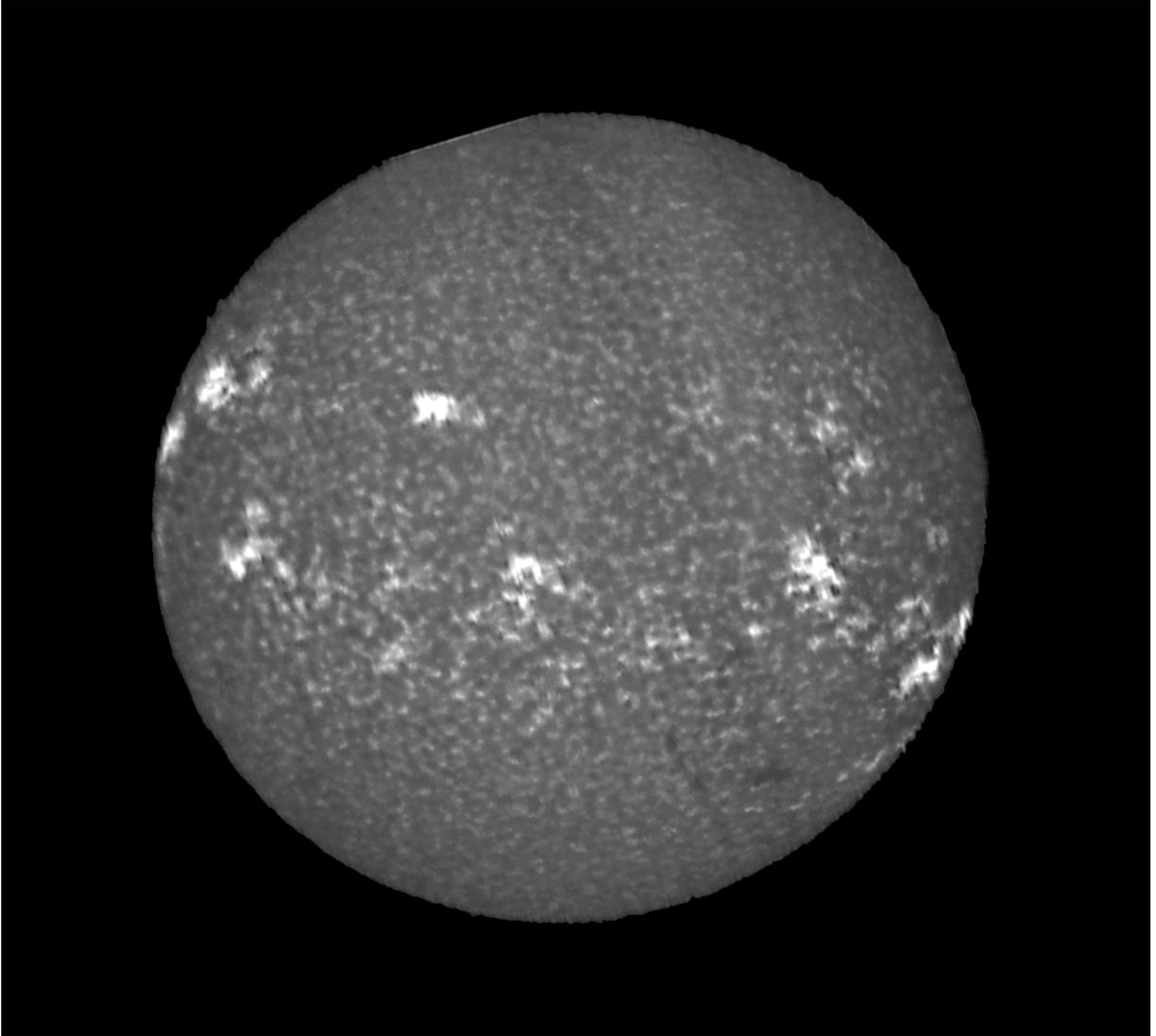


The same image with two exposures, one for the disk and one for the prominences, superimposed by software.

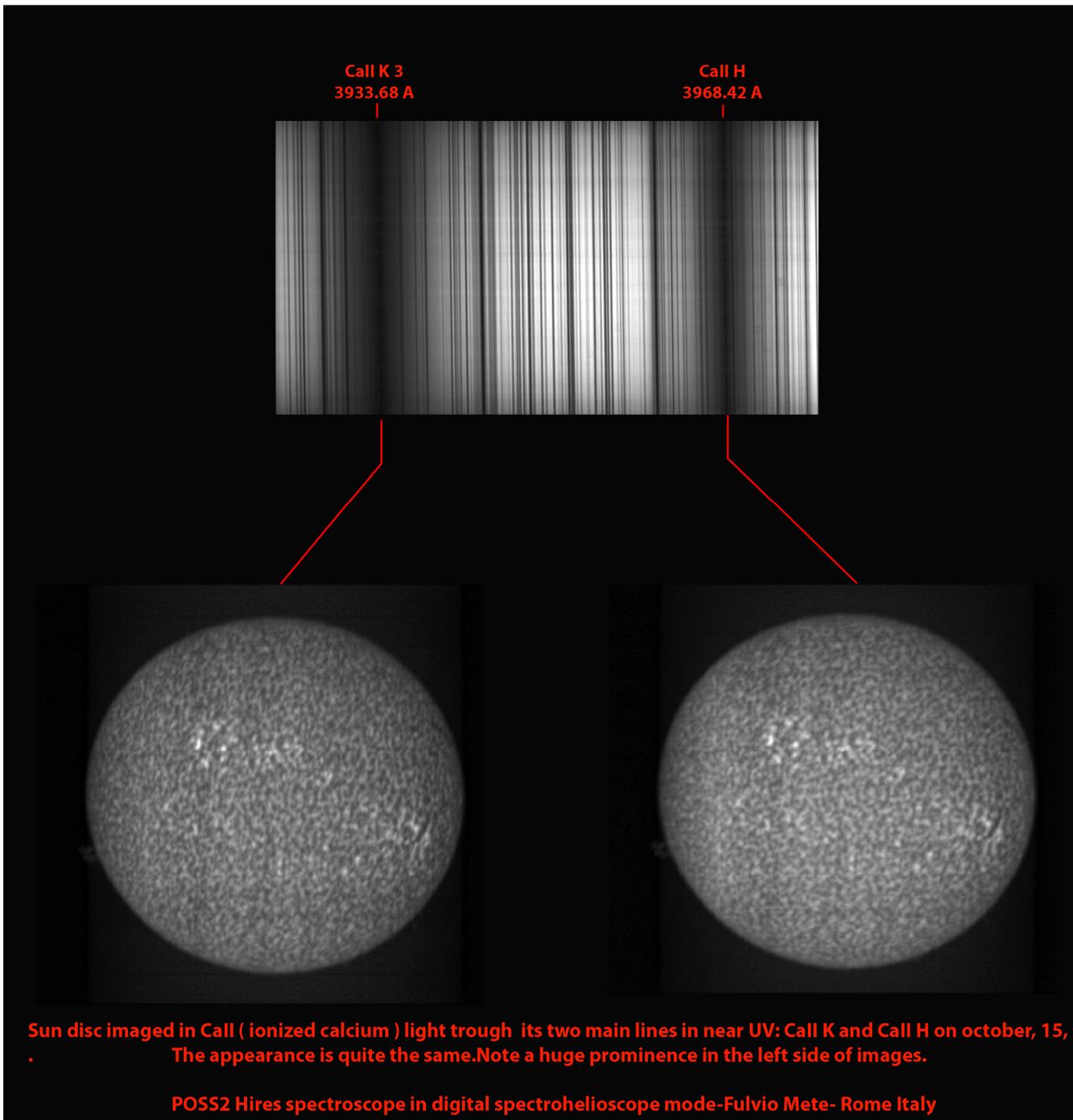


CaII H at 3968.49Å

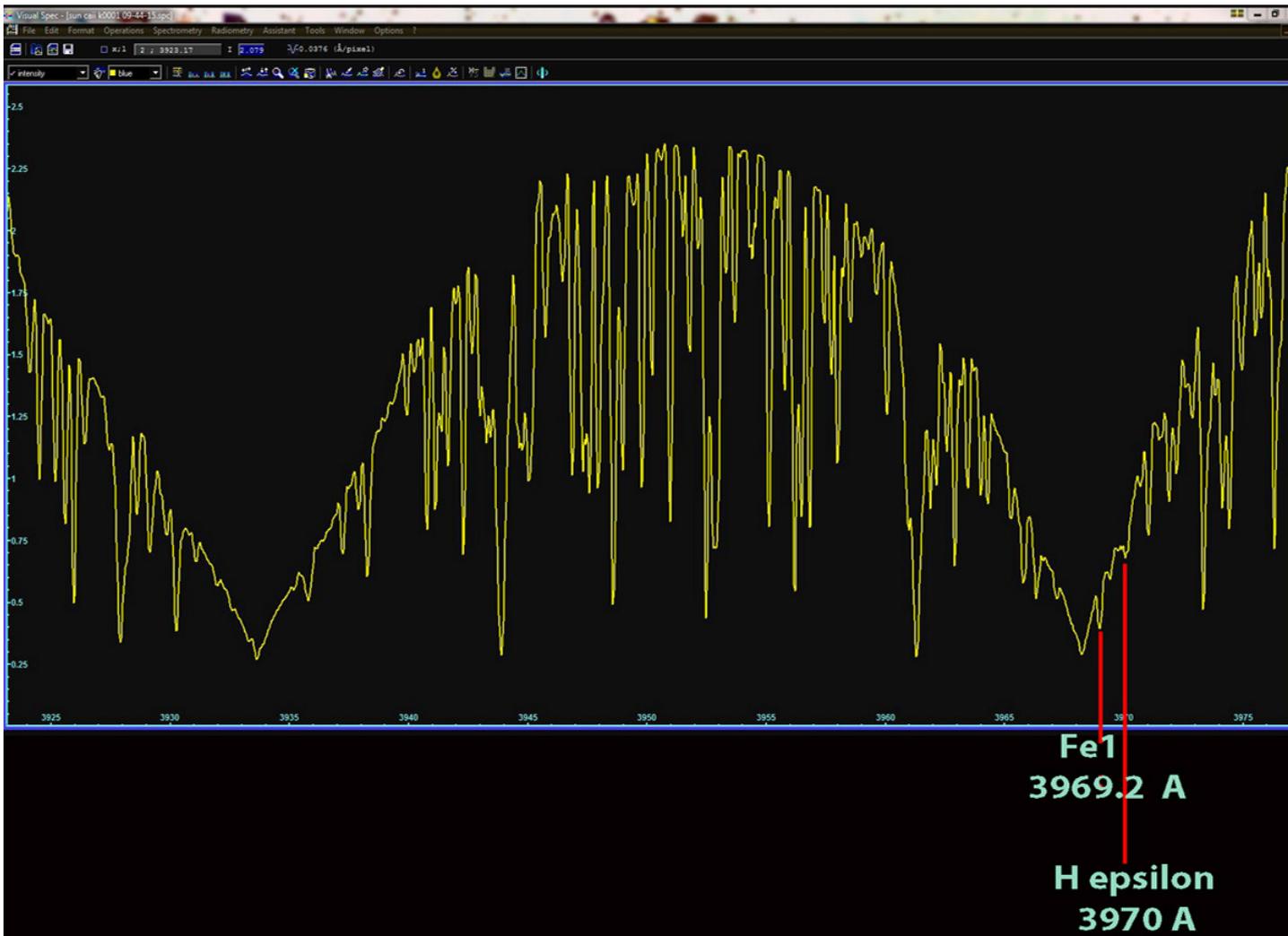
It is the second line of ionized calcium in the near UV.



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



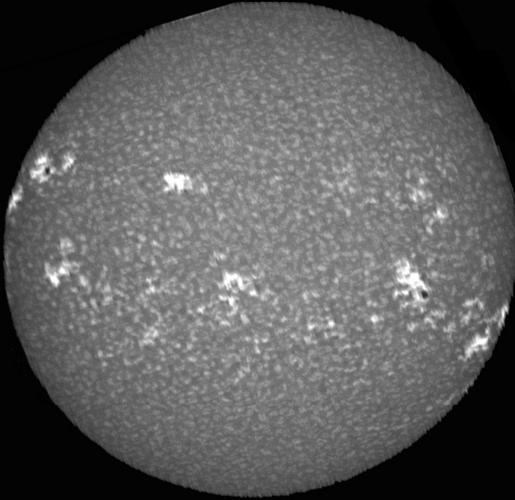
The two images, obtained from a column of one pixel of 0.037\AA in bandpass on the center of both lines, do not show substantial differences. In the case of a wider bandwidth, however, the line would be at risk of being recorded blended with that of iron at 3969.2\AA and of the $H\epsilon$ line at 3970.0\AA .



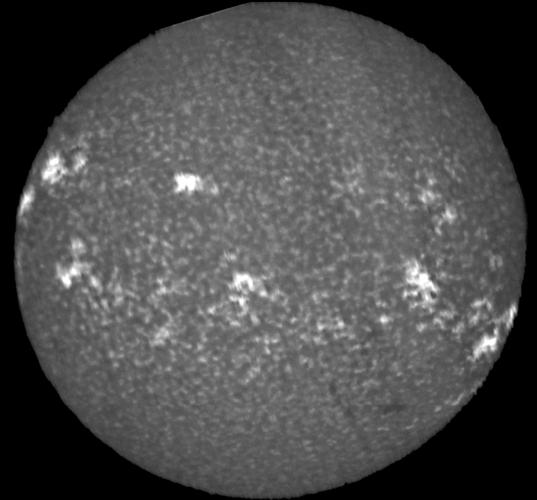
The following image, from 2014, is a comparison between two CaII H light solar images obtained with frames corresponding to 0.2\AA and 1.44\AA , both centered in the middle of the line. The difference is minor, but visible.

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

1.44 A



0.2 A



Processing and flattening of spectroheliograms

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

1- Processing

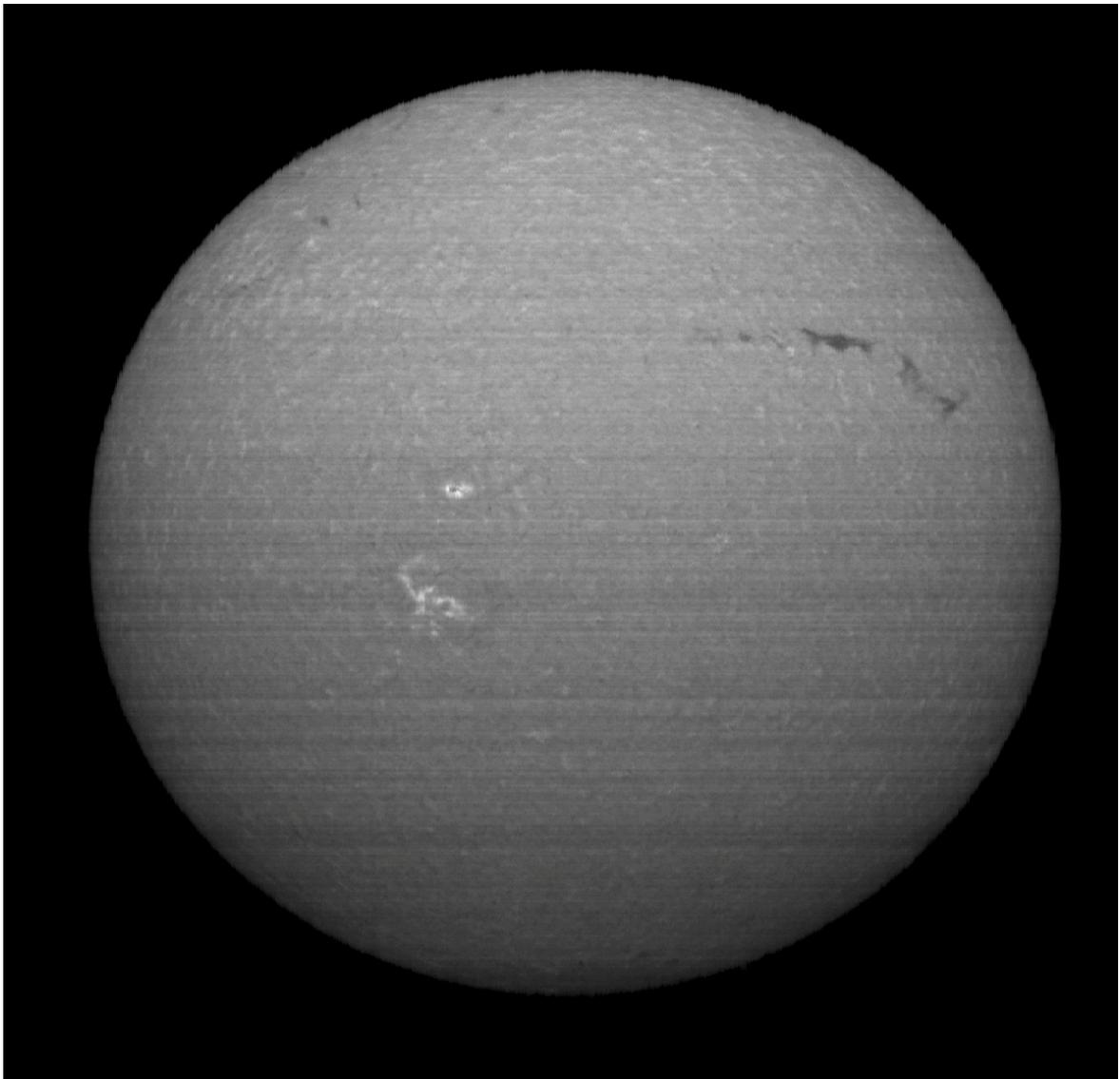
By processing I mean only a few cosmetic steps to make the images more pleasant from an aesthetic point of view. Obviously modifications to these file (Fits, PNG, BMP) make them unusable for any scientific activity.

As an example, which I do not use often, but provides aesthetically pleasing results, is to modify with Photoshop the central image of a series, by multiplying it by the ones (or one) at the ends of the series.

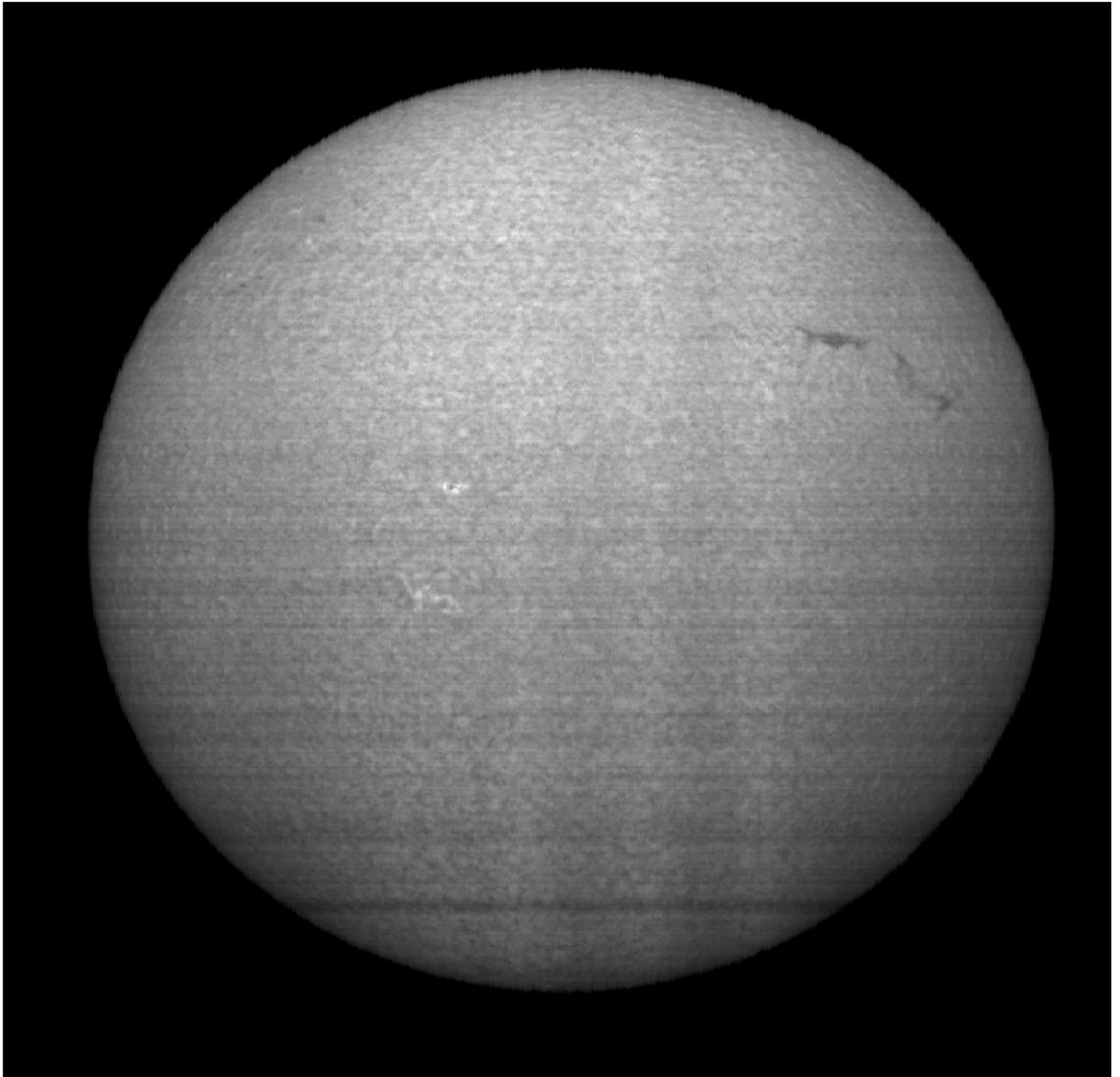
Let me explain. Consider, that from a given solar video scan treated with one of the software programs mentioned above, that we could get, 41 images of the H α line (this is certainly possible with SLiM that converts the video in a number of png files, up to 100) each from a one pixel column, one centered 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 blue end, 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 α image by VHIRSS:

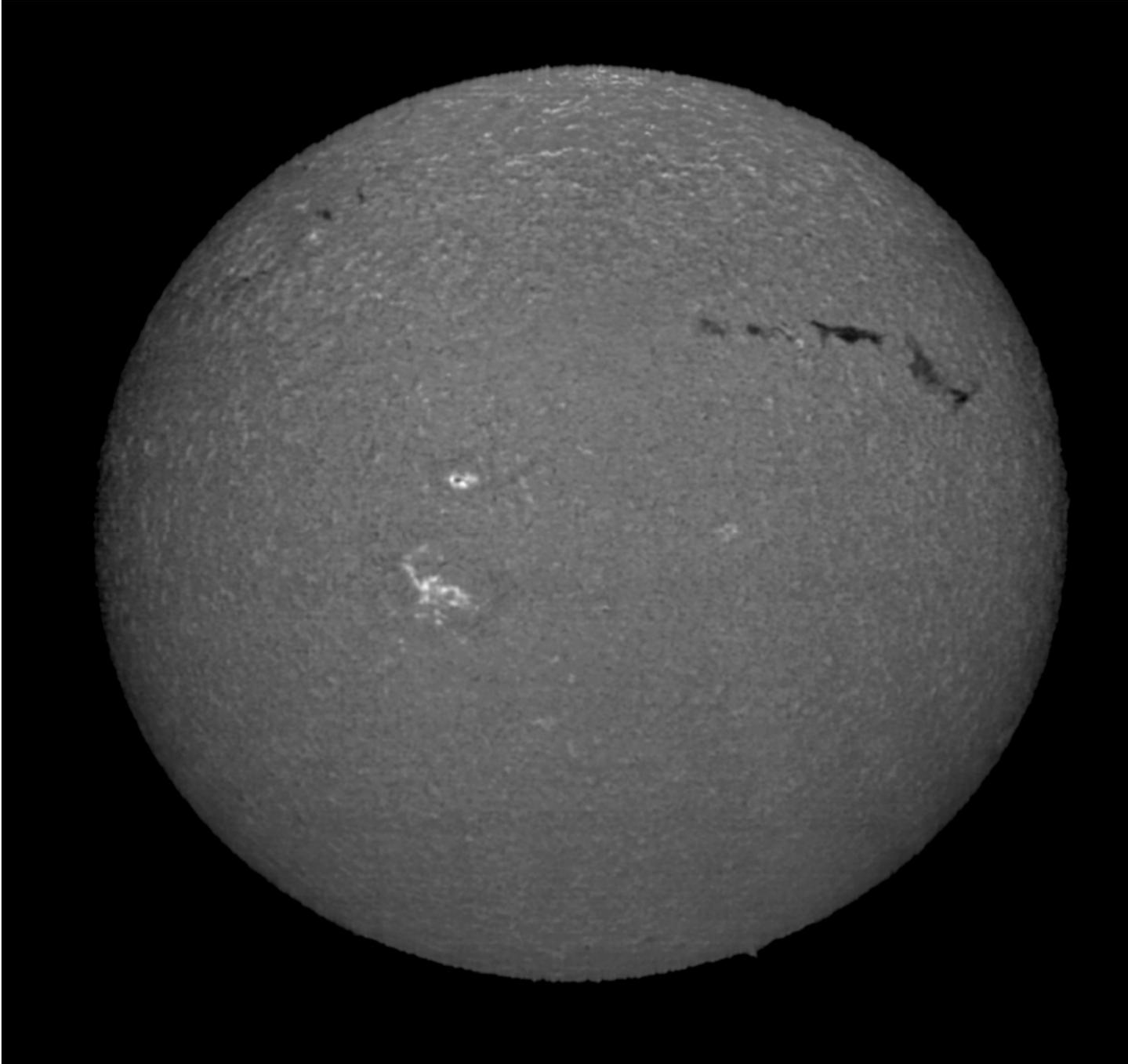


The image of the series at the very center of the line



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.

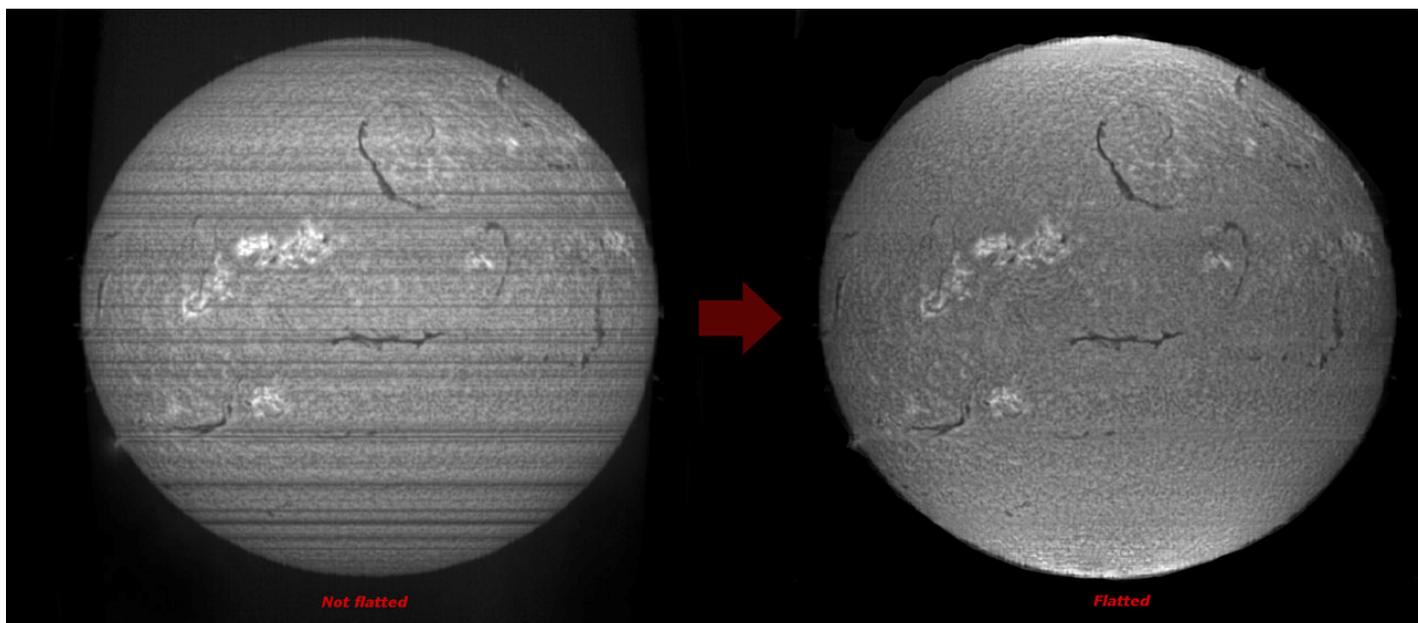


2 - The synthetic flat

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 SLiM, indicate the procedure to carry it out. In any case, these are operations of a certain complexity, so I posed the question of finding a simpler and quicker way for this task. I knew that Astroart software allows, in all its versions, 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 AA
- 2- On the duplicate, perform the binning X average operation
- 3- Subtract this binning image from the main one (arithmetic> subtract)
- 4- To improve the visibility of the image, perform an "add offset" (arithmetic> 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. 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.

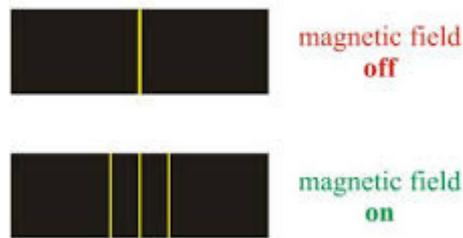


Not just imaging

After this overview on the possibilities offered by the digital SHG, 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 to professional instruments costing millions of euros or dollars. But let's go step by step.

A brief reference to the Zeeman effect

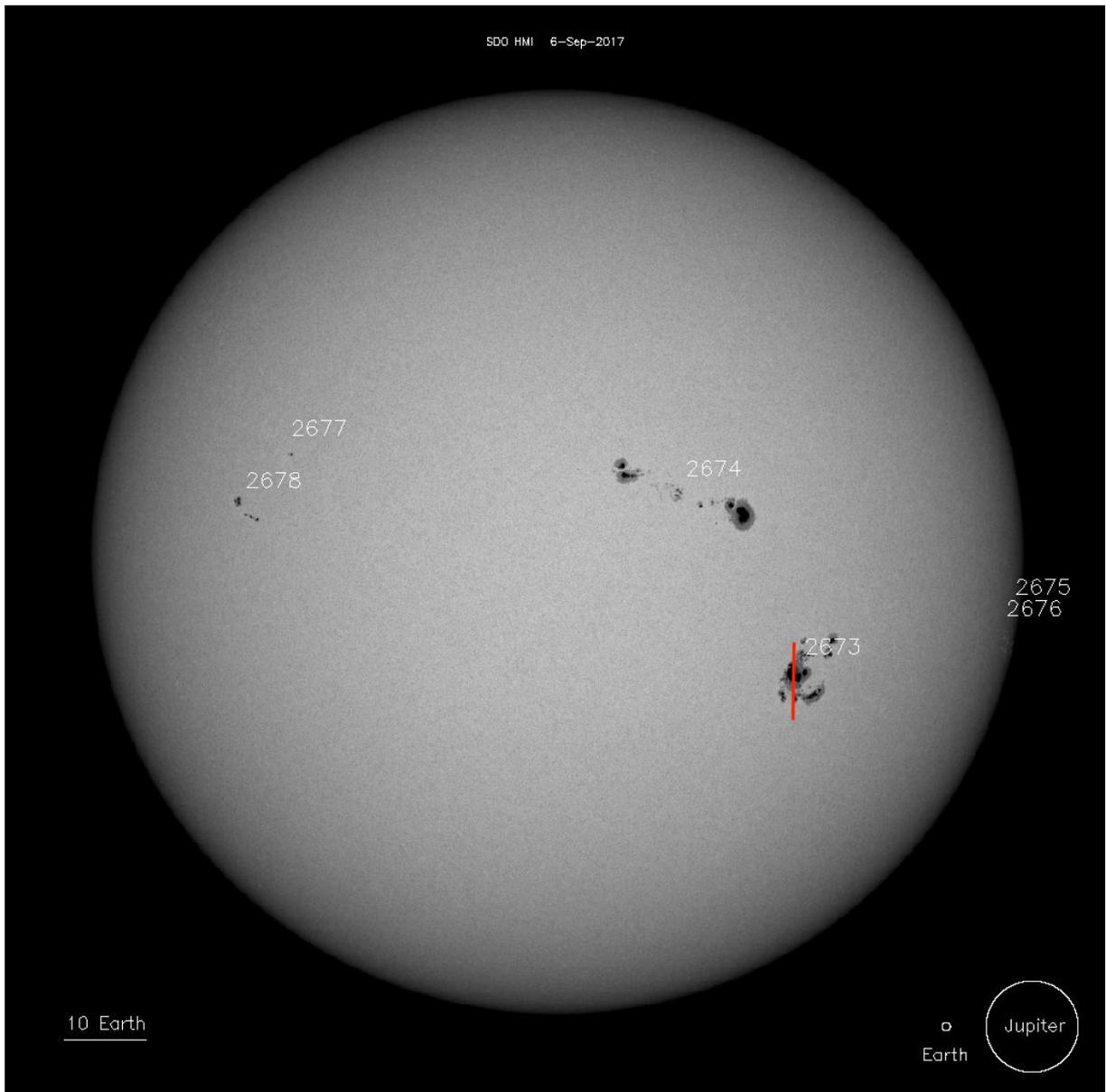
The Zeeman effect consists of enlarging or splitting into several parts of a spectral line by the effect of a magnetic field. More specifically, the Zeeman effect can be defined as the physical phenomenon connected to the decomposition of the atomic energy levels or the spectral lines due to the action 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 his name, 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 now talk 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.



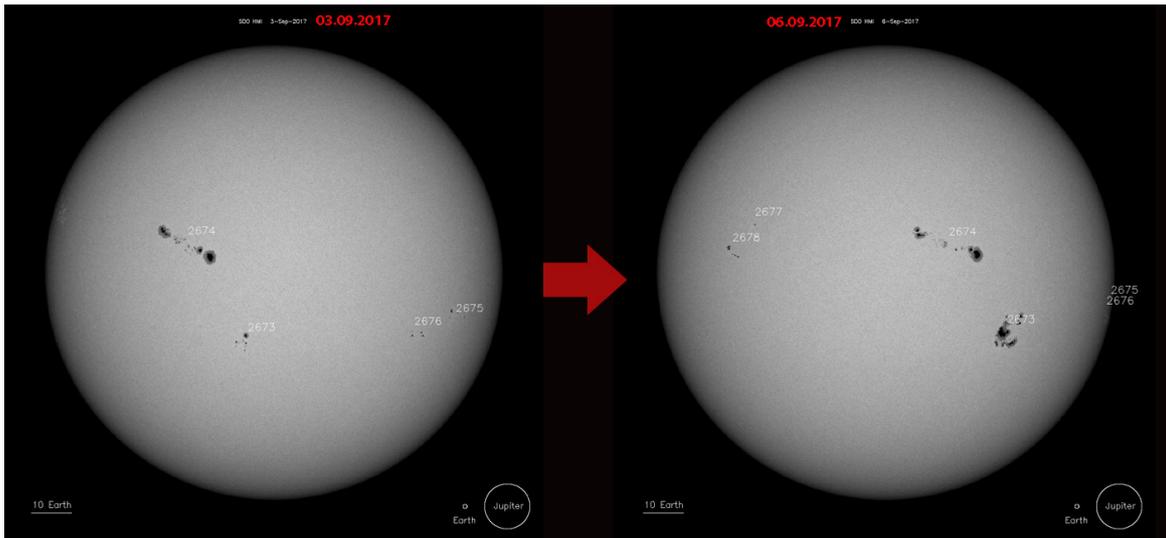
If the line is in emission we speak of direct Zeeman effect, while if it is in absorption, of inverse Zeeman effect. From the point of view of amateur astronomy, the phenomenon in question is very difficult to observe due to the simple fact that it requires very high spectral resolution powers (in my opinion $R > 60,000$) and a certain familiarity with the solar spectrum lines for the identification of the iron lines affected by the phenomenon, among which first those FeI at 6173 and at 6302Å. 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 SHG and a DMK 41 camera, with a 1280 x 1024 Sony sensor on a Losmandy G11 mount. This instrument, built to professional criteria, was excellent under all the aspects, however, for such a difficult task it was necessary to strengthen even more its features and potential. A decisive increase of the performances could be obtained, all other conditions being equal, only by working on the slit. I therefore decided (not without some regrets) to replace the original motorized adjustable slit (with its sophisticated and complex spring system), with a fixed 5 micron slit, purchased from Edmund Optics, whose edges were precision laser cut 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 solution, 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.

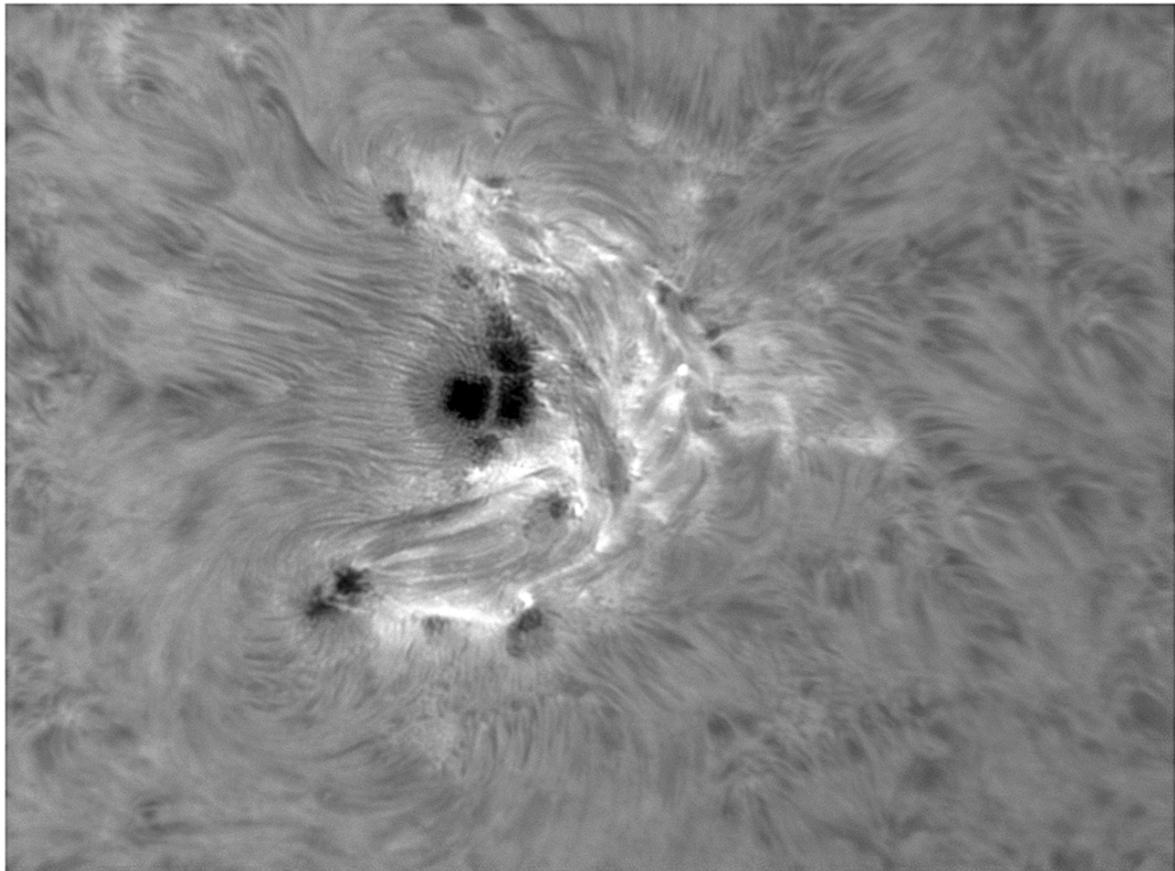
The case of the most intense sunspot of 2017, AR 2673, was an example. The observation was carried out on September 6, 2017. This sunspot was part of a rather complex active region as seen in the figure below (Source: SDO-HMI) which also shows the position of the slit during the observation.



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



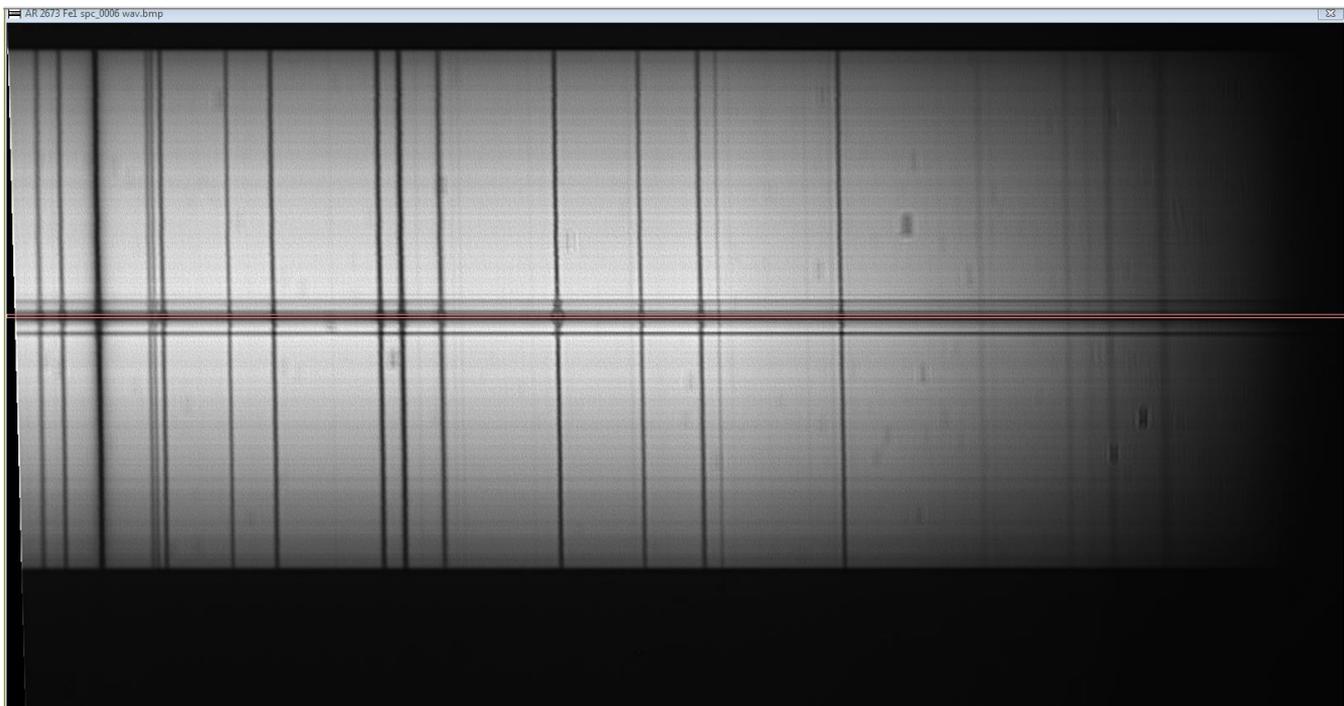
Evolution of AR 2673 in only three days, from September 3, to September 6, 2017.



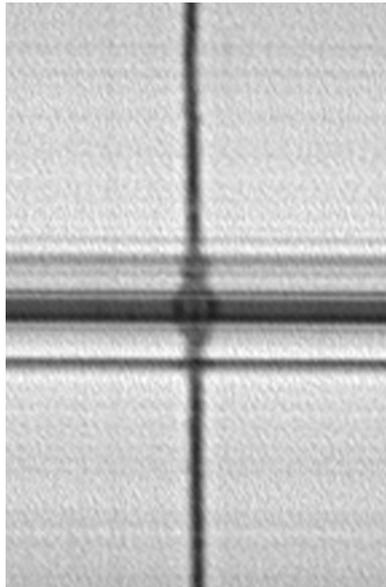
The complex activity around the sunspot AR 2673: photo by the author in $H\alpha$ light with a modified (with a 70mm ERF in the optical path) achromatic refractor 150mm aperture and 900mm focal length, and a $H\alpha$ Daystar Quark chromosphere filter.

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 precise measurement of its magnetic field in non-polarized light.

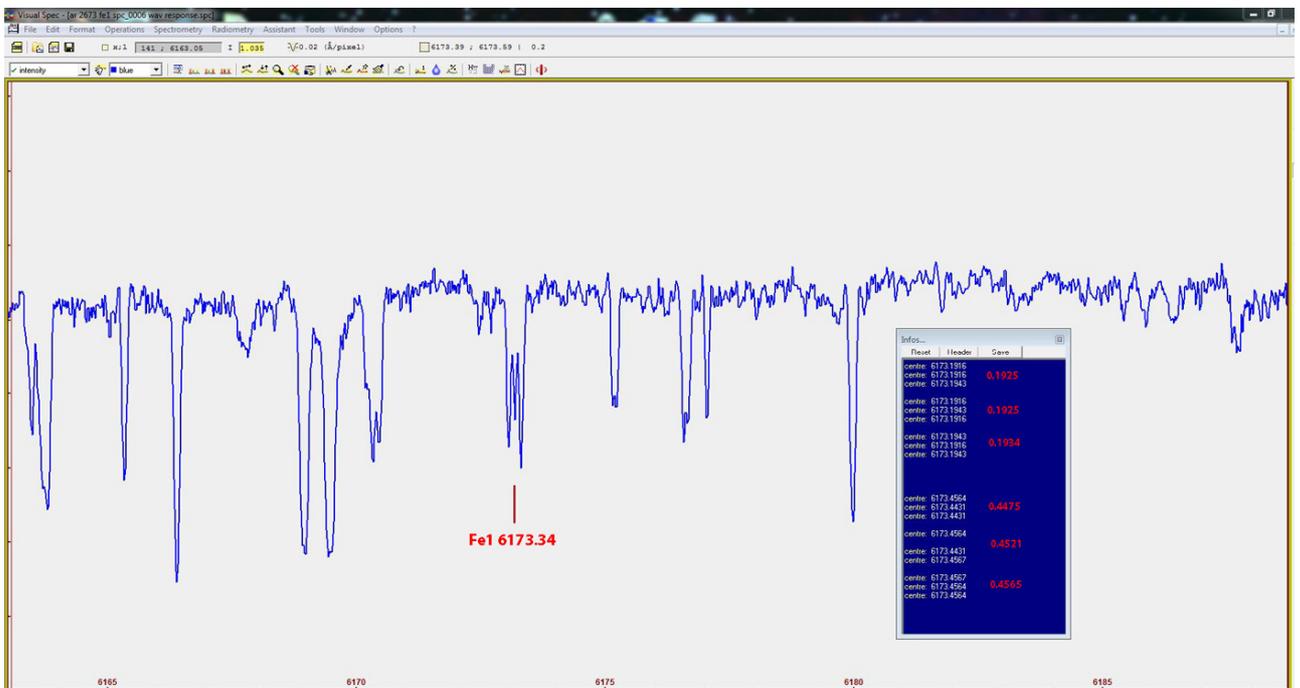
The chosen spectral line was that of the FeI at 6173 Å. For the acquisition of the videos, an Imaging Source DMK 41 camera was used, with 1280 x 1024 pixels, and the dispersion was 0.02Å/pixel. The spectrum on the line was as follows: the most intense central transverse line is the appearance of the 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 was 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). The image below shows the spectral profile from 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 measured $\Delta\lambda$ was 0.1296.



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

λ è la lunghezza d'onda della riga;
is the wavelength 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 speed 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 FeI line at 6173.34Å with a Landè factor value of 2.5 (values rounded to 1/100) the generic formula became:

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

In this case, $\Delta\lambda = 0.1296$

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

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 ***

This demonstrates how an instrument essentially conceived for spectroheliography can be successfully applied to a task in some ways much more challenging and difficult. Measuring the Zeeman effect, was once the prerogative of some solar towers, like the one of the Rome Observatory, where this task of measuring magnetic fields of sunspots was carried out in the 1970s in a collaborative work with that of Mount Wilson, in USA. Now achieved by an amateur in Rome.

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

Note

*) For more detail on the working methods used in obtaining the measurement, 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 basic camera costing a few tens of euros or dollars.

It is a further demonstration of how the progress of computer 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

A handwritten signature in black ink, reading "Fulvio Martini". The signature is written in a cursive, flowing style.



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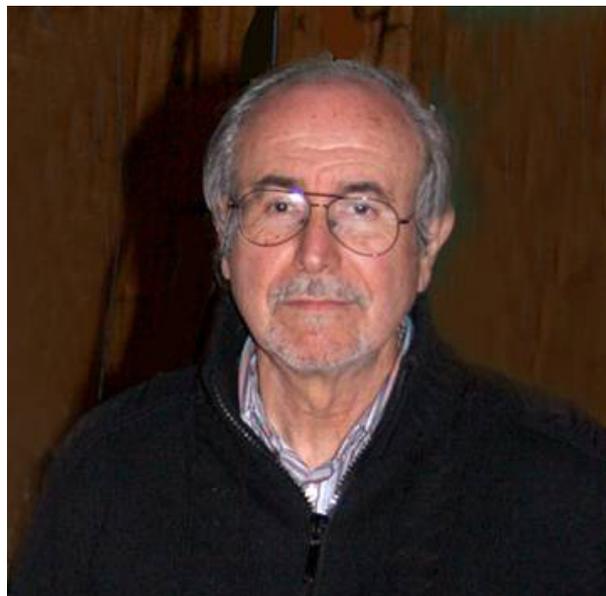
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The author



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 astronomical magazines (Coelum, Nuovo Orione, Astronomia UAI), as well as articles in English and French in foreign publications. He has designed, built and still builds DIY 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/>