DIGITAL SPECTROHELIOGRAPHY

Second updated edition

Spectroscopy is that branch of physics that studies the spectra of electromagnetic radiation emitted or absorbed by matter. Spectroscopic analysis allows us to identify the chemical composition and physical state of the body emitting the radiation.

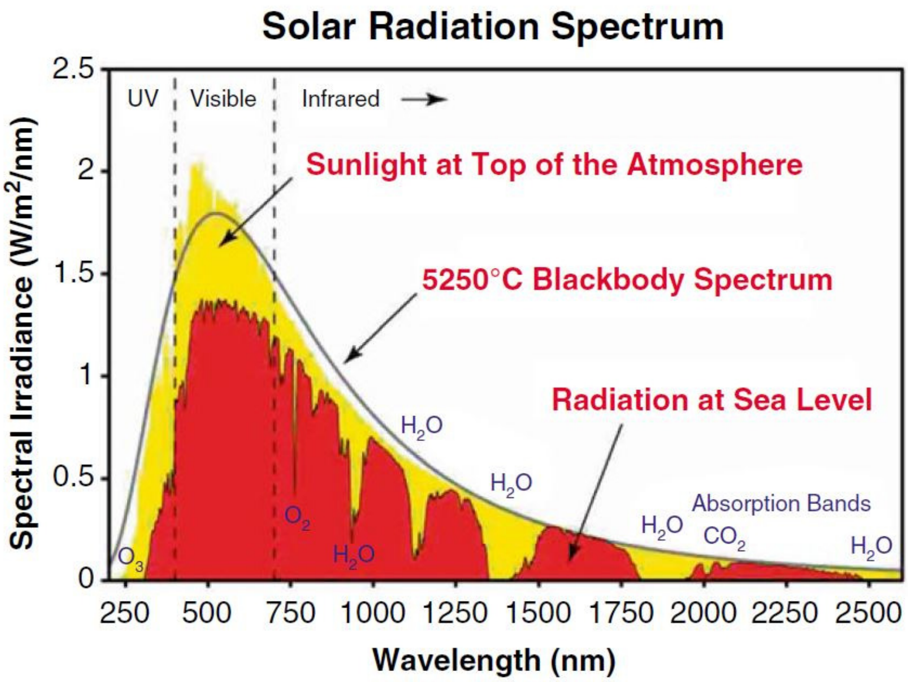
Newton's experiment on the breakdown of white light can be considered as the beginning of modern spectroscopic research. Over three centuries ago Isaac Newton (1642-1727) demonstrated that white solar light could be broken down into light of different colors using a prism. He also discovered that a shorter wavelength corresponded to a greater angle of refraction, and that the spectrum went from violet to red.

Spectroscopy, as soon as it was born, would soon become the most powerful means of investigation in astronomy.It provided an extraordinary means of discovering the physical and chemical properties of stars and would produce results that changed the face of astrophysics and our very existence with discoveries which profoundly affected the conceptual and philosophical fabric of the universe that surrounds us.

After the first experiments on the decomposition of light with a glass prism carried out by Isaac Newton and Francesco Maria Grimaldi in the seventeenth century, a first systematic study of the solar spectrum was carried out in the early nineteenth century by Joseph Von Fraunhofer who catalogued 574 dark lines within the solar spectrum, assigning a letter to the most obvious ones (the famous H and K of Calcium and the C and F of hydrogen). He also demonstrated that the energy distribution of the Sun varies as a function of the wavelength , peaking in the green, around 500 nm.

It is therefore no coincidence that the sensors of digital cameras and reflex cameras present their maximum quantum efficiency precisely in this area of the spectrum, in which the human eye also has the maximum sensitivity. Fraunhofer was unable to explain the phenomenon of the dark lines in the solar spectrum. Only in 1859 did Gustav Kirchoff (1824-1887) interpreted these lines as selective absorption of light by chemical elements present in the solar atmosphere. Kirchoff demonstrated experimentally that incandescent solid bodies, liquids and gases at high pressure show a continuous spectrum, the colors follow one another without interruptions of any kind (continuous spectrum), while incandescent gases at low pressure emit a number of bright lines on a dark background (emission spectrum).He also demonstrated that the dark lines produced by a low density, low temperature gas, interposed between a continuous spectrum and the observer, occupied the same position as the bright lines caused by the same gas when incandescent (absorption spectrum).

Referring to everyday life, a classic example of a continuous spectrum is that of a common incandescent or halogen lamp. A mercury or neon lamp has an emission line spectrum, while a common example of an absorption spectrum is the solar one.



Distribution of the Sun's energy as a function of wavelength, (WIKI).

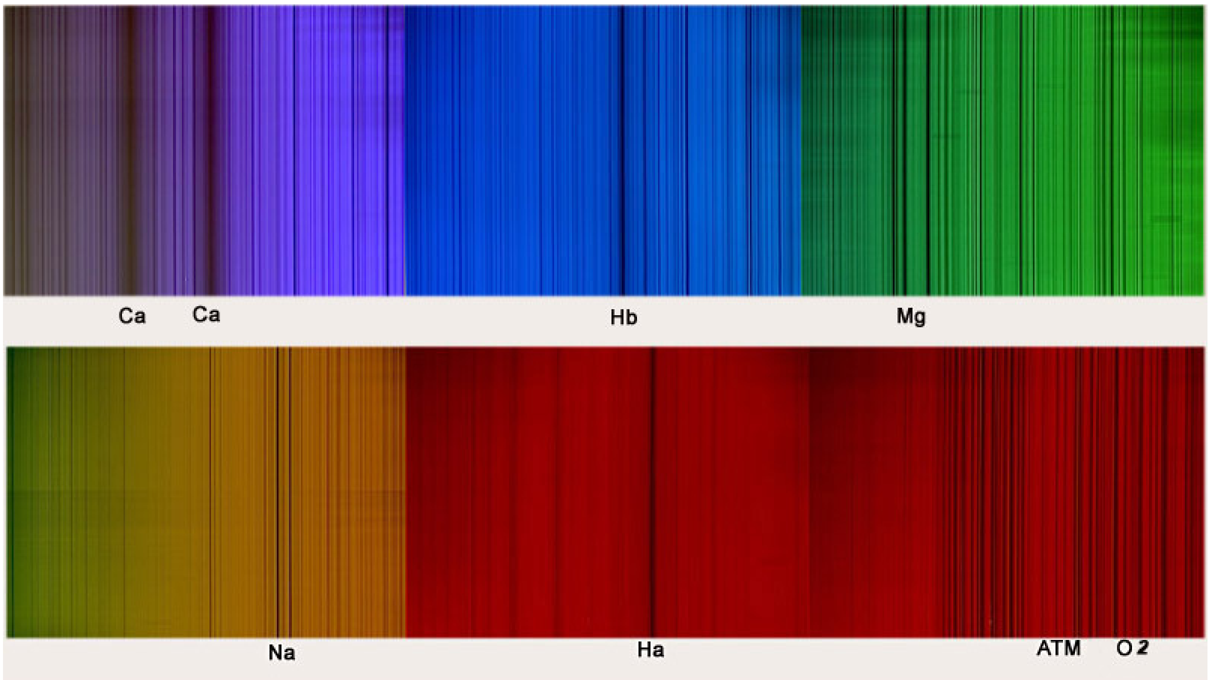
From the graph above we can also deduce data on the relative distribution of this energy with 7% in the UV (<3800 Å), approximately 53% in the visible (3800-7000 Å) and 40% in the Infrared (> 7000 Å) , which demonstrates the absolute necessity of observing the sun with eye-safe filter systems.

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 where 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 umbra of a sunspot, etc.

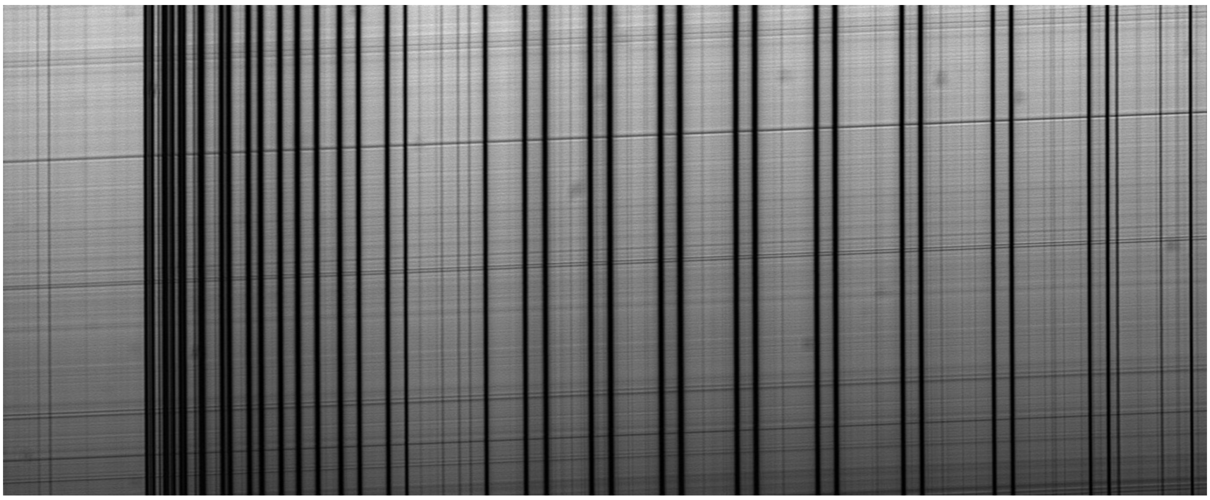
Furthermore, in the solar spectrum there exists a phenomenon of variation with the heliocentric angle for which a spectrum obtained at the centre of the Sun differs, even if not in a very pronounced way, from a spectrum obtained at the limb. The "standard" solar spectrum it can be obtained in two ways: either image the centre of the solar disk making sure that there are no spots in the imaging field, or image the sun as a star, and more precisely a G2V class star. Also characteristic of the Sun, like other stars , is the abrupt decrease in spectral intensity towards violet at the wavelength of 3646 Å, the so-called "Balmer jump" or Balmer discontinuity.

The solar spectrum

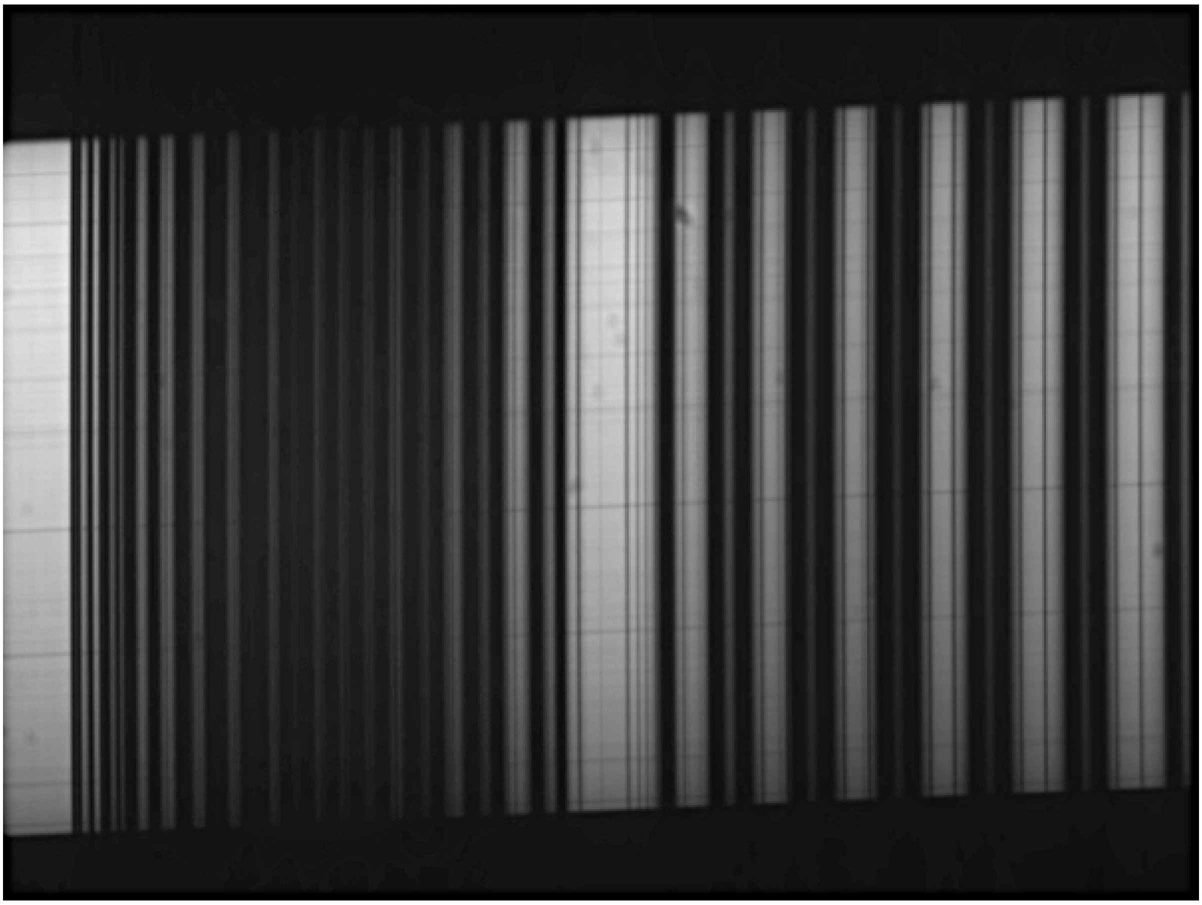
The spectrum of sunlight appears rich in absorption lines even with a modest spectroscope: some of them are actually caused by the Sun, while others belong to the Earth's atmosphere (telluric lines). The actual solar spectrum constitutes a unique laboratory for scientists physics enthusiasts and also for astronomical spectroscopy enthusiasts. The lines of the Balmer series of Hydrogen, Calcium, Magnesium and diatomic Oxygen are evident and appear, at medium resolution, as in the image below (TSA spectrograph), photo by the author.



Most of the weak lines belong to water vapour (H_20) and change in intensity depending on the degree of humidity, while others belong to diatomic oxygen (O_2), the latter concentrated largely in the deep red at the boundaries of the IR, at 6800 and 7600 Å (in order, the first and second of the figures below, photos by the author).



O_2 at 6800 Å



O_2 a 7600 Å

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

1-The chemical elements present on the Sun, given that the lines associated with a given wavelength constitute actual fingerprints characteristic of each individual element.

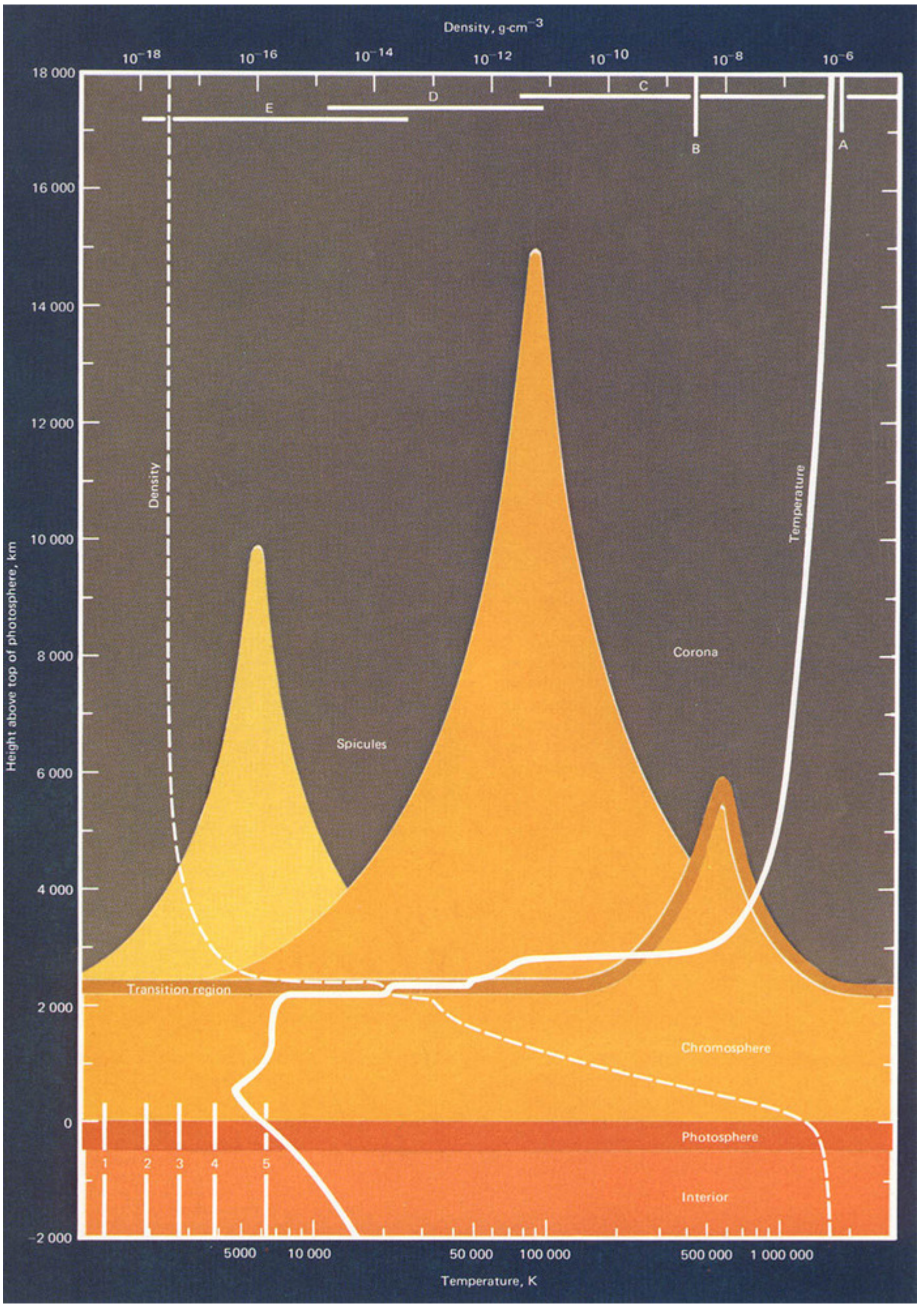
2-The atomic abundance of the element, deduced from the intensity of the lines.

3- The temperature at which the elements producing the line or their atomic transitions are found, given that the transitions at different atomic levels occur at different temperatures. The temperature can also be derived from the width of the line concerned.

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

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

The following figure (source NASA-Skylab) shows the diagram of the photosphere, chromosphere and solar corona based on height, temperature and density. From it you can see the distribution of the points at which certain phenomena and transition occur .

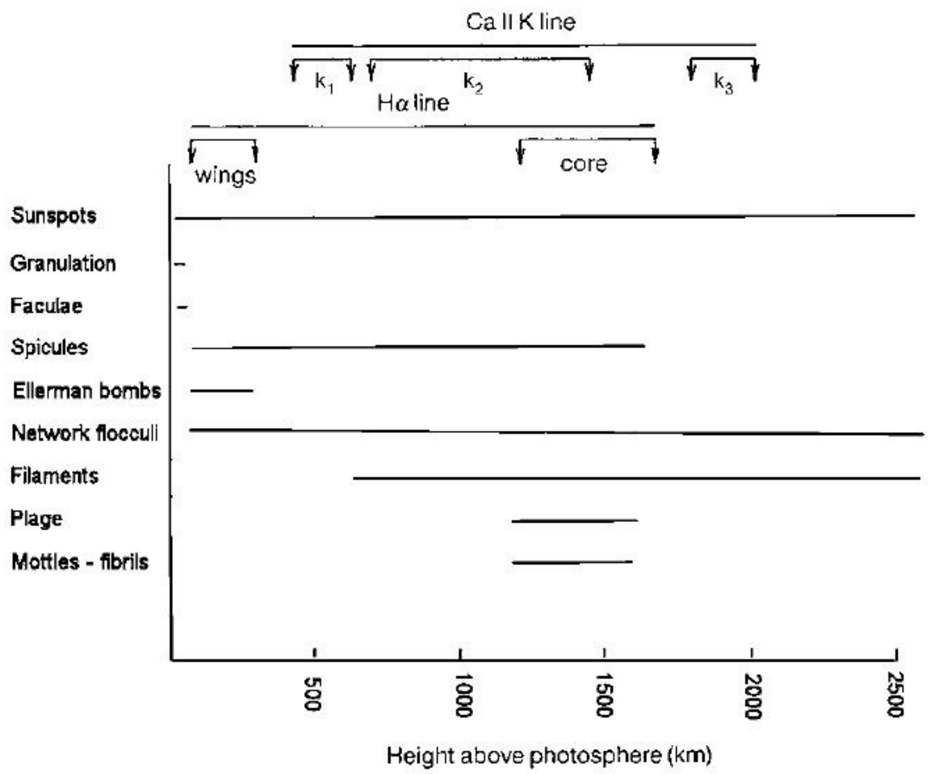


The table below (https://solarnutcase.livejournal.com/9556.html) shows, for the main lines, the element to which they belong, the EW (equivalent width) and their location in the solar atmosphere, with data related to height and temperature.

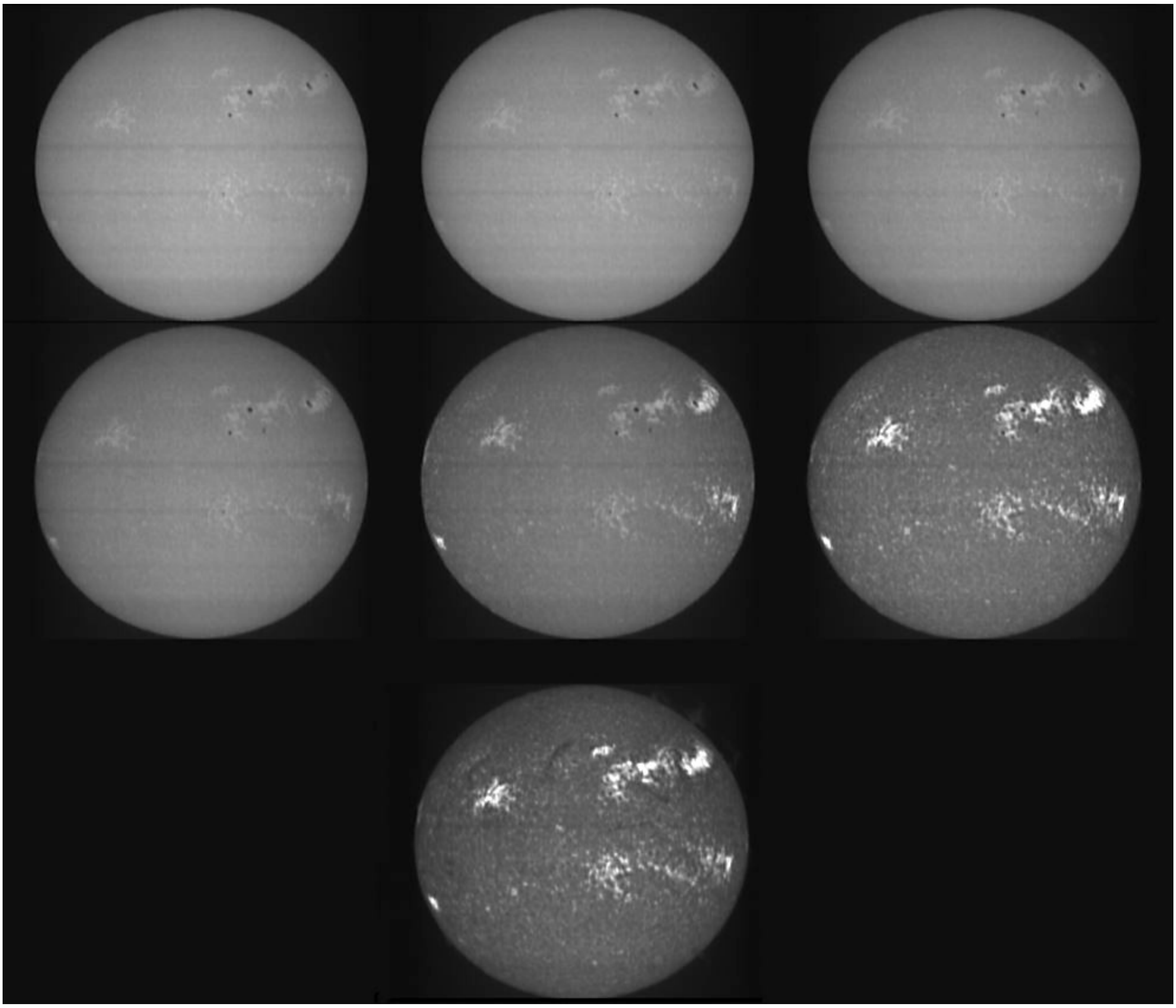
Wavelength (nm)	Name	Species	Equivalent width (nm) Disk Centre	Region	Height above Photosphere (Km)	Temp (K)
Soft X-rays				Corona	>5000	2,000,000
121.57	Lyman a	H		Upper chromosphere	2200	20,000
155		C IV		Transition region	2500	100,000
279.54	k	Mg II	2.2	UV emission, high chromosphere	500-1600	
280.23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

To further clarify the concept, the following diagram shows us how certain physical phenomena present on the sun (sunspots, faculae, filaments, plages, etc.) present a different appearance not only depending on the element in whose light they are recorded or observed (E.g hydrogen alpha or ionized calcium) but also if the observation is carried out at the centre of the line of the elements or on the wings, since going from the wings towards the centre 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 (CaII K3) line is located in the highest part of the chromosphere, around 2000 km above the photosphere, at the borders of the transition zone: not only that, but going from the edge towards the centre of this very interesting line, provides details of the structure of the chromosphere going from 500 to over 2000 km above the photosphere and going from around 5500 K to almost 10,000 K in temperature.



An evident demonstration of what was previously mentioned is the sequence of images of the solar disk that goes from the tip of the wing towards the blue of the CaIIK line to the boundaries of the continuum, up to the centre (CaIIK3) of the line itself. The brightness of the faculae and the visibility of the filaments on the disk intensify as one proceeds towards the centre of the line and therefore towards the highest part of the chromosphere. Sequence of images obtained by the author with the home-built digital SHG VHIRSS.



As we will see, therefore, spectroheliography is not just a simple substitute for the popular narrow band solar filters, but a scientific instrument that allows us to analyse each solar line, from the wings to the centre, operating a precise scan of the solar atmosphere.Now, there are thousands of solar lines, even 24,000 of them included in the atlas by Charlotte Moore and others, freely downloadable in the original text at the link:

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

Some of them are duplicated and tripled, i.e. too weak to be recorded with amateur means. However, in the opinion of the writer, there are potentially 7-8000 spectral lines which could be explored with very high resolution professional SHG. The most important of these, about fifty: Iron, Hydrogen, Calcium, Magnesium, Sodium, Helium, roughly a few more than those reported in the following table (source Columbia University, N.Y) are they lend themselves to being recorded by amateur instruments at medium-high resolution.

The table also shows the width of the lines in nm, which is important for spectroheliography purposes, as will be seen later.

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**

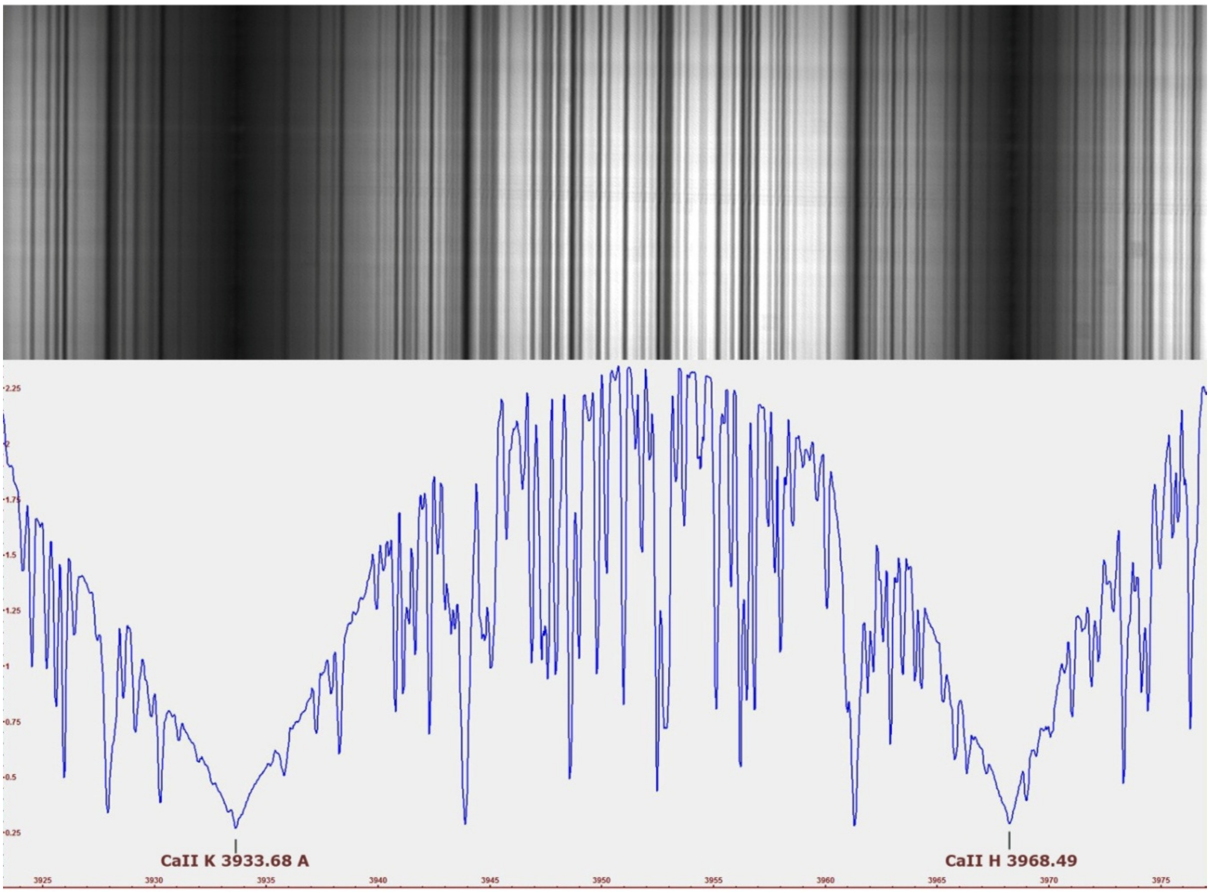
But already about fifty relatively easy lines (perhaps a hundred including the slightly more difficult ones), makes us understand the extreme usefulness and versatility of spectroheliography. Assuming they were available, and they are not, how much would it cost the amateur to purchase some fifty or hundred very narrowband solar interference filters? I'd suggest prices could range from € 200,000 to € 400,000, not to mention that filters with such a narrowband that they are capable of selecting lines or parts of a line of 1/50 of Å are probably not available to the amateur.

The most important lines of the solar spectrum

Below are the high resolution spectra of the most important elements present in the solar chromosphere, with the reference wavelengths (author's VHIRSS and POSS2 instruments).

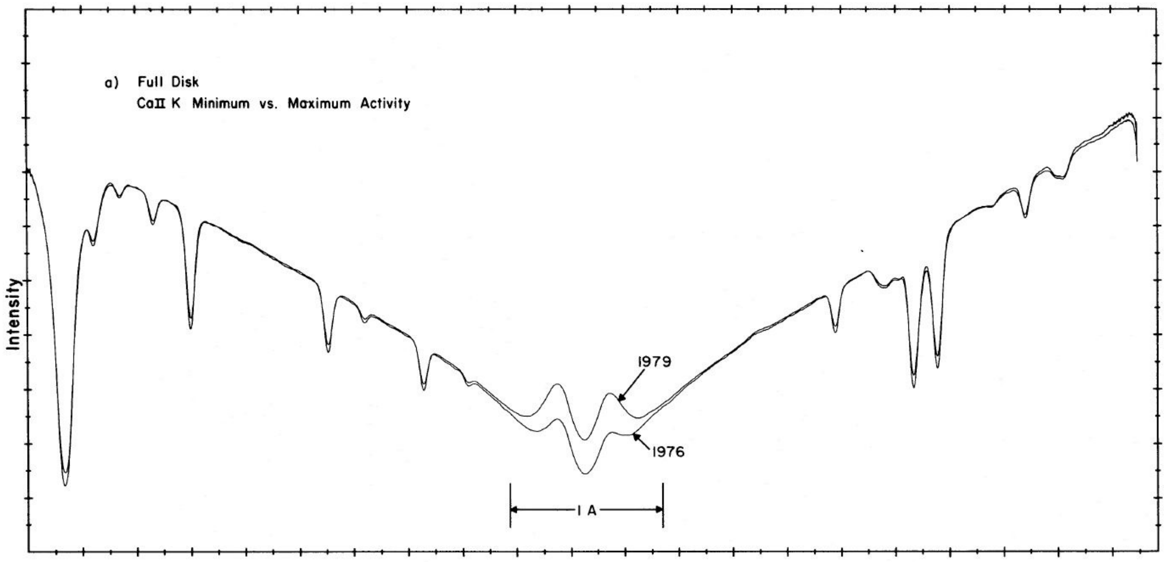
<u>Ionized calcium CaIIK and H lines</u>

POSS2 CaII K & CaIIH lines



The CaII K line is very important in the study of solar activity and the chromosphere in particular. The NSO (National Solar Observatory) of Sacramento Peak in New Mexico (USA) carried out, for a long period of time, from 1976 to 2015, a monitoring activity of the line in question, evaluating, among other things, the parameters of the emission index (EM) corresponding to the EW (Equivalent Width) of an interval of 1 Å centred on the line, and the intensity values of the core K3 (0.15 Å) of the line itself. Since October 2015 the

Sacramento Peak monitoring program has been suspended, as data from the SOLIS – ISS (Integrated Sunlight Spectrometer) project, active at the NSO – Kitt Peak are now used,with a spectrograph capable of resolution R= 300000 and a wavelength range from 350 to 1100 nm. Monitoring also extends to the CaII H line.



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

In addition to the ultraviolet, the ionized calcium line also appears in the near infrared, at 8498, 8542 and 8668 Å (Calcium triplet). The line most used by professionals, the one at 8542 Å , would however be rather difficult for an amateur to image, not so much due to the spectroscope, which would require a grating optimized for IR, but due to the poor sensitivity of amateur cameras at this wavelength.

However, the introduction in recent times of CMOS cameras with back-illuminated Sony sensors has changed the situation somewhat, making cameras with high sensitivity in the near IR also available.

The hydrogen lines observable on the Sun.

The hydrogen spectrum is the simplest of the spectra given that this element is made up of a nucleus containing a proton around which a single electron moves. Electrons move in quantized energy orbits. The 1s orbit is the innermost one, the ground state, to which the minimum energy corresponds. If the electron that is in a high energy orbit passes to a lower energy one, it releases radiation having a certain wavelength, giving rise to an emission line.

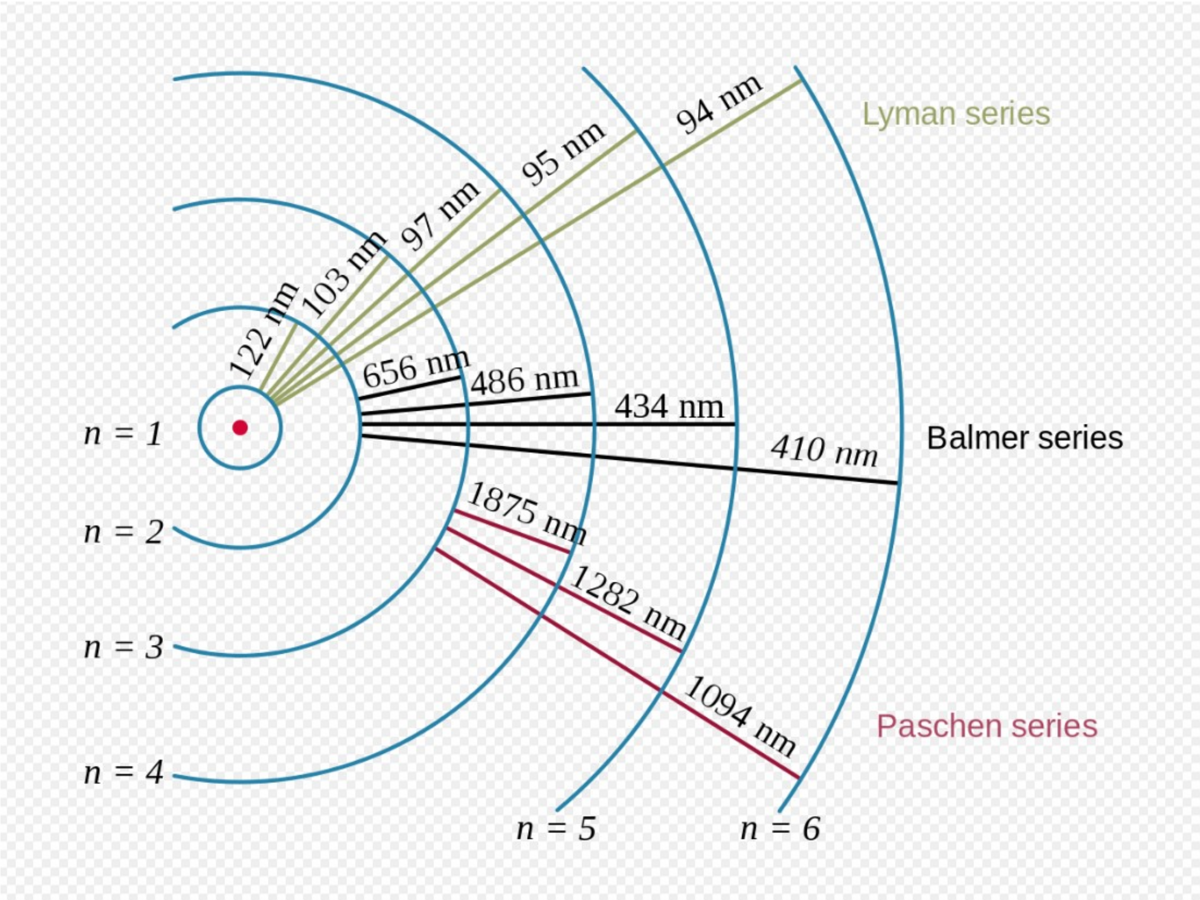
The transitions that electrons make from the peripheral orbits to the more internal ones can be ordered according to decreasing energy values: the highest variations are recorded when an electron passes from a peripheral orbit to the one corresponding to the ground state. The set of all these electron jumps that end in the 1s orbit gives rise to a series of spectral lines which are called the Lyman series, the first lines of which are indicated with Lα, Lβ, Lγ and correspond to the ultraviolet lines .

At immediately lower energy values there are jumps of the electron from the peripheral orbits to the second stationary orbit: we have energies typical of the visible spectrum and we obtain lines of the Balmer series. The first line originates from a jump from orbit 3 to orbit 2 and is indicated with Hα, the second from 4 to 2 and is indicated with Hβ while the third indicated with Hγ corresponds to the jump from orbit 5 to 2 and so on. The same thing is repeated for the Paschen series whose lines correspond to the energy of the IR lines.

Serie di transizione dell'Idrogeno

Livello piú basso	*transizione principale*
$n = 1,\ Lyman$	$L_\alpha = 1216\mathring{A}$
$n = 2,\ Balmer$	$H_\alpha = 6563\mathring{A}$
$n = 3,\ Paschen$	$P_\alpha = 18750\mathring{A}$

The following figure shows the scheme of the energy levels and main series of the hydrogen atom (Source Wikipedia-Hydrogen spectral series).



The Balmer series in the visible spectrum is undoubtedly the most interesting from our point of view, also because the ionized hydrogen Hα at 6562.8 Å constitutes by far the most abundant element in the solar atmosphere, the chromosphere, also giving it the red colour that distinguishes it.

Balmer's formula for the series that takes its name from him, in the visible, is the following:

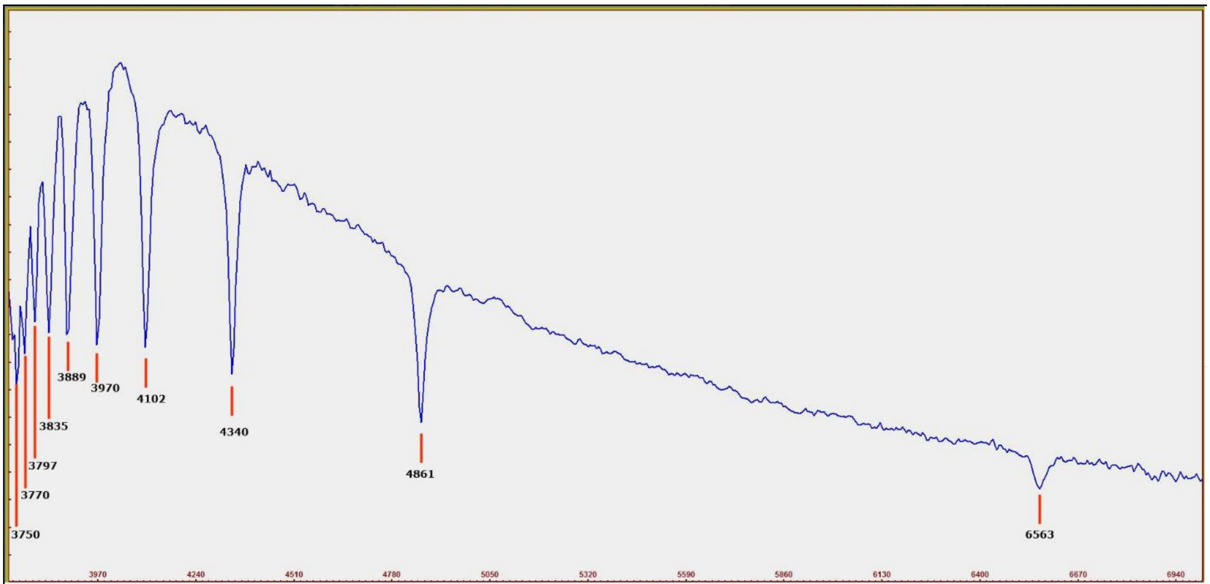
λ = B (m^ 2/ (m^2- 2^2))

where B is the Balmer limit at 3646 Å; m is any integer m≥2

Below, the absorption spectrum of the star Vega annotated with the Balmer series of Hydrogen up to the transition 12 > 2 as calculated by the author. (Author’s spectrum).

(For example, for the transition 10>2 is:

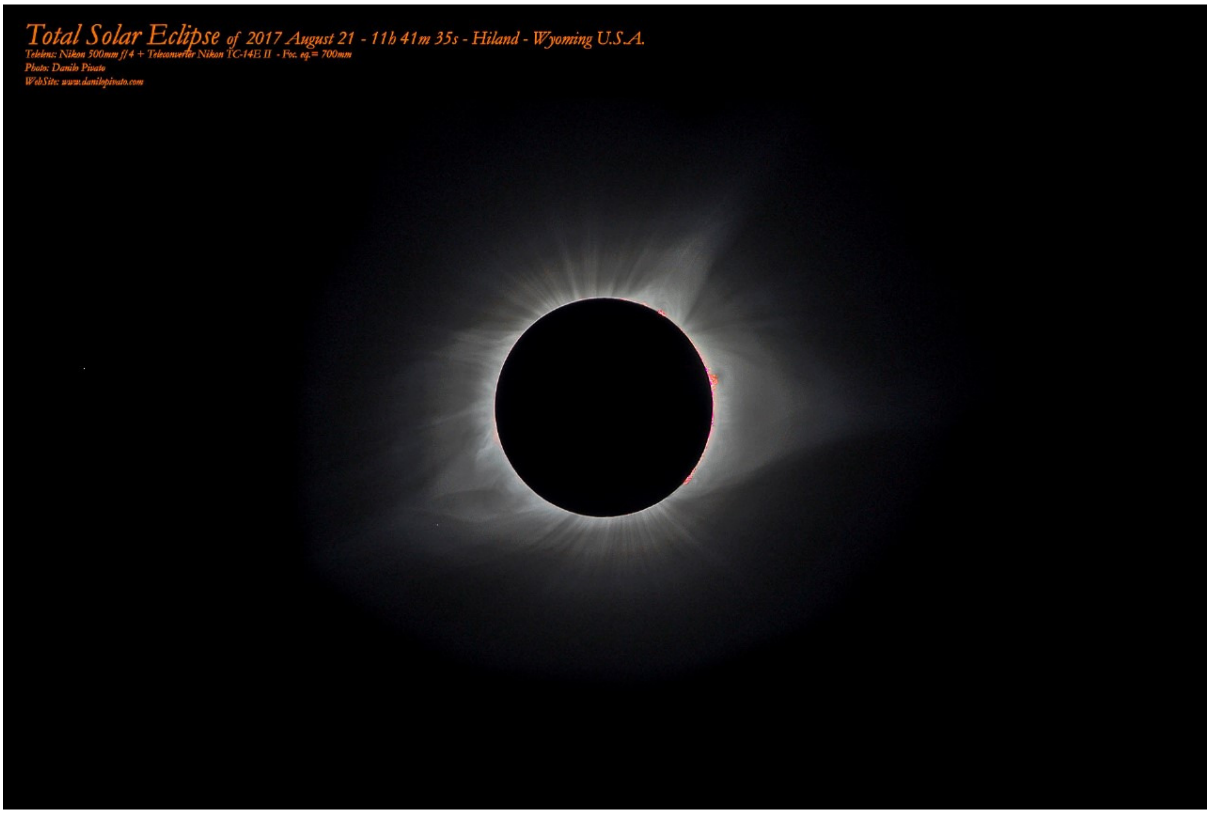
3646 x (100/96) = 3797 Å



Transizione	3→2	4→2	5→2	6→2	7→2	8→2	9→2	10→2	11→2	12→2
Nome	H-α	H-β	H-γ	H-δ	H-ε	H-ζ	H-η	H-?	H-?	H-?
Lunghezza d'onda (Å)	6563	4861	4341	4102	3970	3889	3835	3797	3770	3750
Colore	Rosso	Verde	Blu	Violetto	Violetto	Violetto	(Ultravioletto)	(Ultravioletto)	(Ultravioletto)	(Ultravioletto)

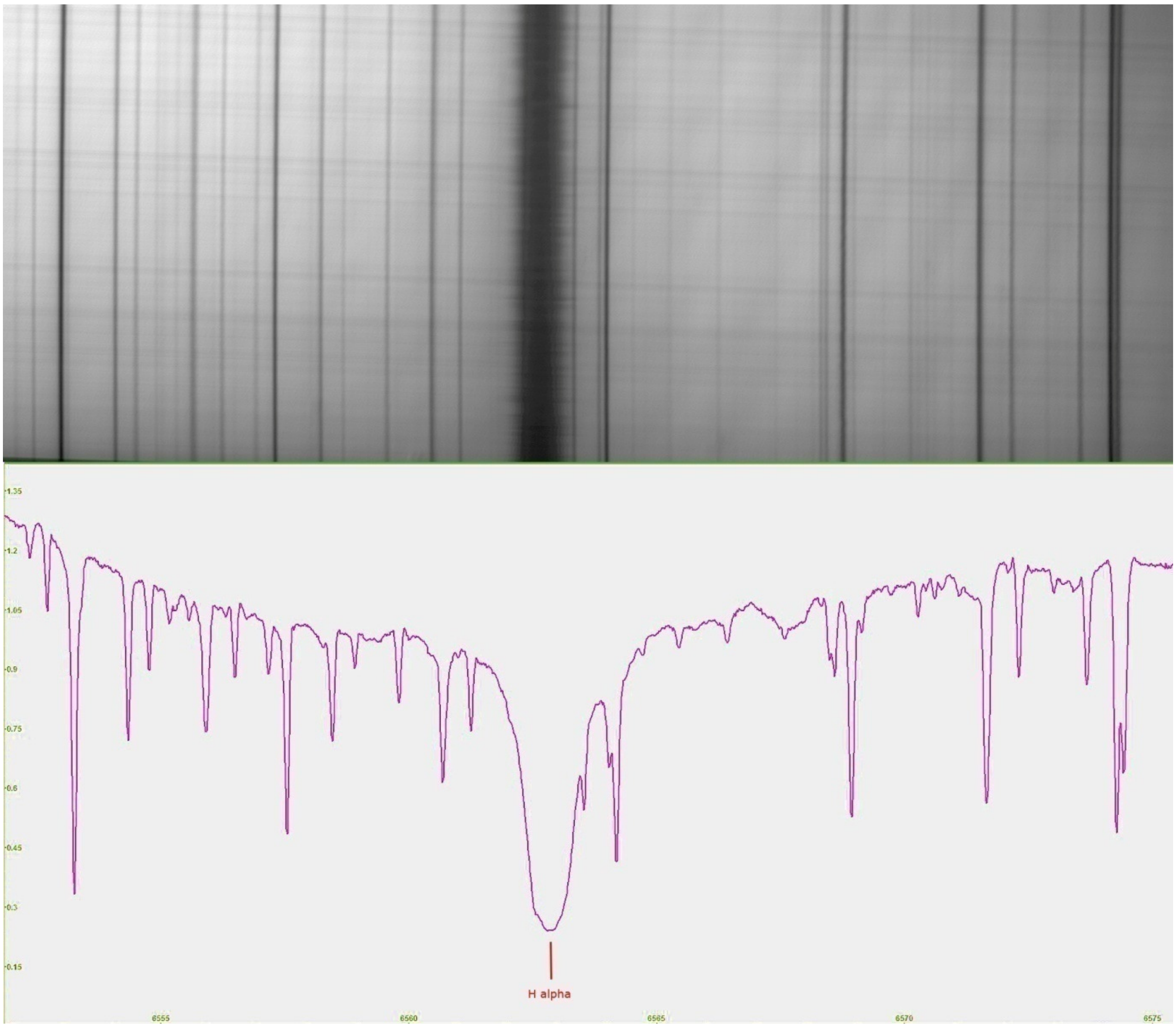
<u>The H alpha line</u>

As mentioned, the 3>2 transition of Hydrogen at 6562.8 Å (Hα line) causes the emission line that characterizes the chromosphere and gives it the characteristic deep red colour, which is easily observed in the solar edge during total eclipses, as in the following image by amateur astronomer Danilo Pivato taken during the 2017 eclipse .

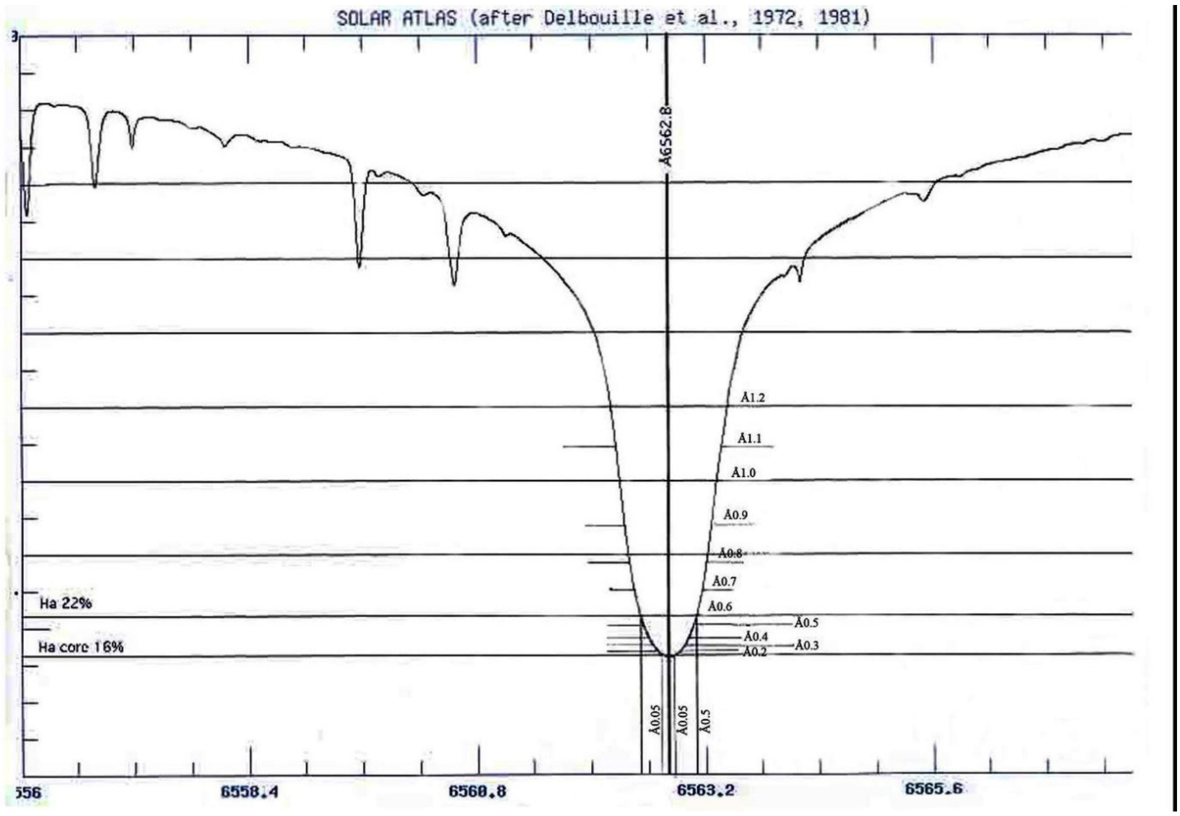


While the wings of the line come from the lower chromosphere, almost on the border with the photosphere, the central part of the same belongs to the high chromosphere, on average around 1500 km.

In high resolution (VHIRSS instrument) the Hα line in absorption appears as follows.



Profile of the Hα line in absorption showing the spread of the core and wings: the FWHM is on average 1-1.2 Ǻ (source: Debouille Solar Atlas_ Bass 2000).



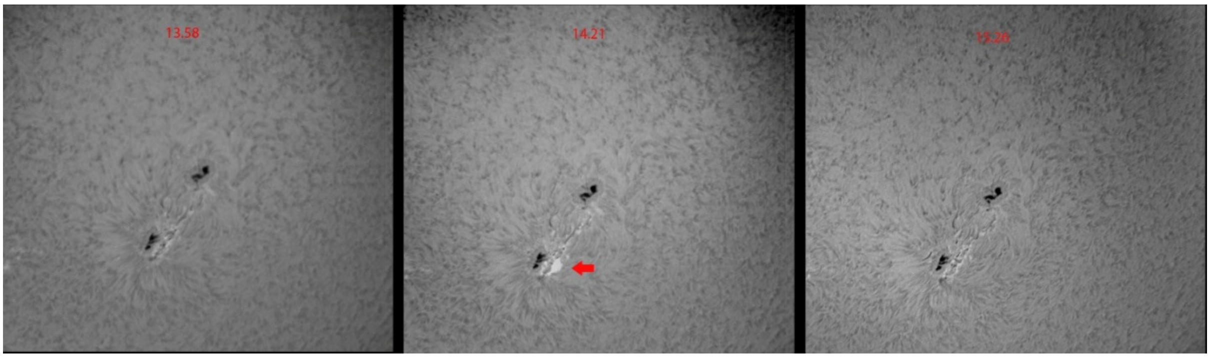
The Halpha line can therefore be considered the most important, together with those of ionized calcium, for the study of the solar chromosphere and the phenomena that occur in it. It is also the easiest absorption line to identify by those less expert in solar spectroscopy.

The Hβ line

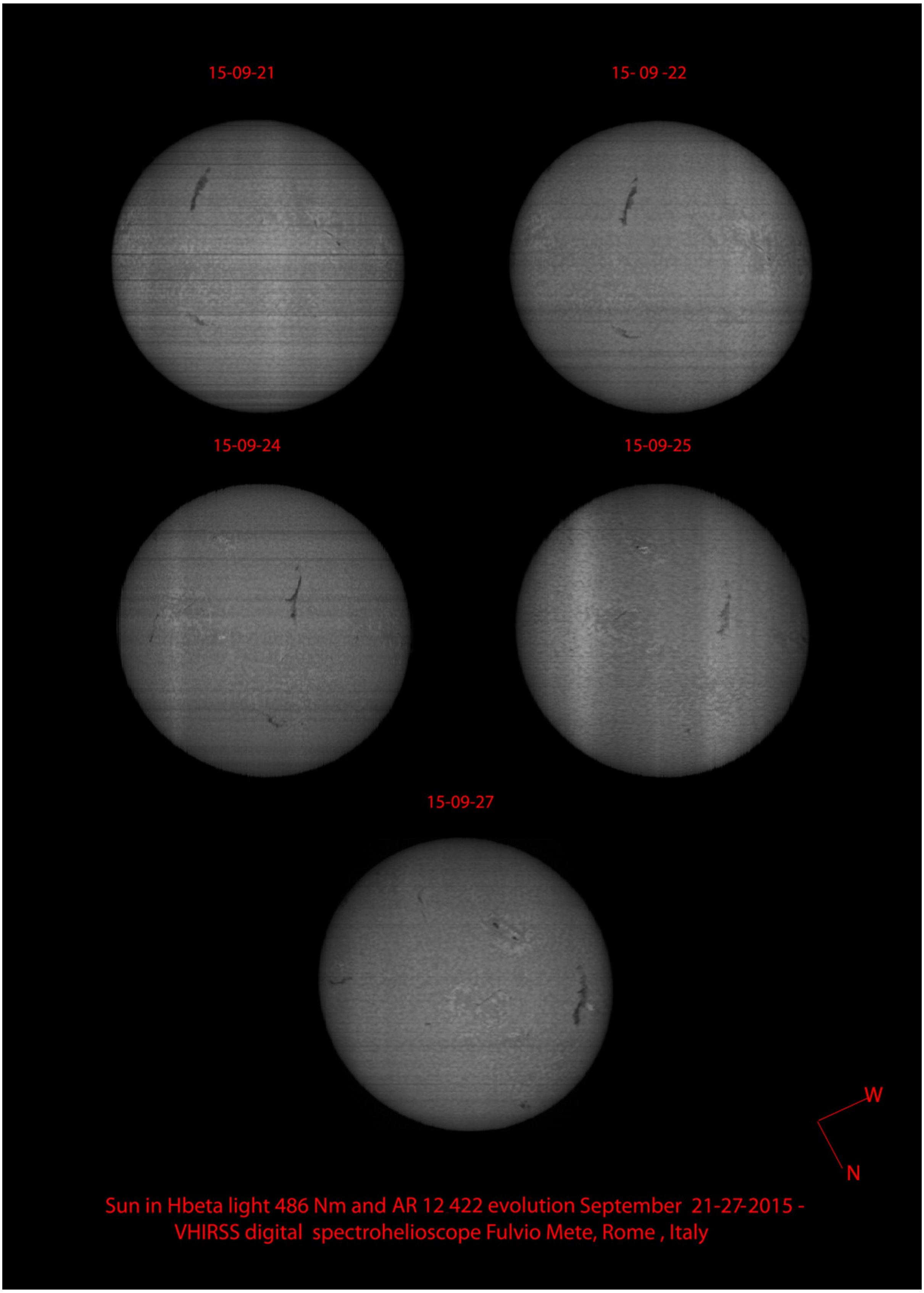
The Hβ line at 4861.34 Å would seem at first glance to be less important for the study of the solar atmosphere, both due to its smaller width compared to the Hα and the attenuation of the details themselves, primarily plages and filaments. However, it is necessary to evaluate the good observability of solar flares in the spectroheliograms in this line.

The author, participating in the professional survey “F-Croma” was able to verify this characteristic with a small flare observed on 27 September 2015.

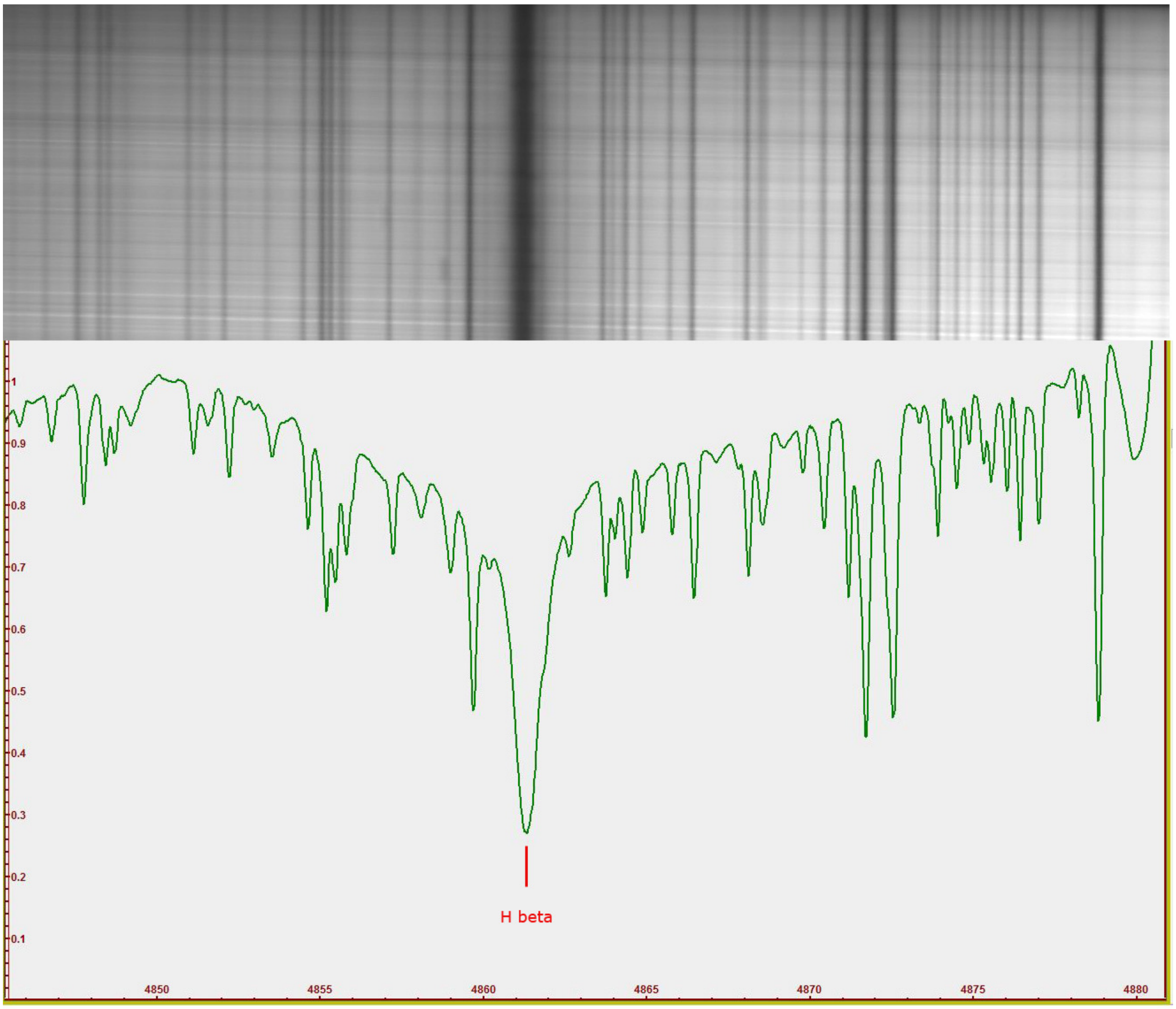
As the background plages appear darker, explosive plasma phenomena such as flares tend to be more evident.



The following image shows the sequence of spectroheliograms in Hβ light obtained by the author during this observation campaign with the VHIRSS.

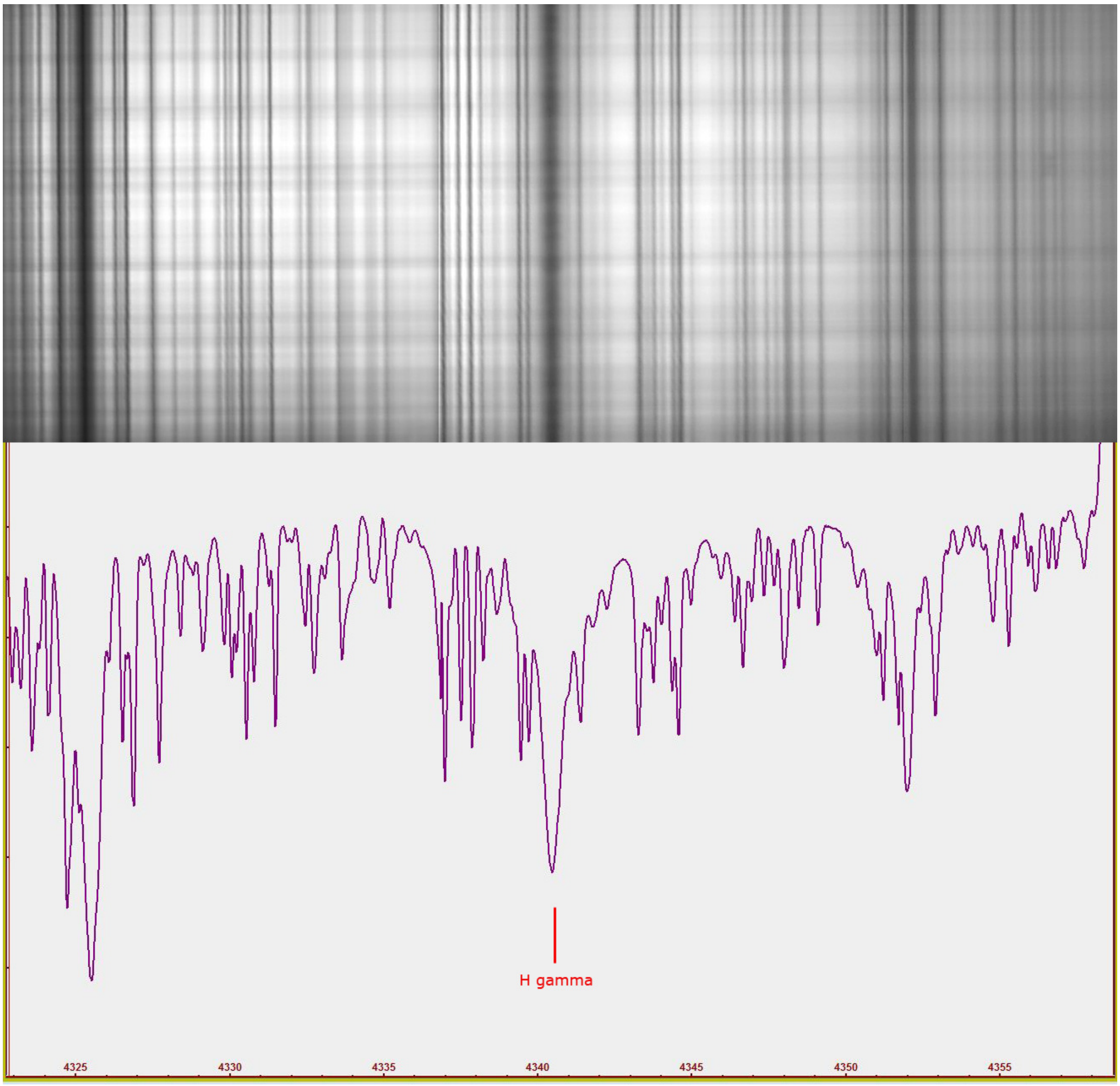


In the image below the Hβ line as obtained at VHIRSS focus.

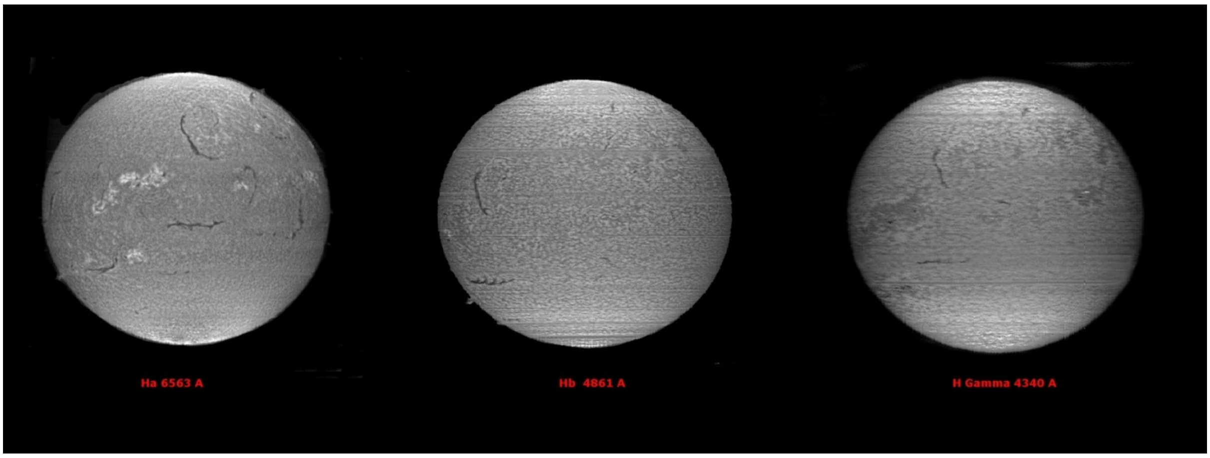


<u>The Hγ line</u>

The same applies for the Hγ line at 4340.47 Å as for the Hβ line, in the sense that in the spectroheliograms obtained in this line the visible details are much less bright and evident than in the other two.



The following image shows the comparison between the spectroheliograms obtained with VHIRSS of these three Hydrogen lines.It is clear that, going from Hydrogen alpha to the lower wavelengths, the plage areas lose their brightnes and pass to increasingly darker grey, while the filaments lose contrast.

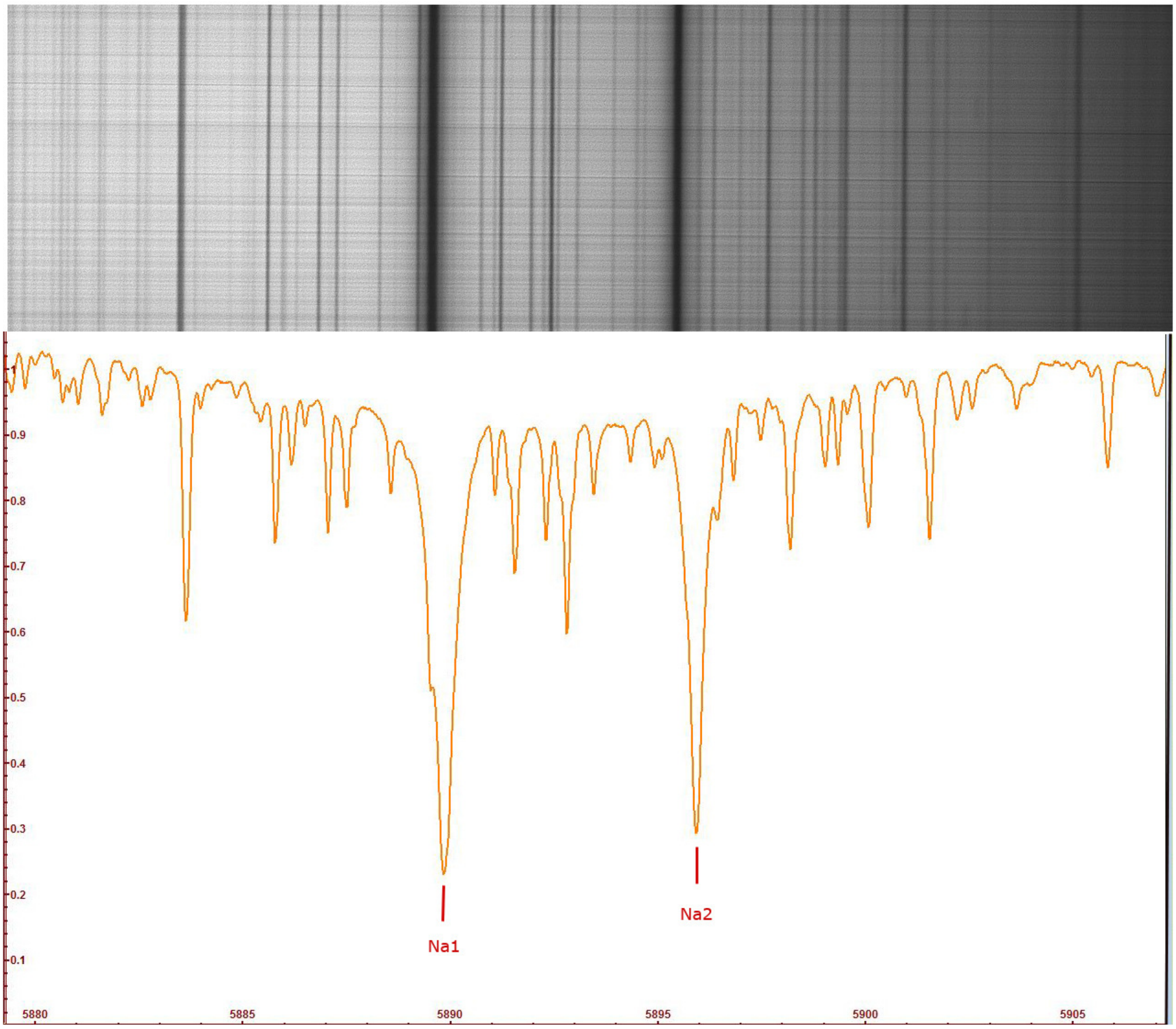


The Na lines 1 and 2 (sodium doublet).

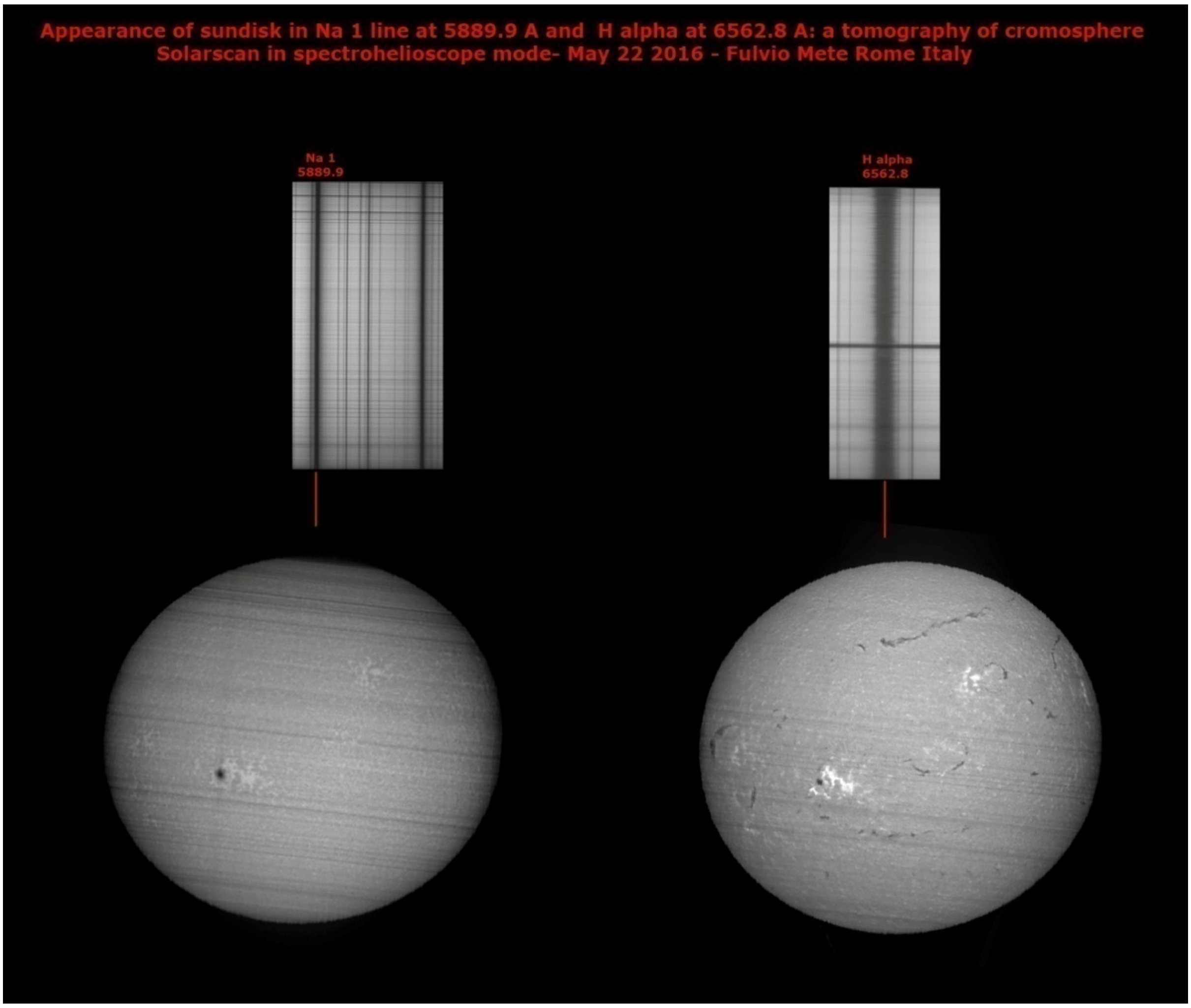
These lines, at 5889.97 and 5895.94 Å respectively, at low excitation, belong to the lower part of the chromosphere and are evident when the lower chromosphere is heated, often showing the nucleus of the impulsive phase of the flares, or the faculae.

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

In the following image taken with the Solarscan spectrograph the two sodium lines: the lines inside the doublet do not belong to the Sun (with the exception of the nickel line, which is more pronounced), but to the Earth's atmosphere.

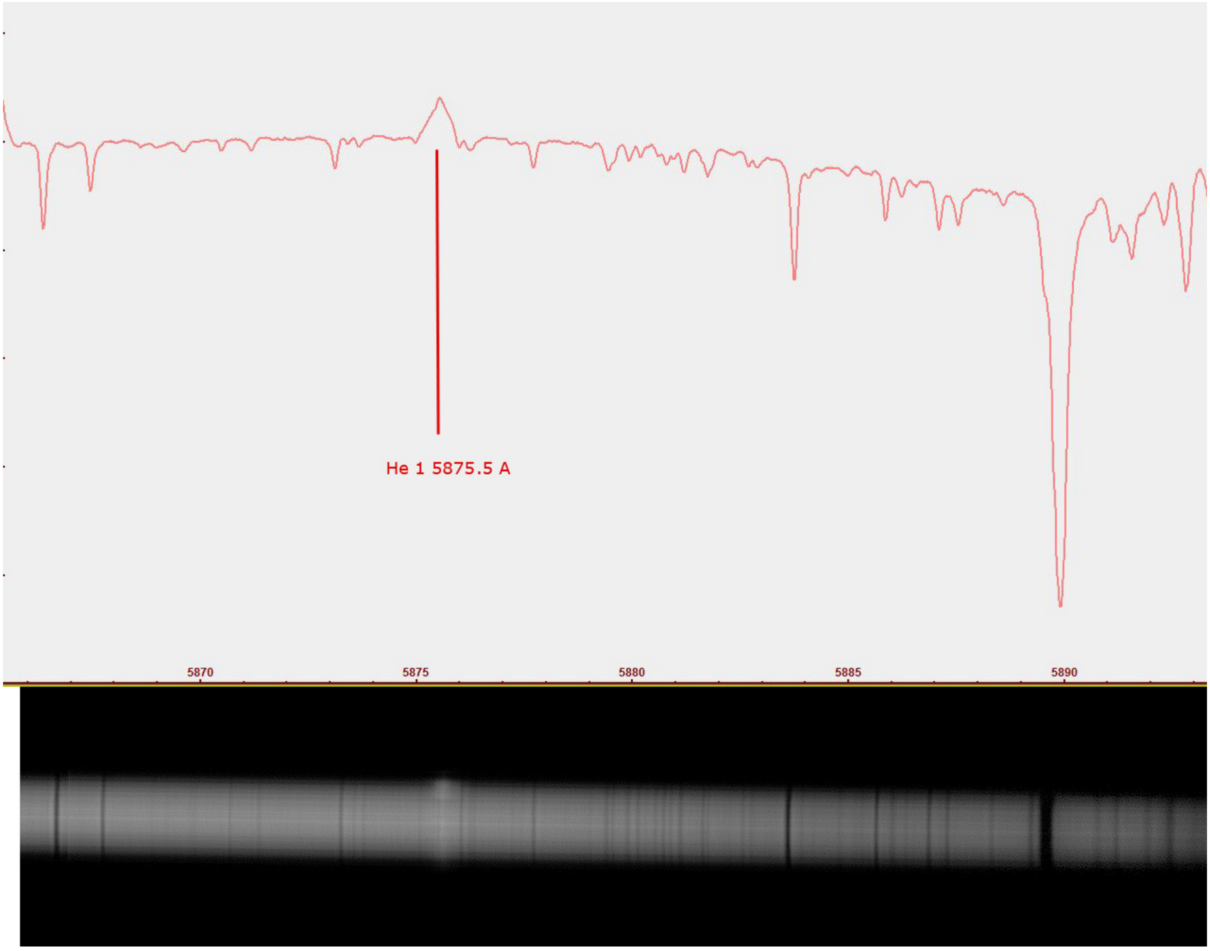


Below is a comparison between the sodium NaI and Hydrogen Alpha spectroheliograms , showing the differences between the low and high chromosphere and between two very different elements, an alkaline metal and a gas which is the first chemical element in the periodic table and the most widespread element in the observable Universe.



The Helium line

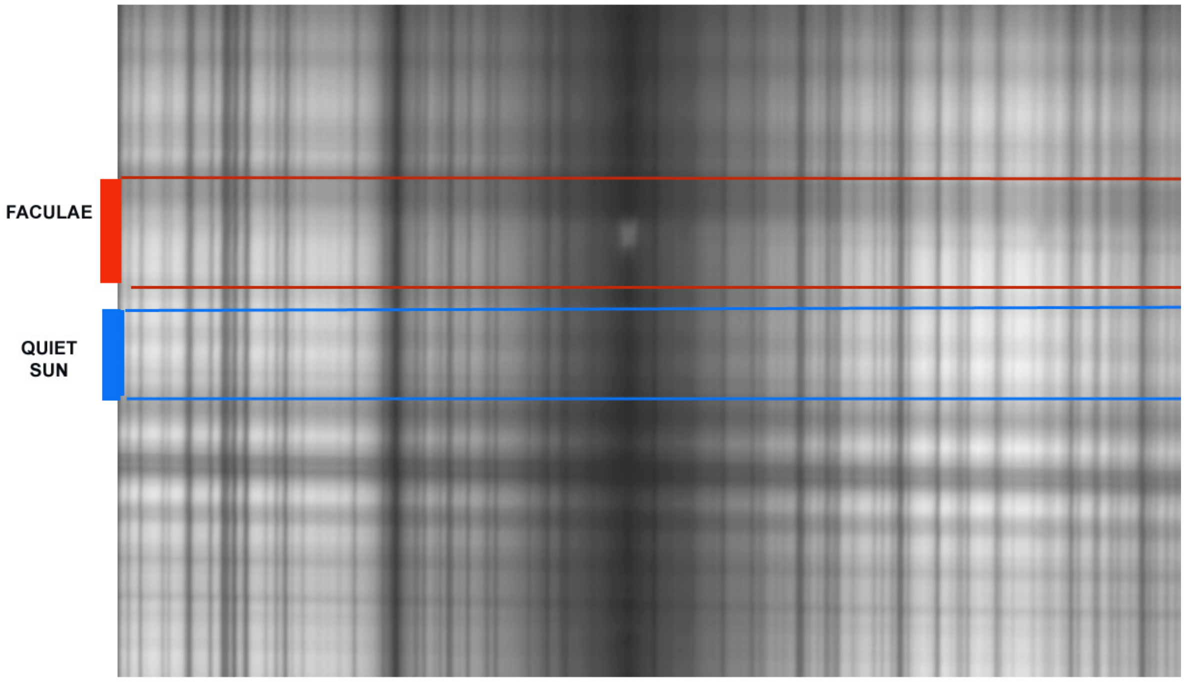
The Helium line at 5875 Å in absorption is rather difficult to identify due to its elusivenessAs an emission line it is much easier.This can be imaged by placing the slit of the spectrograph on the edge of the solar disk.

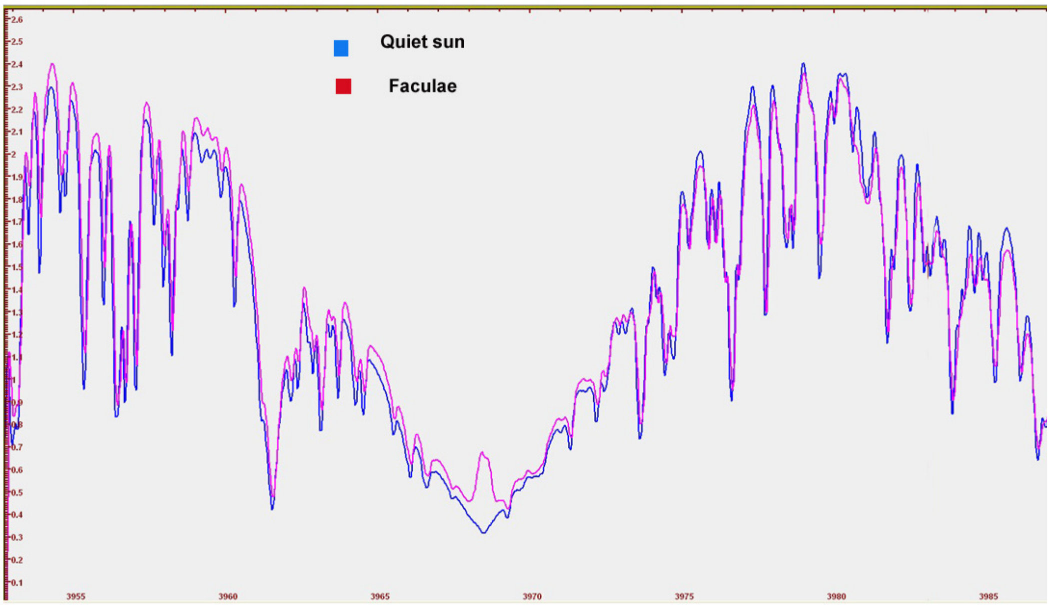


The ionized calcium CaII K and H lines

These are the famous lines of ionized calcium at 3933.68 Å, and 3968.49 Å whose characteristic is the particular sensitivity to the magnetic fields of the active regions and sunspots, in which they pass from absorption to emission,giving rise to the brilliant faculae that we observe on the disk. In The example below (author's annotation.) shows the passage of the CaIIH line from absorption to emission in the vicinity of an active region.

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





Spectrohelioscopy

Spectrohelioscopy can be defined as the ability to observe the solar disk and its characteristics in the various wavelengths of the elements of its spectrum. In the case of photographic recording it is called spectroheliography. In the following discussion, reference will essentially be made to spectroheliography , that is, solar observation using a photographic medium, traditional or digital.

Brief history of Spectroheliography

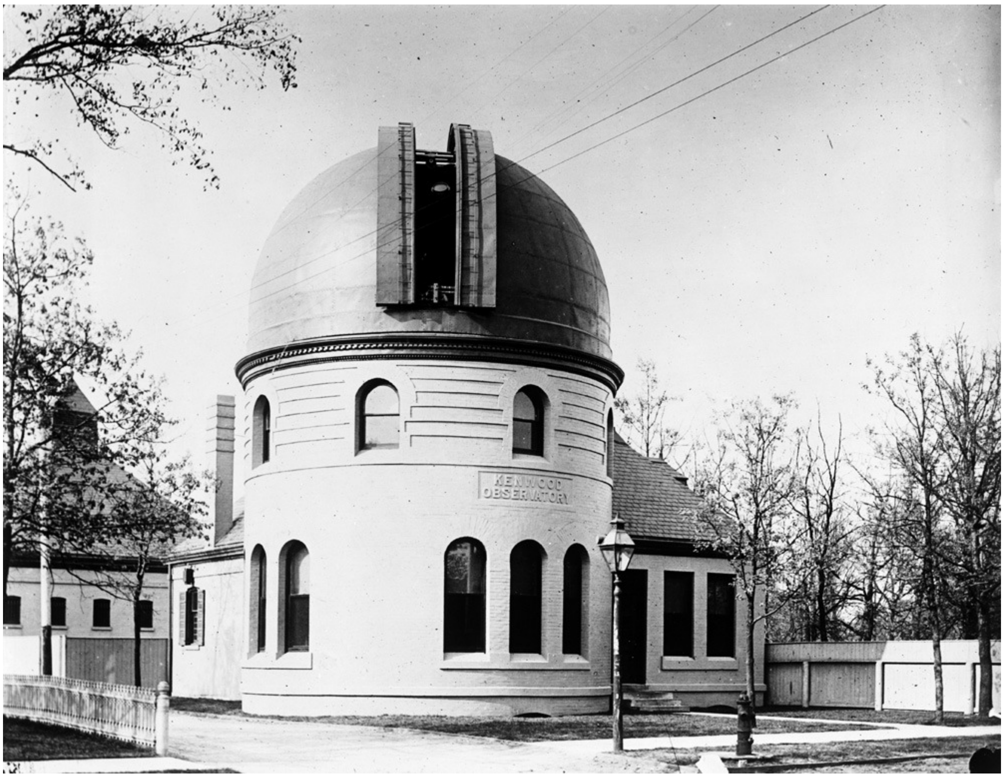
The spectroheliograph (SHG) was developed by George Ellery Hale in 1892, for the observation and photographic recording of the sun in various wavelengths. Hale was born in Chicago, USA, in 1868, he began his educational journey already seventeen years old at M.I.T, and then at Harvard College Observatory. He became director of the Kenwood Astrophysical Observatory in 1890. He worked on the most important observatories of the time, such as those at Yerkes and Mount Wilson.

George Ellery Hale (Source: Wikipedia)

The SHG was invented independently by Hale and the Frenchman Henri Alexandre Deslandres, but to Hale goes the credit of having perfected the invention to the point of creating a very powerful means of investigation of solar physics. The development of the collodion dry photographic plates, together with the invention and distribution of first generation diffraction gratings by the physicist Henry Rowland paved the way for the recording of spectroheliographic images.

Hale's work on SHG dates back to 1889, the period in which he developed his first ideas on the subject, which were subsequently documented some years later in the article "The Rumford spectroheliography of the Yerkes Observatory" published in 1903. The first prototype of the instrument was completed in 1892 and installed on the 12" Brashear refractor in the Kenwood Observatory he owned. The spectroscope used two 1080 mm focal lenght optics as collimator and imaging lens, while the grating was a 100 mm reflection one with 568 l/mm: the entrance and exit slits were 82 mm long, able to receive a solar image of 50 mm in diameter.

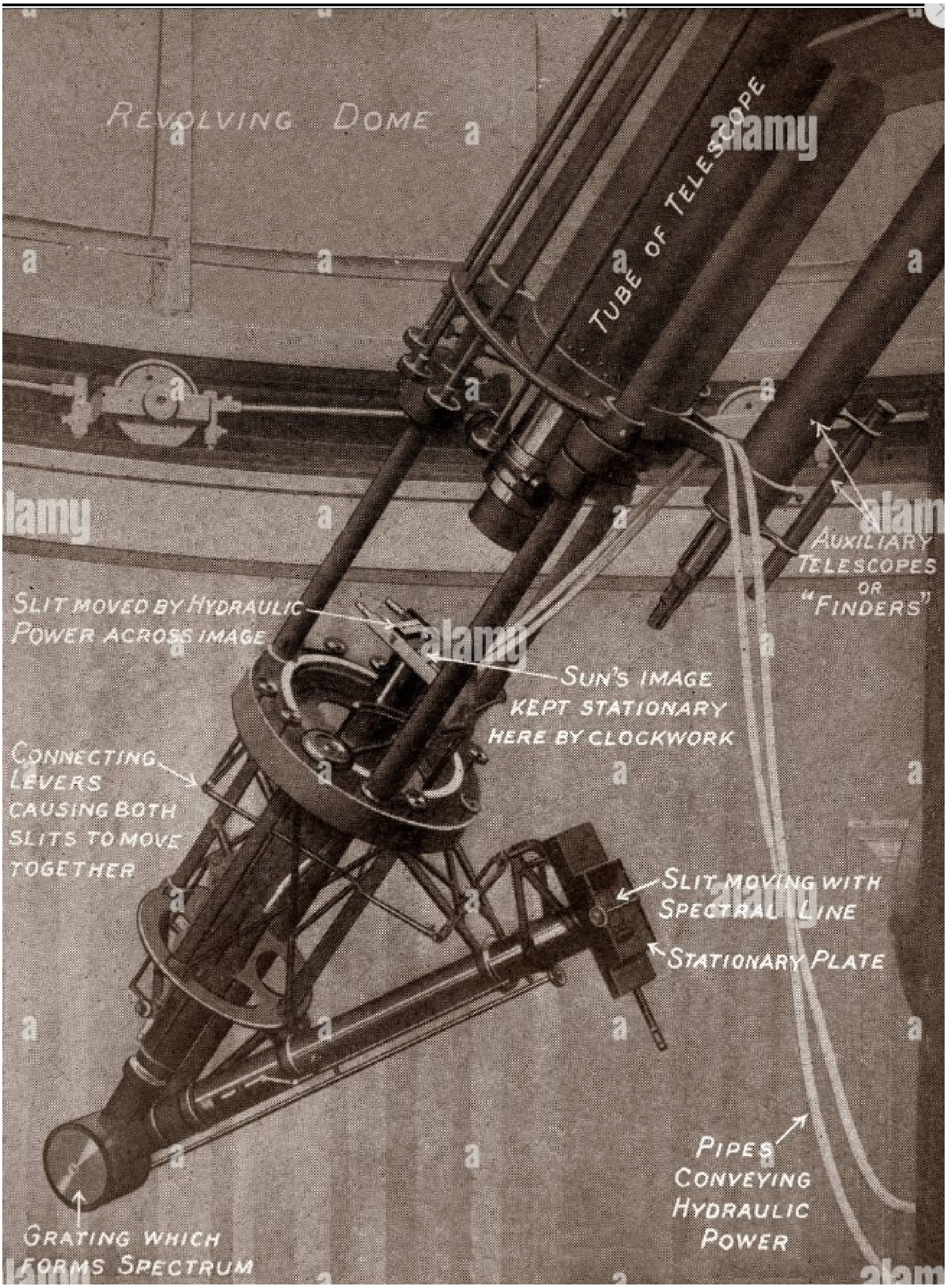
Deslandres, for his part, installed the SHG he invented at the Meudon Observatory, in Paris, in 1908.



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

<u>Hale's SHG</u>

The Kenwood was Hale's personal observatory, built in 1890 by his father William Hale, where the 12" Brashear refractor with the SHG was installed. Note the layout of the instrument, in "classic" configuration with the complex movement system of the slits . (Alamy photo - public domain).



Hale's SHG at the focus of the Brashear refractor

He was one of the creators of the 60-foot solar tower at Mount Wilson Observatory in 1908, which later served as a model for similar ones around the world.He also contributed to the design of the gigantic, for the time, 5-meter telescope at Mount Palomar which was named after him. He was interested in the magnetic activity of the Sun and in particular that of sunspots and 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 .

Professional SHG in service

Professional terrestrial SHG still in service in Europe are: the Meudon SHG in Paris, that of the USET - Royal Observatory of Belgium. Their spectroheliographic monitoring activity on the Sun is reported on the BASS 2000 website. https://bass2000.obspm.fr/home.php?PHPSESSID=f7b32e7ccd1002f04ca3bc9707bf0007

There is also a SHG at the Geophysical Observatory of the University of Coimbra in Portugal.

The SHG of the Meudon Observatory

The Meudon Observatory was a precursor, here in Europe, of professional spectroheliography, starting its activity in 1908, with the spectroheliograph of H. A. Deslandres. Its enormous archive of spectroheliograms, predominantly of the Hα and CaII K lines spans 10 solar cycles, 110 years of history of solar astronomy. This enormous quantity of images of the sun over the years has contributed to improving our knowledge of the solar dynamo and its variations. (https://www.observatoiredeparis.psl.eu/the-meudon-spectroheliograph.html?lang=en)

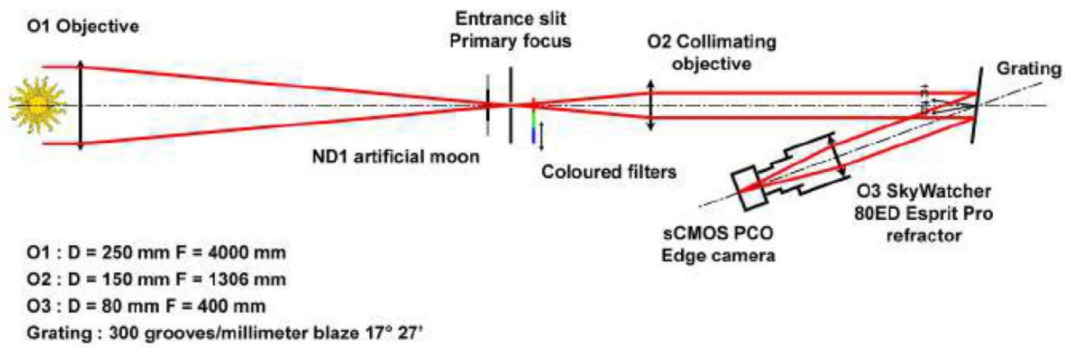
In this context, the Meudon SHG underwent a significant renovation in 2018, with the aim of improving the performance of the previous instrument, also adding some lines such as Ca II H.

Characteristics of the Meudon SHG in the new 2018 version. (Source "The new 2018 version of Meudon SHG " J.M Malherbe – K. Dalmasse) https://arxiv.org/abs/2001.02638)

As in the previous version, the sunlight is directed horizontally by a coelostat, two 400 mm flat mirrors. towards a 250 mm doublet optimized for the red and violet part of the spectrum: this forms a 37.2 mm image on the slit of the spectrograph. A diaphragm reduces the entrance pupil to 170 mm, providing a theoretical resolution of 1" in the red part of the spectrum: this resolution is however reduced to 2" by the local atmospheric turbulence. The slit has an opening of 30 microns (1.5" on the sun). The entry objective is motorized with an E/W movement, and a hard scan typically 60 sec. Movement reduces resolution by 1.5 to 2", but however there is no consequence on image quality due to seeing. The focal length of the collimator objective, a 150 mm doublet which is fixed, is 1300 mm. The dispersion medium is a 300 l/mm grating with a blaze angle of 17°.27'. The spectral order (3, 4, 5) is selected by a system of 3 narrowband filters centred on 400, 500 and 650 nm located behind the image plane. The camera objective is a Skywatcher 80 ED Esprit of 400 mm focal length. The camera used it is a Fairchild 2020 with a 2048x2048 square pixel 6.5 micron CMOS sensor, the EQ is 20%, 65% and 70% in CaII K, H beta and H alpha respectively.

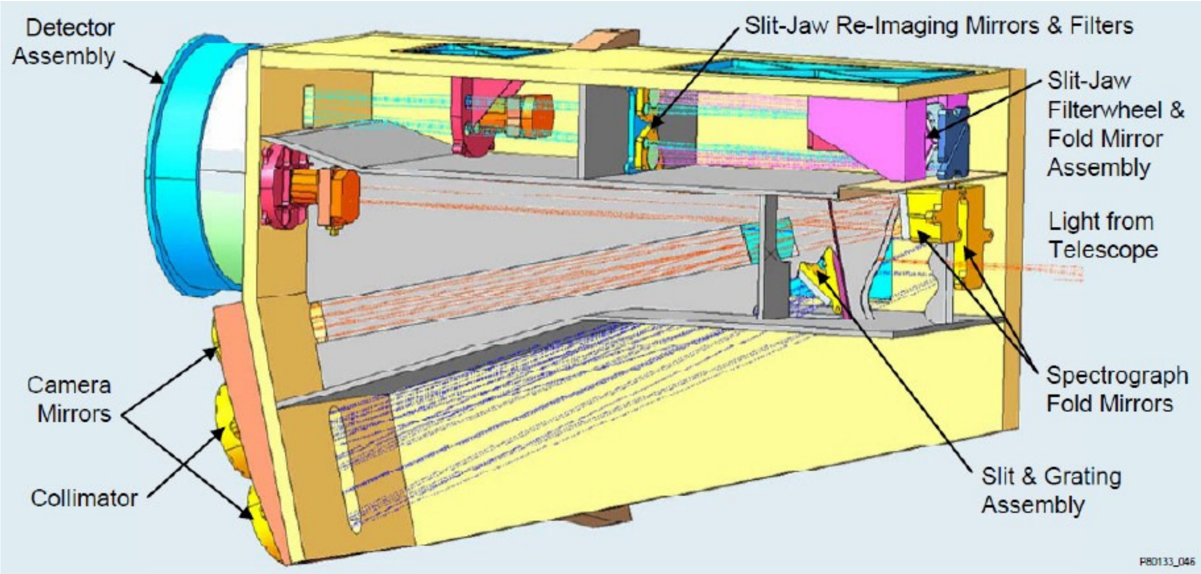
The entire solar disk and prominence observations are carried out on a daily basis.

Layout of the Meudon SHG



Professional satellite SHG

The instrumentation of the IRIS (Interface Region Imaging Spectrograph) satellite is aimed at observing, at a resolution never seen before, the solar atmosphere above the photosphere with the aim of investigating the mechanisms that cause the enormous increase in temperature between the photosphere and corona.For this purpose, 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 flares and CMEs. It makes use of an ultraviolet telescope and a very high resolution, of which the layout is shown (Source NASA/LMSAL) capable of recording both images and spectra: Iris therefore constitutes the state of the art and the most modern and advanced expression of spectroheliography.



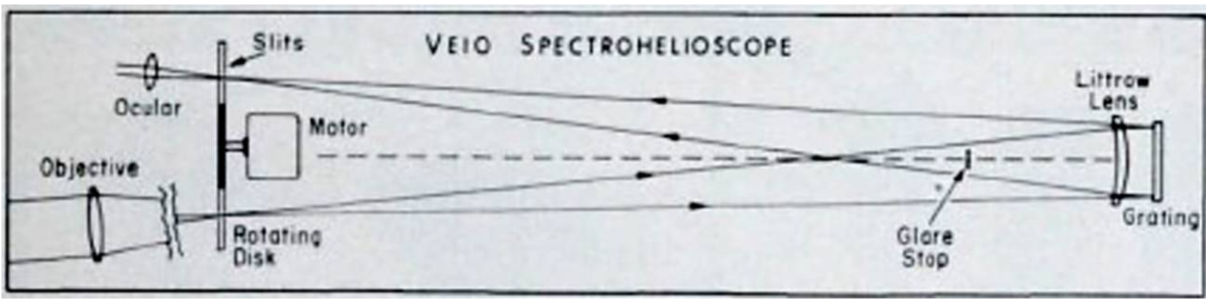
Traditional amateur SHG

At the dawn of my interest in spectroscopy and spectroheliography I was attracted, and I would say fascinated, by the powerful work carried out by Fredrick Veio, an amateur astronomer from California, in the sector of amateur spectroheliography. Veio was in fact the forerunner of this field of research among the amateurs, with his famous article in the January 1969 issue of Sky and Telescope, in which he illustrated the construction and operation of a traditional spectrohelioscope (SHS) of great simplicity and medium dimensions (at the time digital was yet to come) built in 1964.

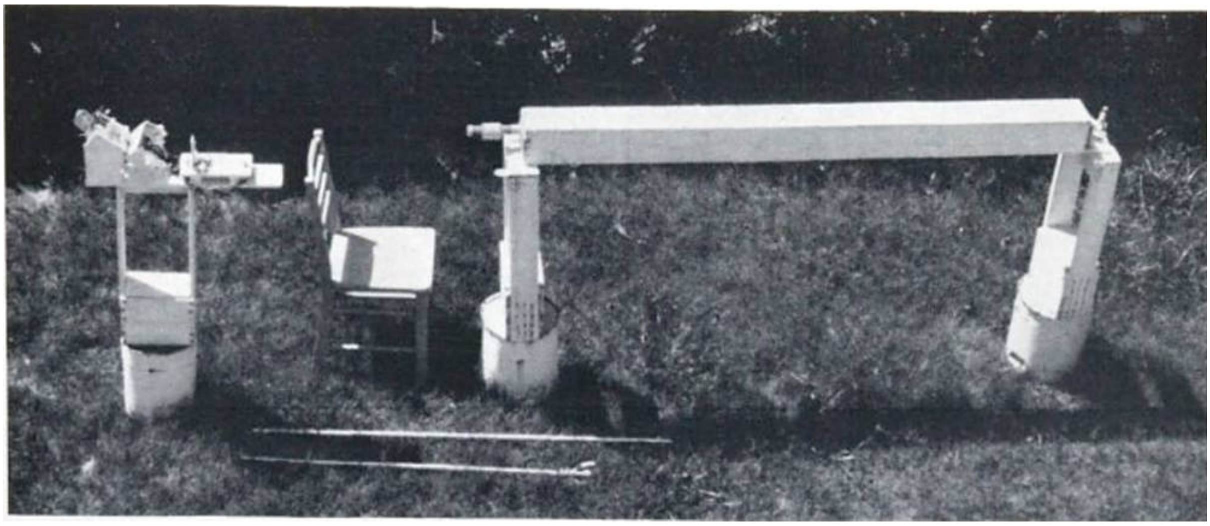
The instrument was based on two refractive elements, a fixed lens of 64 mm and 2700 mm focal length, powered by a 100 mm coelostat which sent the solar light to a Littrow spectroscope with a 50 mm meniscus and a grating 32 mm for 1200 l/mm. The synthesizers were two 108 mm glass disks with 24 radial slits of 0.15 mm which provided a resolution of 12 arcsec on the solar disk. In a traditional SHS, like that of Hale, so to speak, the fundamental element was constituted by the entry and exit slits and even more so by the input and exit image synthesizers which, rotating at a given speed synchronously, sent a scanned solar image to the slits and allowed observation or photography of a certain part of the solar disk in the chosen wavelength. The most widespread synthesizers among amateurs were those with rotating prisms (so-called "Anderson prisms") which however had the problem of being expensive and difficult to synchronize, while for his first project Veio chose the system of rotating glass discs with radial slits designed by F.Stanley. This first SHS project with refractive elements is also the one shown on page 4 of his book "The Spectrohelioscope" from 1999.

My friend Fred Veio passed away on October 2, 2022, at the age of 92, but "gone, but not forgotten", his pioneering legacy in the field of amateur spectroheliography remains of enormous value.

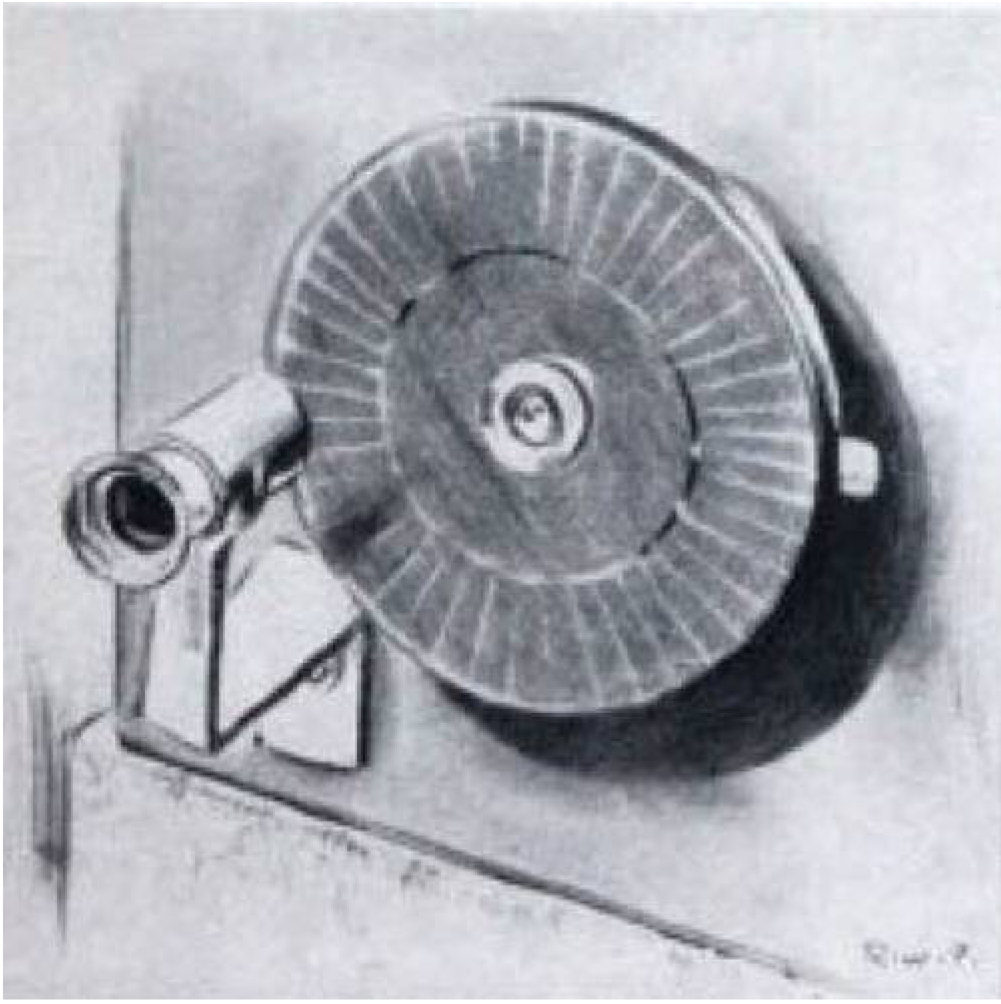
The following images illustrate the design and appearance of his first SHS mentioned above.



The Layout of the instrument (Source Sky and Telescope, January 1969)



The Veio SHS



The system of rotating slit disks similar to the one chosen by Veio as an image synthesizer.

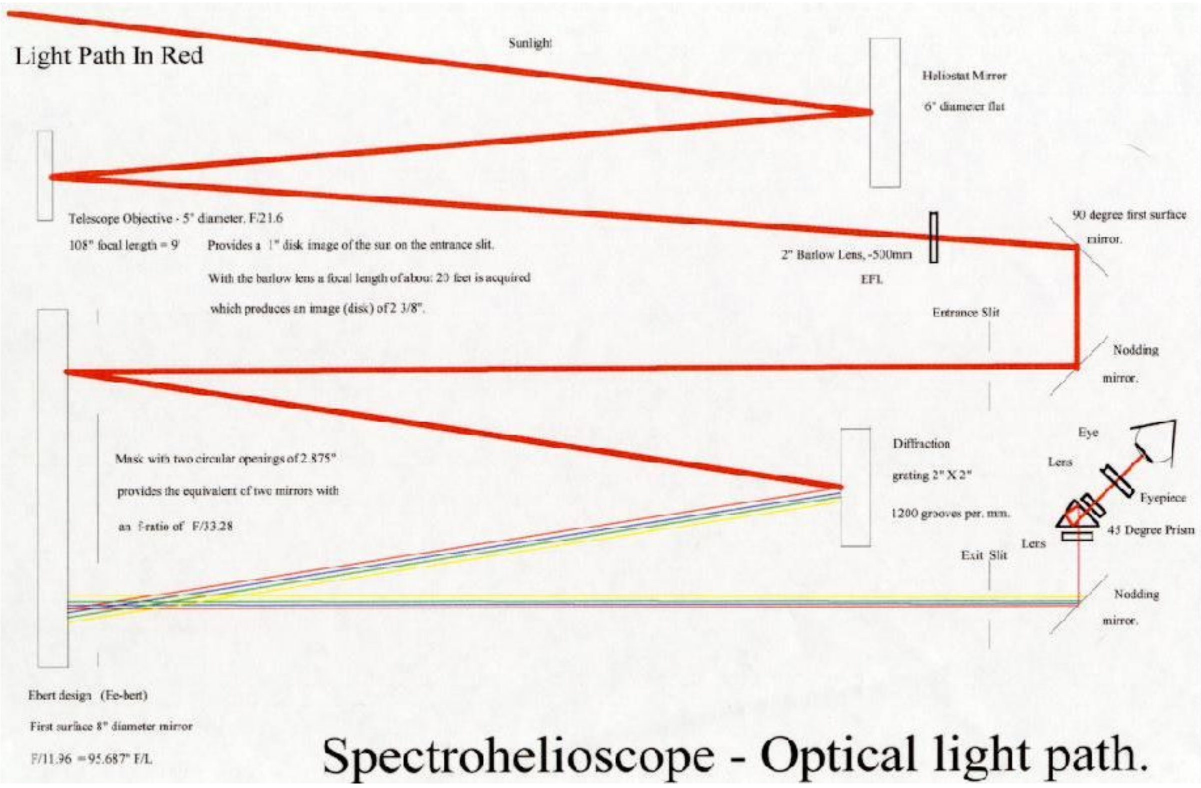
Veio was the precursor, but other self-builders, such as Leonard Higgins, followed his path.

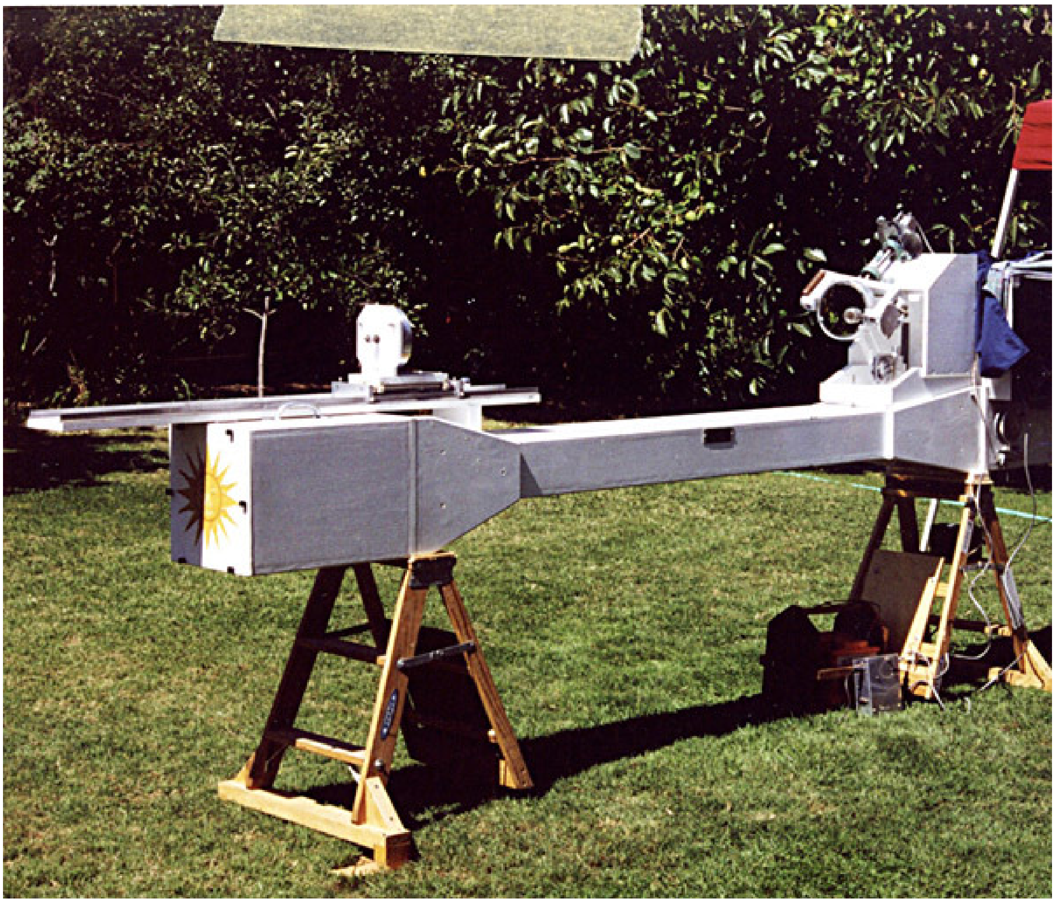
Shown below is the scheme (the latest in a series of projects) of a traditional amateur SHS/SHG by the well-known American DIYer Leonard Higgins with the guidance and help of Fredrick Veio in 1998.

source: http://spectrohelioscope.org/page2.htm

It utilises a long focal length refractor objective that delivers the solar image to a spectroscope in Ebert configuration; the use of mirrors oscillating at a given frequency (nodding mirrors) before the entrance and exit slits ensures the synthesis of an entire solar image from the line of interest, an image that can be observed visually and photographically.

Note the large size of the instrument, which utilises a coelostat. Source: http://spectrohelioscope.org/page2.htm





Higgins' SHS

As can be seen in the example, the two essential components of the SHS/SHG are a telescope and a spectroscope. The telescope can be of various optical configurations, but for solar observation lens or all-mirror configurations are mandatory. The catadioptrics could not operate unless they had a solar filter at the input, which would negatively affect the performance of the instrument for the scarcity of incoming light, considering the very small opening of the slits.

The revolution of Digital Spectroheliography

The development of information technology in recent years has made it possible, in amateur SHG, to use digital video cameras and specific computer programs to reconstruct the image from the lines of the spectrum: the video camera records the solar image moving across the slit with the spectrograph pointed at a given spectral line and the software extracts an image of the sun in that line. This is how digital spectroheliography was born and this field of application is now within the reach of a much larger audience of amateurs due to the greater (relative) ease of building (or purchasing) even modest-sized spectrographs. The digitization of spectroheliographic images has therefore replaced the particularly complex use of synthesizers, oscillating mirrors, rotating disks or Anderson prisms, with simple computer programs. Obviously with digitization it does not support visual observation.

At the beginning, the final yield of images from digital SHG was of inferior quality to that of traditional SHG, but with the progress of the development of CCD and CMOS sensors and the great evolution of image construction programs, the visible details are now clearly better, while the gain due to the reduced size and weight and therefore ability to use and portability is simply enormous. Moreover, it is enough to make a comparison between the classic amateur instrument illustrated above (about 3 meters in length) and my VHIRSS, weighing 8.6 kg and 110 cm in length, transportable anywhere with maximum ease. It is worth starting out and highlighting that specific instruments of this kind do not exist in the consumer market, apart from a medium resolution project to be printed in 3D, Sol Ex, to be accompanied with an optical kit produced by the well-known French company producing spectroscopy instruments Shelyak:

http://www.astrosurf.com/solex/sol-ex-presentation-en.html

However, for instruments dedicated to this activity with high dispersion and spectral resolution (R> 30000/40000) with high performance, the DIY path is currently the only viable one. The results, in terms of details visible on the sun, exceed those of commercial solar filters and are similar to those of professional observatories.

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 spectroscope, in various possible configurations;

4 – A camera: CCD or CMOS video camera with a sensor of adequate size and resolution.

We will now review the characteristics of these components.

The telescope

The telescope carries out the task of sending the solar image to the slit, that is, it carries out the same work as the solar telescope which sends the solar image on a narrow band Hα or CaII filter, such as those which have had and continue to have such widespread diffusion among amateur astronomers. Let us therefore imagine that instead of a solar filter there is the slit and the spectroscope, with the big difference that while the filter selects a single line, Ha, CaII or other, the spectroscope can theoretically select from a very extensive quantity of lines, and therefore equivalent to an equally large quantity of solar filters, despite being a single instrument, with a much narrower bandwidth than traditional filters on the market.

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

Catadioptrics

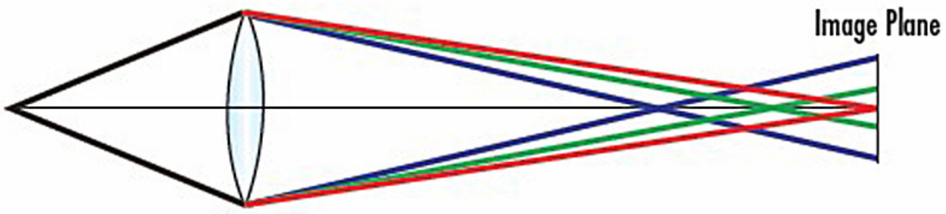
In my opinion, catadioptrics should be excluded for the obvious reason that, given the short focal length (f2-f3) of the primary mirror, the solar heat would be detrimental to the support of the secondary and its lens hood, as well as to the lens hood of the primary itself, releasing inside the closed tube such a quantity of heat that observations are impossible or inefficient due to the turbulence. Naturally, this problem could be bypassed by using a rejection filter of adequate size and bandwidth, i.e. an IR-UV cut in front of the plate, but both solutions would be very expensive (around €1500 for 20 cm openings) and not very satisfactory from the point of view of versatility as they would force us to use only some lines in the case of the ERF, and instead excluding some in the case of IR-UV cut filters which normally have a spectral range of 4000-7000 Å. A Canadian amateur astronomer has obtained good results with a 10 cm MTO Rubinar catadioptric, placing before its front lens a UV IR cut filter of similar size and with a wide band pass, which however allowed the CaIIK and H band to pass (Baader Planetarium UV-IR cut filters normally exclude it). Needless to say, this solution could only be satisfying if one already owned such a filter, which otherwise, ordered ad hoc with specific characteristics and large openings (10-11 cm) would cost high figures, in the order of over 2- €300.

Lens telescopes: refractors

a) Achromatic refractors

At first glance, achromatic refractors constitute the ideal telescopes to perform the task of an SHG telescope: low cost; possibility of using a wide range of focal lengths and diameters. Furthermore, if well made and without spherochromatism, 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 focus point at varying wavelength,means that if, for example, I focused the SHG on the Hα line and I want to go to the CaII K line I will have to refocus not only the telescope, but also the spectroscope, since the respective focuses intersect. Clearly it is not a tragedy, but it is nevertheless a nuisance.

In the following image the chromatic shift of an achromatic lens source (Edmund Optics- Gregory Hollows and others – Wavelenght effects on Perfomance)



Chromatic Focal Shift

The good news ,as mentioned,is that imaging in monochromatic light eliminates both chromatic shift and lateral chromatic aberration, producing well-corrected images, provided that the spherical aberration is also correct. Now, the diffraction limit, which we know well in astronomical instruments, is given by the smallest theoretical point created by a perfect lens as defined by the so-called "Airy disk", whose dimensions however depend on the wavelength (and this applies to any type of telescope) , as can be seen in the following table (source Edmund Optics):

Color	Wavelength (nm)	Aperture (f/#)				
		f/1.4	f/2.8	f/4	f/8	f/16
NIR (Near-Infrared)	880	3.01	6.01	8.59	17.18	34.36
Red	660	2.25	4.51	6.44	12.88	25.77
Green	520	1.78	3.55	5.08	10.15	20.30
Blue	470	1.61	3.21	4.59	9.17	18.35
Violet	405	1.38	2.77	3.95	7.91	15.81

Theoretical Airy Disk Diameter Spot Size (in μm) for various Wavelengths and f/#s

What are the consequences of using achromatic refractors as telescopes? From the previous table it appears that, with the same diameter and F/D ratio, going towards the violet the Airy disk becomes increasingly smaller and the resolution and contrast increase.

Additionally, good achromatic refractors are corrected for the C line of Hydrogen, the Hα line.and, their focus on the slit, on the optics and on the grating of the spectrograph would produce a monochromatic light output on the camera.

Therefore, even without the use of filters in front of the objective or in the optical path, which still emphasize the contrast , the achromatic refractors are able to send good solar images to the slit both for the lines in the deep red (Hα) and those in the violet (CaII K and H), always, let it be clear, in the absence of spherical aberration from chromatism.

b) Apochromatic refractors

These are the telescopes that are currently seen as being best in class with a wide range of accettable prices. The focal lengths range from 300 to 1200 mm in optical designs that are covered by the four basic types: air spaced triplets, oil spaced triplets, fluorite doublets and ED doublets.

Compared to achromatics, apochromatic refractors do not present significant chromatic aberration, except for a slight residue in some ED doublet. The strong point is excellent control of spherical aberration, with images that remain sharp even at high magnifications.

Among these, in my opinion, the choice of refractors with doublets with low dispersion ED lenses such as OHara FPL 53 is the best and the one with the highest quality/price ratio. Refractors of this kind have been on the market for years and therefore can be found second hand at very affordable prices.

Telescope constraints:

-If you want to image the entire solar disk, it must provide an image of the sun with a diameter smaller than the length of the slit,wich is equal on average to about 1/100 of the focal length.

-It must have a sufficient resolving power to show the small solar structures in Hα and Ca II K and H. An instrumental resolving power between 1 and 2 arcsec is sufficient, even taking into account that it is limited by daytime seeing which hardly allows better than 2 arcsec. A good objective diameter is around 100 mm, which provides a theoretical resolving power of 1.2 arcsec. Considering that the Sun subtends on average 1920 arcsec, and that a focal length of 1000 mm would give a solar image of 9.3 mm on the slit , on this one we would have an image scale of 206 arcsec/mm, or 0.2 arcsec per μm.

An objective lens with a 100 mm aperture between f 8 and 10 would therefore be an interesting option, even considering the size and bulk it would bring to the SHG. However, this is not an absolute constraint: in the case of scanning the entire disc there are also suitable refractors with 60-70 mm focal length.

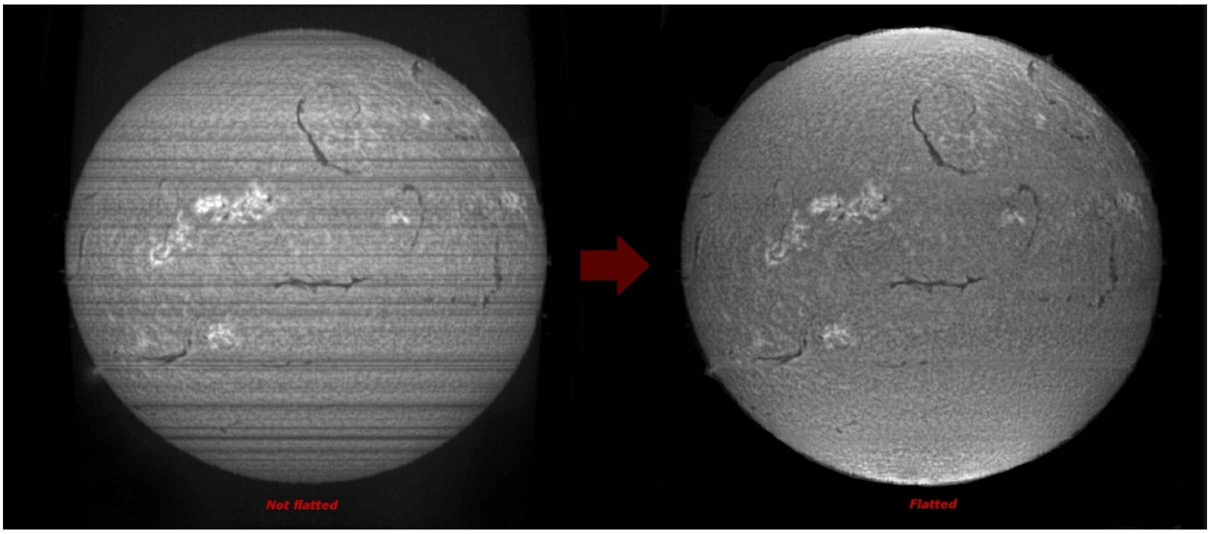
-Possibly it must not be an instrument with a rear lens assembly, potentially liable to deteriorate in their coating ,due to UV and IR radiation.

The slit

This component which constitutes, in its various versions, air gap,etched reflective chrome and so on, the heart of a stellar spectroscope. Even more so constitutes the fundamental element of a SHG, given its direct influence on the quality of SHG images, as and perhaps even more than the grating.

Slit gap has a direct effect on the spectral resolution and therefore image quality of an SHG, but the ability to close an adjustable slit to the minimum possible gap (10-15 microns,for example) is a direct function of mechanical quality and assembly as well the quality and accuracy of slit jaws.

To demonstrate what I mean,it’worth looking at the comparison, between a raw Hα SHG image obtained with one of my SHGs with with a slit with very narrow closed gap where the slit jaws are not machined to optical tolerances (1/4λ), and the same image after processing with a synthetic flat.

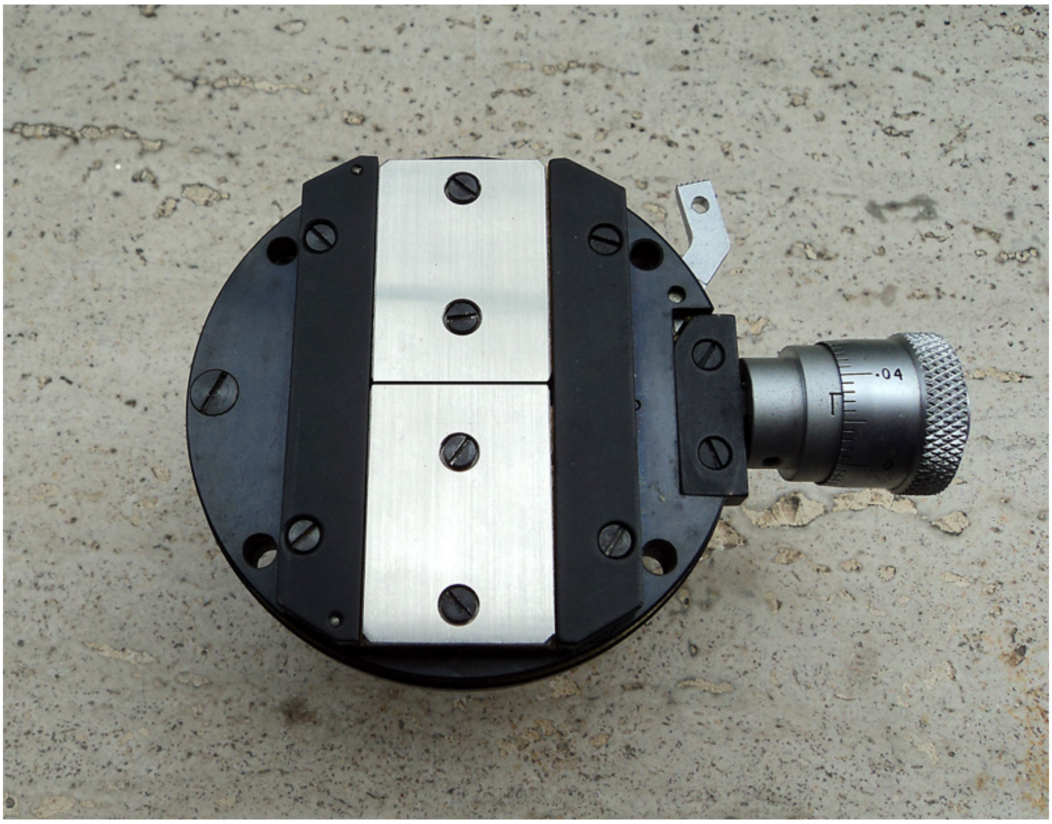


As you can see, the horizontal lines (transversalium) caused by small imperfections of the edges of the jaws, reflects mercilessly on the quality of the final image. But then, just work the plates to a better quality, I can already hear the reader's answer on the question, right answer, but with a catch: the manufacture of the slit jaws to optical tolerances (1/4λ), involves sophisticated and complex manifacturing processes,which would cost more than the spectroscope itself. It is true, as we will see, that the elimination of the transversalium can, within certain limits, can now also be achieved via software, but a well-worked and functioning slit is always a guarantee of excellent images, so it is necessary to consider the different possibilities available to us .These can be summarized as follows:

1-Proceed with the purchase of surplus professional slits on some online stores.

An American retailer, BMI Surplus, has a wide range of optical and mechanical components for spectroscopy, including slits. Prices vary and you need to know how to choose: https://bmisurplus.com/

The following image shows a professional slit adjustable with a micrometer purchased bythe author for € 100 from BMI Surplus: the slit,very good mechanically and of 20 mm length, was then improved by dismantling and reworking the edges of the slit jaws and adding a M 42 x 0.75 female adapter. The mechanical slide and micrometer closure acts uniformly, maintaining the parallelism of the blades to very tight closures. Lack of parallelism can be seen in the final image,where different gaps show as one light and another darker.



As new, such a slit would cost somewhere in the region €500 to €1000, as much as a small apochtomatic refractor, and this should make us reflect on the importance of this component, of a level equal to that of the quality of the optics of the telescope with which we carry out our evening observations.

Another well-known overseas retailer, Surplus Shed, offers at very low prices ($24) adjustable slits made in India with slit jaws of 10 mm in length (about 8 usable) which, although not the best from a mechanical point of view, are acceptable and are capable of being improved with some effort.

https://www.surplusshed.com/pages/item/m1570D.html

To improve the quality of the metal blades of Surplu Shed slits

I normally do the following:

a) Remove the brass slit plates from the frame;

b) Examine the bevelled edge under the microscope at approximately x 400-500 to observe their level of precision (or imprecision);

c) Place the blades on a hard plastic surface (polycarbonate is ideal) applying a thin layer of abrasive paste used in body repair shops between the plastic and the blade (cerium oxide can also be used), and rub the edge of the blade on the support with longitudinal movements with uniform pressure for a few minutes, then repeat the observation under the microscope to verify the degree of improvement and, if necessary, continue the operation until a satisfactory result is obtained.

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

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

The adjustable slit would be preferable as it has the possibility of varying the opening to compensate for changing with light intensity of the incoming optical beam, due to any diaphragms or insertion of filters in front of the telescope, the state of the sky, etc. However, it presupposes a sophisticated mechanical system which in theory should guarantee the simultaneous closure of both slit jaws while maintaining their parallelism in the closing phase. Such a mechanism is obviously expensive and for non-professional instruments may not even be necessary. The adjustable surplus slits, especially if modified as described above, can carry out their task adequately, also because the slit length of 8 mm ,sufficient to accommodate images of the entire solar disk even for not shorter telescope focal lengths and with CCD sensors of adequate dimensions. Furthermore the slit jaws, in brass or steel, have a sufficient thickness to guarantee their resistance to thermal stress that, for a 100 mm telescope without any rejection filter, can reach 7.85 W.

Fixed air slits

Fixed slits, often produced by laser and not by mechanical processing, are the most easily found, even if at prices not exactly popular, in the catalogue the larger optical component suppliers such as Edmund Optics and Thorlabs. However, they have the drawback of having a standard length of 3 mm and a very thin metal support, which, if not adequately protected, could tend to deform under thermal stress. On the other hand, their edges, obtained by laser, have a high level of precision with very narrow gap, although, it must be said, this varies from specimen to specimen. They are available down to a minimum of 5 microns of gap. Lately, slits of 10 mm length have become available, but with an opening of 20 microns, rather high for an SHG.

Etched on chrome

Slits obtained by chemical etching a very thin layer of chromium laid on a quartz support with an opening of 9 microns and a length of 12 mm, mounted on a copper support to dissipate heat, were recently created by an English amateur astronomer, Douglas Smith, and one of these is currently used in my POSS2 UV-dedicated SHG , with excellent results.

The characteristics of this slit are described by Douglas as follows:

Quartz Chips Size: 15 x 15 x 2.30mm

Slit opening: 9 microns +/- 0.4

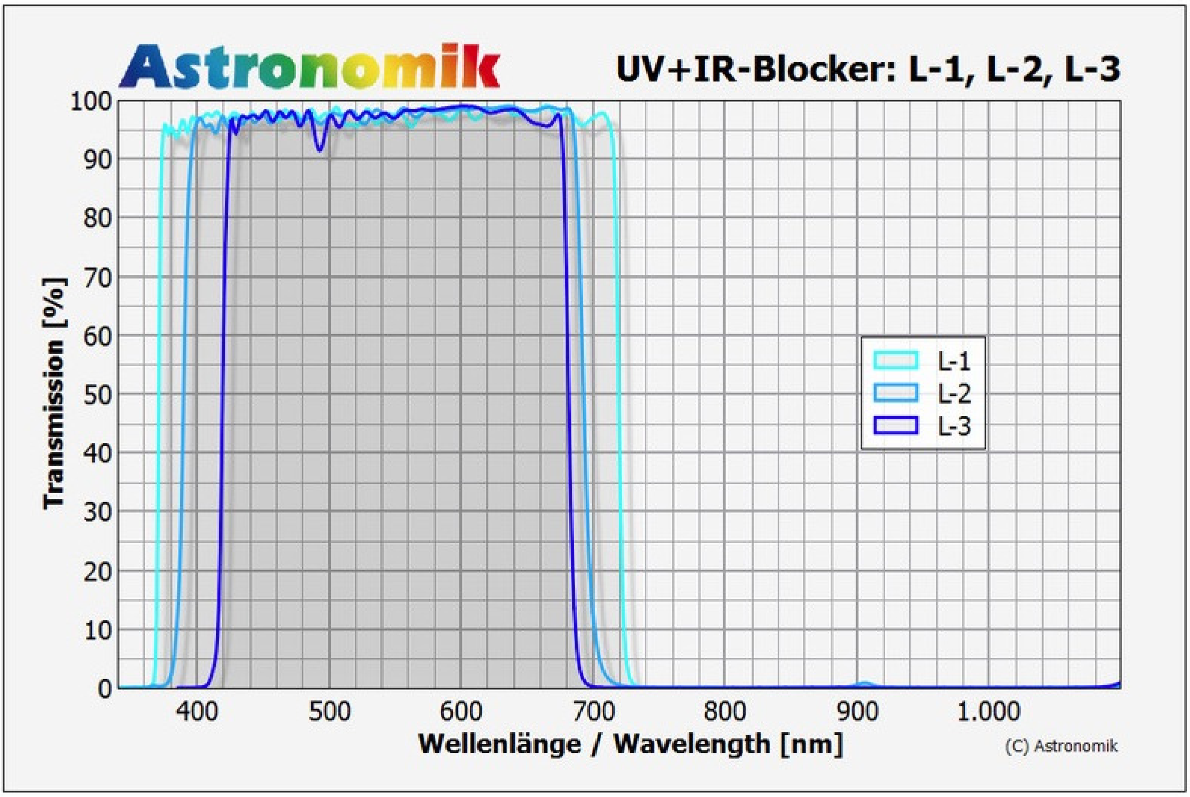
Slit length: 12 mm

Copper disc size: 25.2 mm OD, 12.8 mm ID, thickness 0.9 mm

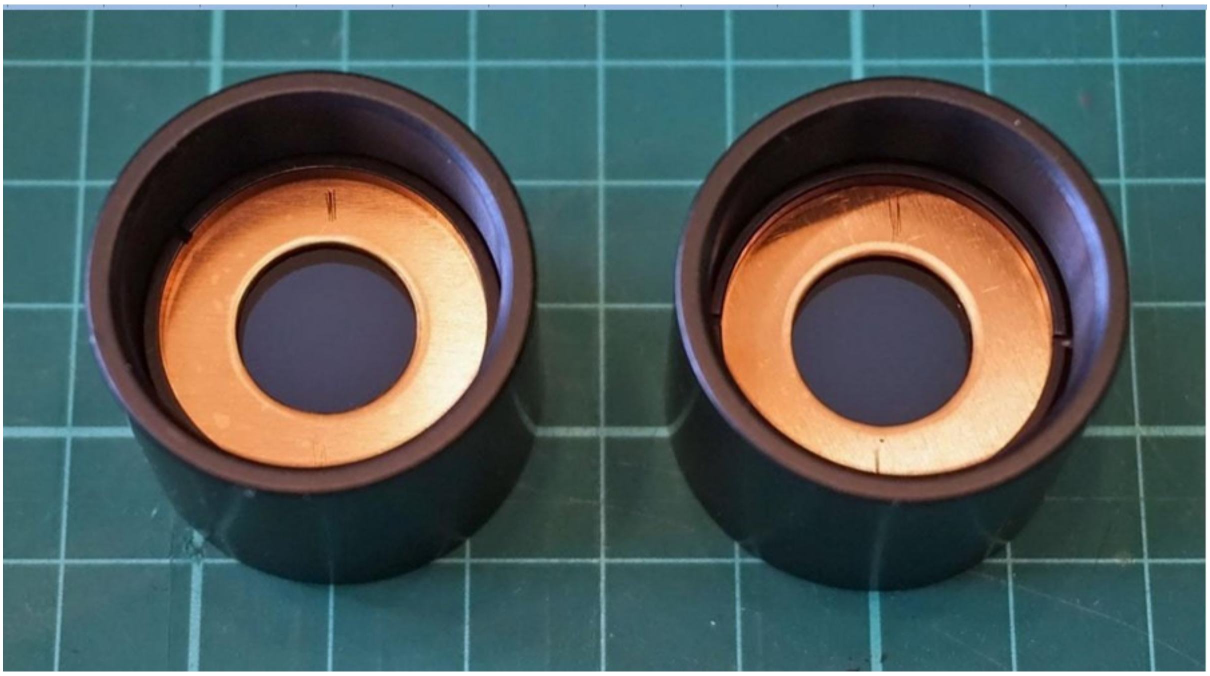
Douglas states that, since fused quartz has a coefficient of thermal expansion much lower than that of glass, it is extremely unlikely that it will break due to heat. Even with a refractor with a 140 mm aperture and 800 mm focal length, the Quartz has never broken when exposed to sunlight focused on it without any attenuation.

However, the very thin chrome mask can be damaged by long exposures to sunlight focused on it. Therefore, it is highly recommended to place a 2 inch UV IR cut filter 15-20cm in front of the slit.

The Astronomik L1 filter is probably the optimal one for observing the spectral lines around 400 nm, such as CaII K and H. However, if Hα is the main interest, then any good quality UV-IR cut can be used.



The assembly is composed of a 15 mm square segment of quartz mounted on a 1 inch copper disk drilled in the centre as seen below .



Other slits on a reflective glass support with an aperture of 10 microns and a length of 4.5 mm are marketed by the French spectroscopy instrument company Shelyak. https://www.shelyak.com/produit/se0223a-fente-alpy-uvex-10-%c2%b5m/?lang=en

Prices starting from €122. Even for these, however, it is advisable, in my opinion, to guard against concentrated solar heat with appropriate ND and IR-UV cut filters.

Design and DIY construction

I would advise against this, as the complexity of the undertaking and the cost do not guarantee better results than those of the possibilities already examined, unless you have a mechanical workshop capable of precision work and the ability to use it.

Importance of the slit length

I mentioned the importance of the length of the slit, which must necessarily be related to the focal length of the telescope that projects the solar image onto it and to the diameter of the projected image of the solar disk. A 3 mm slit lenght used with a 6 mm solar image, all things being equal,gives a final spectroheliographic image covering only half the solar disk.

The Sun's apparent diameter is on average about 32 arc minutes (1920 arcsec) at 1 AU, but, since its distance from the earth varies following its orbit over the course of the year, it varies from 32.5 arcminutes in January to 31.5 arcminutes in July.The diameter of the disk projected onto the slit will therefore, in radians, be equal to:

D = FL x 0.00948 in January

D= FL x 0.00917 in July

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

For a focal length of 1000 mm D will therefore be equal to 9.48 mm in January and 9.17 mm in July (average 9.325 mm), which requires a slit of 10 mm length to record the full solar diameter. For a focal length of 500 mm it would average 4.7 mm, fitting well with a slit length of 5 mm.

.

The size of the slit gap

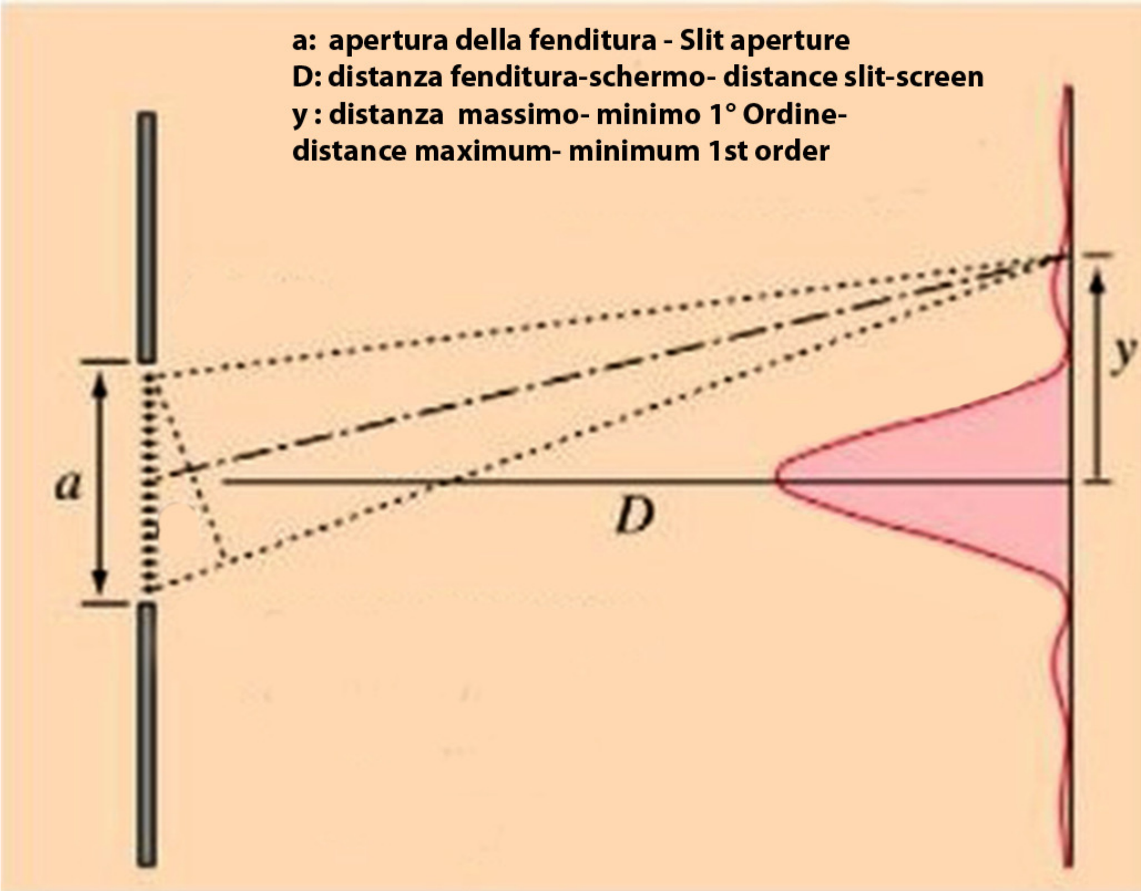
As for the opening of the slit, taking into account the above, a focal length of 1000 mm would provide on average an image scale of (1920/9.325), 205 arcsec/mm, or 0.2 arcsec/μm, which means that a slit gap of 10 microns would provide a spatial resolution of 2 arcsec, sufficient to record details on the Sun. However, it is also necessary to take into account the dimensions of the pixels of the camera: for pixels of around 10 μm everything would be ok, but in case, let's say, of 4.65 or 5 µm pixels the sampling would be approximately 2 arcsec x 2 pixels, half that of the optimal sampling.

A focal length of 500 mm would provide an image scale (1920/4.665) of 411 arcsec/mm, or 0.4 arcsec/µm or a resolution of 4 arcsec for a 10 micron gap. For the Nyquist principle it is necessary to sample 4 arcsec by 2 pixels, and, in the hypothesis of 4.65 or 5 micron pixels, this principle would be satisfied.

Therefore a 10 µm slit opening and a 500 mm focal length telescope would match quite well with a camera with 4.4-4.65 µm pixels such as the DMK 51, but also with cameras such as the ZWO ASI 174. In the case of other CMOS cameras , like the ZWO ASI 183 MM, with 2.5 µm pixels it would be appropriate to use them in binning 2 and in binning 1 only if a higher spectral resolution is needed. Of course there is the downside, and 10 µm gap with a non-professional adjustable slit are possible, but often imperfect to the point of making a 15 micron gaps preferable.Alternative is to use fixed slits of 9-10 microns.

The measurement of the slit opening

In adjustable commercial slits not equipped with a micrometer or other measuring instruments, the problem of measuring the actual width of a given slit opening can be real. Fortunately the slit gap can be determined with the classic diffraction experiment, using a laser pointer and directing the beam through the slit onto a screen placed at distance D.



The formula to define the slit opening a in mm and microns is:

$$a = \frac{\lambda \times m \times D}{y}$$

Where:

-λ is the wavelength of the laser in Å (6500 red and 5320 green);

-m is the order (which is assumed to be the first)

-D is the distance of the screen from the slit in mm

-y is the distance in mm between the maximum and one of the minimums of the first order of the two first order images of the diffraction pattern.

(if all in mm the formula must be multiplied for the conversion factor A/mm 1/10 ^7).

E.g. with D= 500 mm; λ = 6500 Å ; y = 10 mm, we have:

$$a = \frac{1 \times 500}{10} \times 6500 \times \frac{1}{10^7} \text{(conversion factor Å/mm)} =$$

$$\frac{500}{10} \times \frac{6500}{10000000} = \frac{3250000}{100000000} = 0.032 \text{ mm} = 32\ \mu$$

This formula seems to be more precise than the one of previous edition

Spectroscope configurations for the digital spectroheliography

Below I will discuss the two main spectroscope configurations most commonly used in amateur digital spectroheliography .

1- The spectroscope in classic configuration

This configuration has been and is perhaps the most widespread in many DIY projects. It is based on the use of two optics, generally refractive to minimize the dimensions, one which 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 38-40°), which collects the diffracted optical beam coming from the grating, the spectrum, to magnify it and send it to the camera.

The F/D focal ratio of the collimator should be equal to or very similar to that of the telescope that send the solar image onto the slit.

An example of a solar spectroscope in a classic configuration is that used in digital SHG project "Sol Ex" by C.Buil, with the "INTI" conversion software by Valerie Desnoux and others used to prepare the final spectroheliograms.

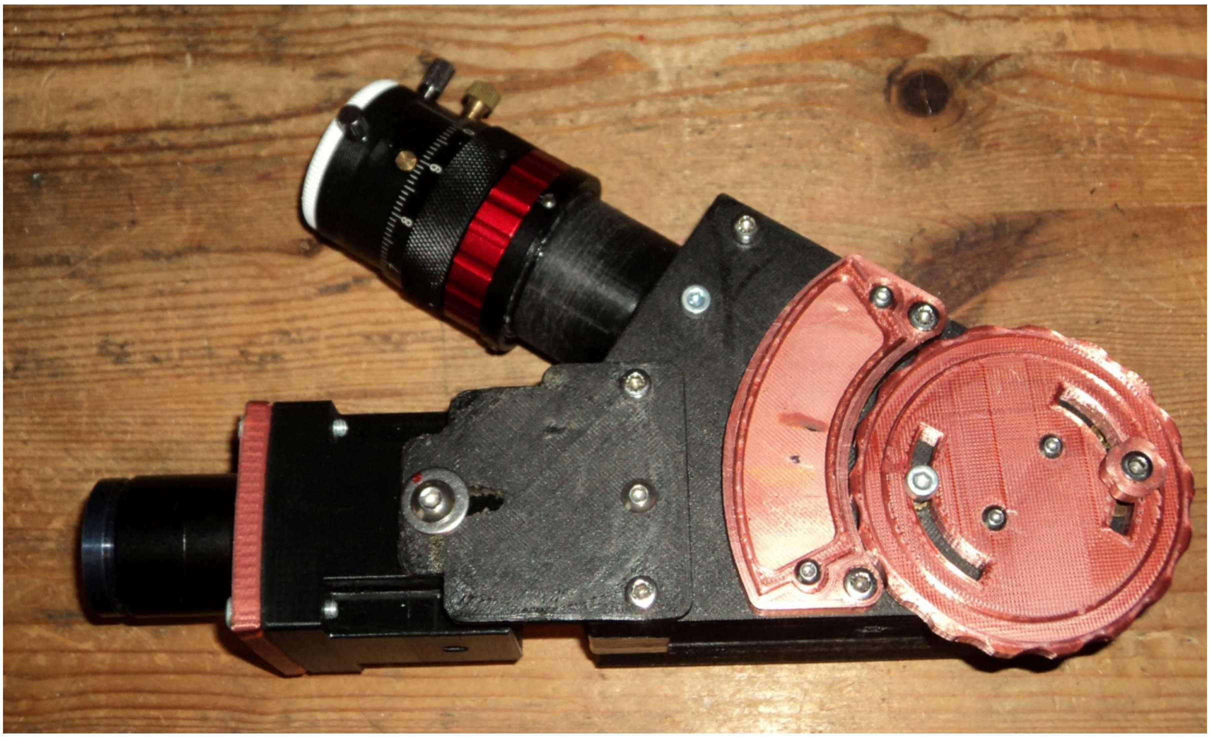
http://www.astrosurf.com/solex/sol-ex-presentation-en.html

http://valerie.desnoux.free.fr/inti/index.html

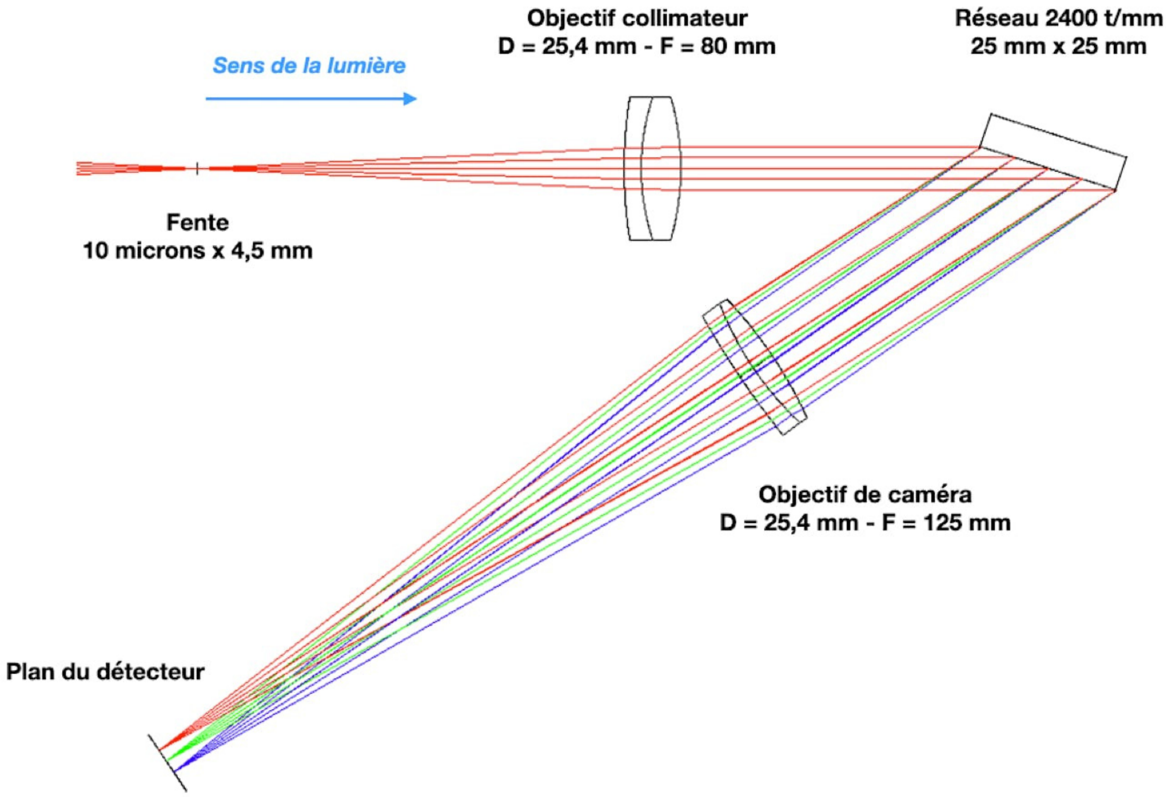
The Sol Ex project uses 3D printed components and an optical kit from the Shelyak company.

Below is an image of this instrument and its layout.

As can be seen, the angle between the collimation and imaging optics is 38° and the focal length of the collimator is 80 mm, while that of the camera objective is 125 mm.

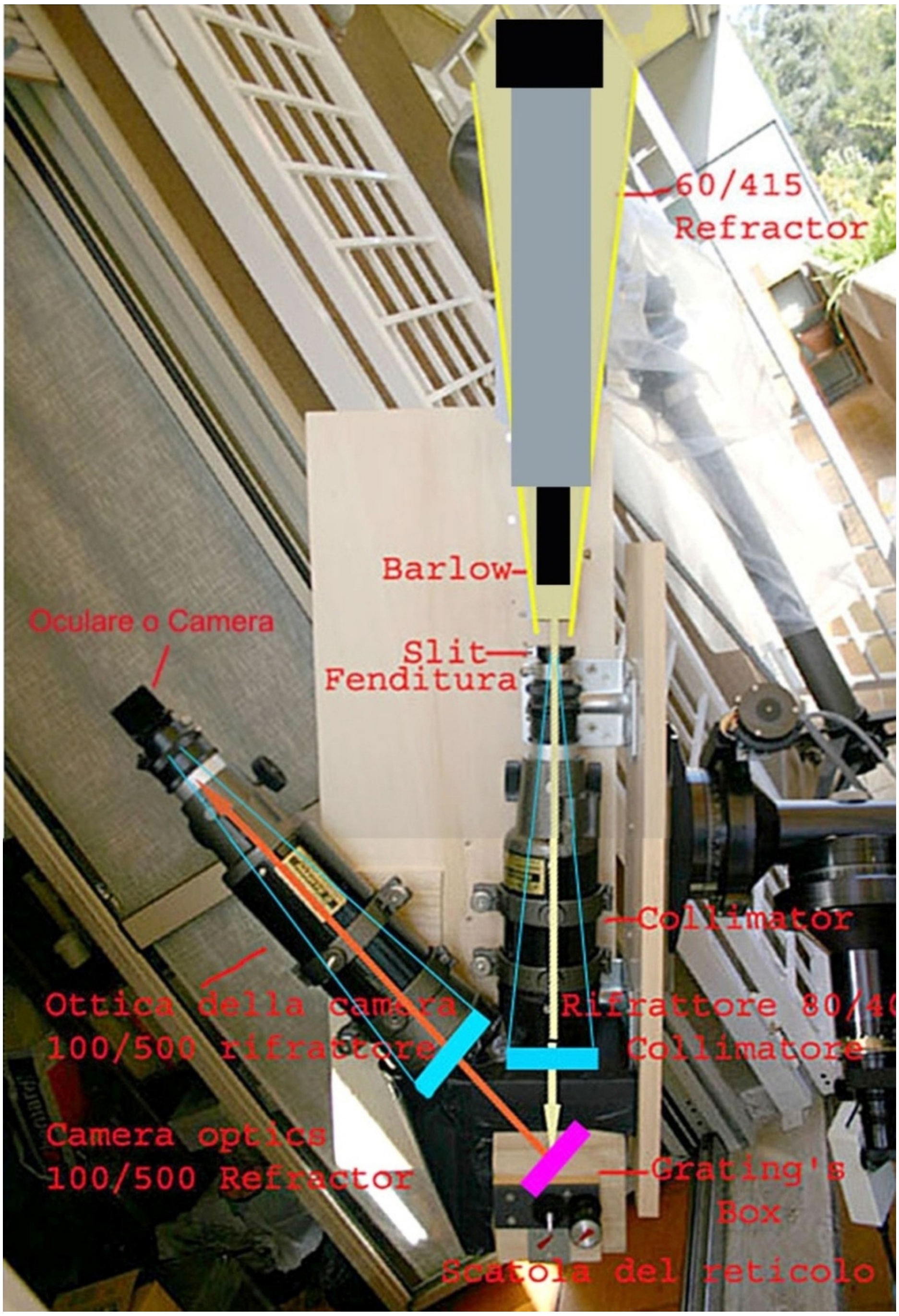


3D printed Sol EX



Optical Layout of Sol Ex

This optical configuration, optimal for short focal lengths,is in my opinion, problematic for medium-long focal lengths, from the point of view of bulk and weight, requiring three optical elements to be used for spectroheliography. Below is an example of DIY SHG by the author using a 60/415 short focal length achromatic refractor as a telescope that sends the solar image to the slit and a "classic" version spectroscope made up of a collimator 80/400 achromatic refractor) and, as the camera optics, a 100/500 achromatic refractor. The size and excessive weight of this configuration led me to consider alternative designs, like the Littrow autocollimating configuration as spectroscope in my SHG.



2 - The 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 various optical configurations for spectroscopy, although excellent in terms of the quality of the images obtainable, proved to be lacking, 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 an extra to the project. Furthermore, the more sophisticated configurations, moreover with a number of optical elements, requires careful collimation, often difficult to acquire with accuracy, and that 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 optical configuration 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 a collimator and the camera, making the light perform a double passage: at the entrance, from the slit as a beam of light directed to the lens and the grating and back, after hitting the latter, in the form of a diffracted beam (spectrum) directed to the camera or to the eyepiece via a prism or a small deflecting mirror .

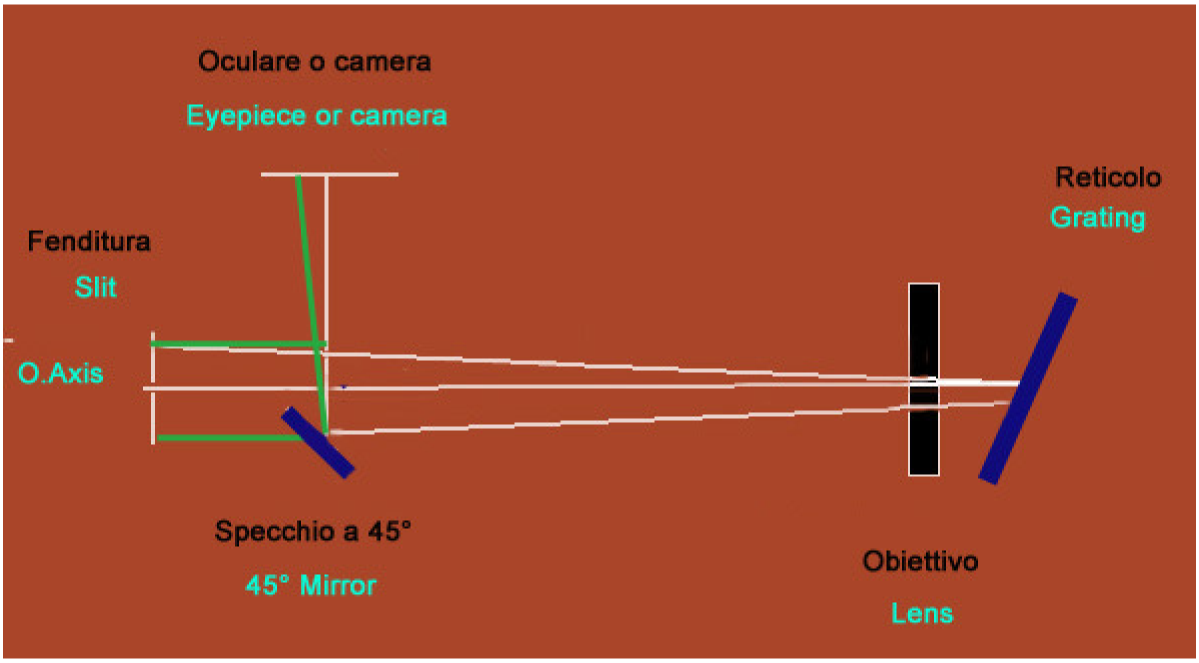
This configuration, minimizing the angular deviation, has two enormous advantages:

1- High dispersion and high resolution;

2- Extreme instrument compactness (compatible with the focal length used).

Among the disadvantages, there is the scattered light resulting from the double reflection on the optical surfaces and a slight curvature of the spectrum (smile), which is however far lower than that of the classic configuration.The the image below shows the layout of the Littrow configuration adopted with VHIRSS, with the relay mirror far from the camera, at the base of the box.

Furthermore, in my instrument, the Littrow configuration was modified by placing the slit approximately 10 mm from the optical axis, in the direction perpendicular to the longitudinal axis of the slit; so I'm talking about a "modified Littrow".

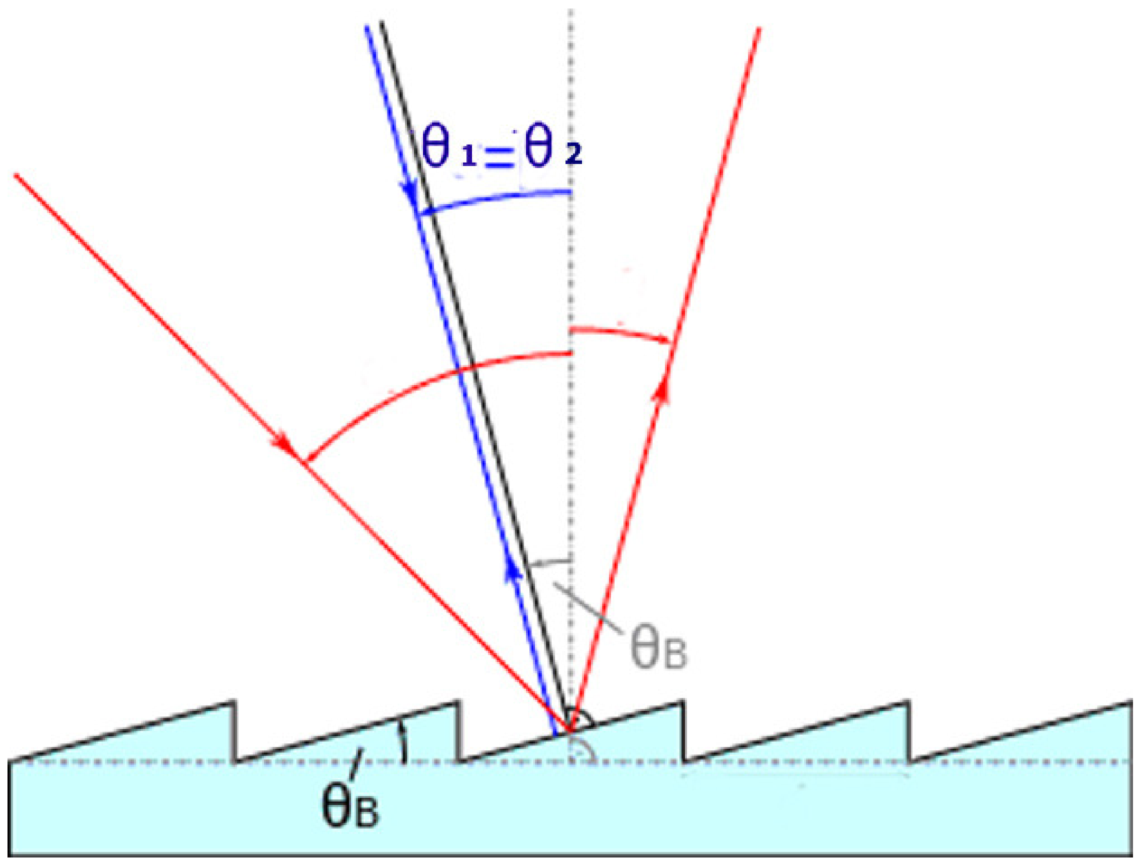


<u>The Littrow configuration in detail</u>

In the Littrow or Autocollimating configuration, as has been said, there is only one optic which acts simultaneously as collimation and camera optics. <u>In it the incident and diffracted light ray have the</u>

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 grooves on the grating).

As shown below is $\theta 1= \theta 2= \theta b$, where θb is the blaze angle. In the Littrow configuration the anamorphic factor, the ratio between the angle of the diffracted outgoing ray and the incoming one $\theta 2/\theta 1$ is equal to 1.



The general formula of the grating

$$m \times \lambda \times r = \sin \theta 1 + \sin \theta 2$$

(Where m is the order; λ the wavelength and r the number of lines per mm of the grating)

For the Littrow it becomes:

$m \times \lambda \times r = 2\sin \theta b$ (1)

from which:

$\sin \theta b = m \times \lambda \times r / 2$ (2)

$\theta b = \arcsin (m \times \lambda \times r/2)$ (3)

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

$\theta b = \arcsin (1 \times 5000 \times 10^{-7} \times r/2) = \arcsin [(5000 \times 1200)/(10000000 \times 2)] = \text{Arcsin } 0.3 = 17.45°$

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

In the previous example, the angular dispersion A in Å per degrees, is defined by the relation:

$A = [(\cos \theta b / r \times m \times 10^{-7}) \times \Pi / 180]$ (4)

Where r is the number of l/mm, m the order. It will therefore be:

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

As regards non-blazed holographic gratings, considering that they convey the maximum light energy towards order 0 (m=0), a blaze angle θb will be considered equal to 0, (cos θb=1).

A Littrow for the SHG

Let's say we want to design a Littrow spectroscope for a SHG. As discussed above, the winning points of this configuration are the resolving power and adequate optics,but with reduced dimensions and weight: it's therefore necessary to find a solution that would satisfy both requirements.

The spectral resolving power depends on the following factors:

- *The number of lines per mm of the grating* (increases as they increase)

- *The dimensions of the grating* in the hypothesis that it is completely covered by the incoming optical beam. (increases with the size of the grating)

- *The opening of the slit* (increases as it decreases)

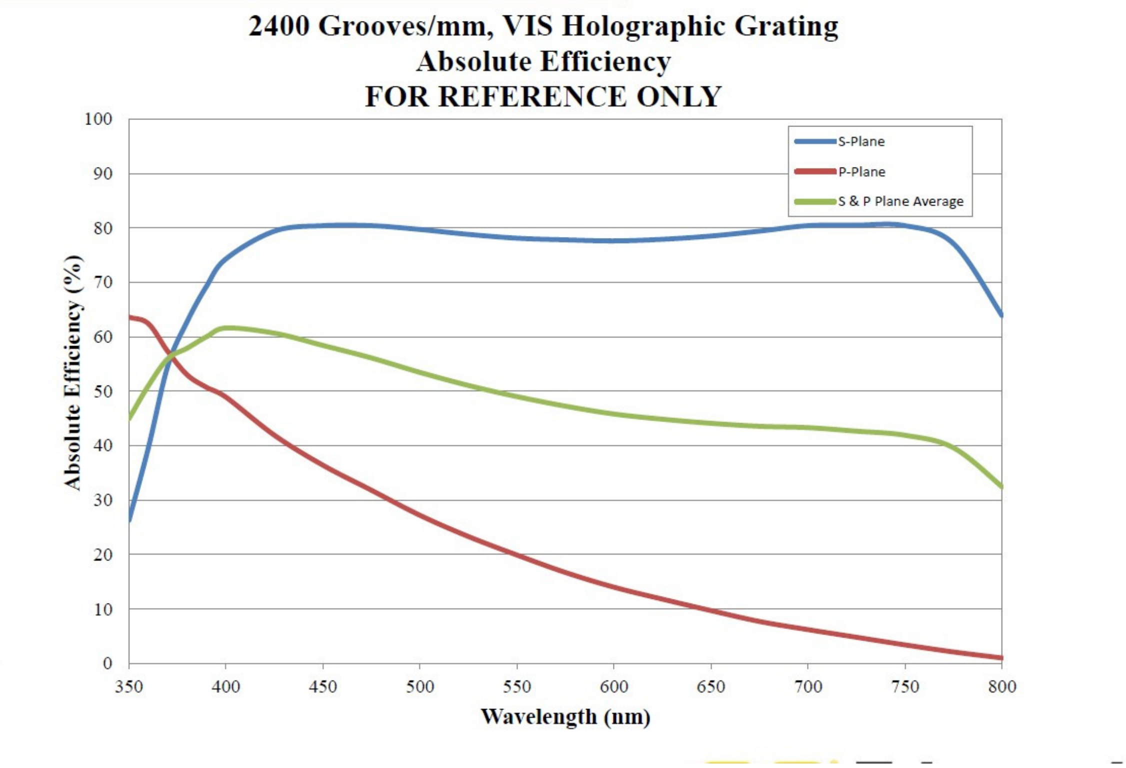
- *The size of the camera pixels* (increases as they decrease).

Dispersion, on the other hand, tends to decrease as the resolving power increases, the two elements can therefore be considered to be in an inverse relationship.

Regarding the first two points, it will be necessary to choose the reflection 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. The “ruled” gratings. ” blazed for the visible at 500 nm with 1800 l/mm (the maximum possible) in the 50 X 50 format generally correspond to these requirements.Unfortunately, these gratings are no longer found today in the catalogue of the main manufacturers.

The non-blazed holographic 50 x 50 mm gratings with 2400 l/mm are available in the Edmund Optics and Thorlabs catalogue; this type of gratings with the higher number of lines 1800/2400 have an efficiency almost equal to that of ruled gratings at relatively affordable prices. The figure below shows a graph of the efficiency of the 2400 l/mm holographic gratings (Source Thorlabs). All the Littrow SHG I used, except one, (4 in total) are equipped with this type of gratings.

Based on my experience with these instruments, I can also state that these gratings have high efficiency from near UV (Ca II K-H) to deep red (H ɑ).



S and P planes represent the different polarization levels, but non-polarized gratings also exist.

It is now necessary to choose the type of slit, whether fixed or adjustable, the slit lenght dimensions and gap, and in this regard we could make two hypothesis: that of a quality slit closed at 15 µm and at 10 µm adjustable or not.

For the camera we will assume a sensor with small but not too small pixels, so as not to reduce the sensitivity of the camera, let's say 4.4-5.8 µm.

We must now add the factors impacting on spectral resolving power.

Diameter and focal length of the spectroscope optics

In the hypothesis of wanting to use a telescope at f 7/8 to project the image of the solar disk onto the slit, a spectroscope optic of approximately this focal ratio will be necessary, while the diameter of this lens must cover the diagonal of a 50 mm square grating (50x 1.4) and therefore be at least 70 mm in diameter. An 80 mm lens would be even better, and must be at least at f 7-7.5. In this regard, there are excellent ED lenses of this diameter on the consumer market with FPL 53 glass which adapt perfectly to our needs and which can be found quite easily on the second hand market at prices around € 300-350. Personally I have used these ED lenses for most of my instruments, from 80 mm to f 7.5 (600 mm focal length). I currently own three of them, part of the VHIRSS, POSS2 and Solarscan instruments, which cost me on average € 250 each second hand: an almost ridiculous price in relation to their excellent performance.

Spectroscope parameters

We need now to establish the parameters of a self-collimating spectroscope equipped with a 2400 l/mm holographic grating 50 mm square and a 600 mm focal length lens, with a slit opening of 10-15 microns and a camera with 4.4-5.8 µm pixels (such as Imaging Source DMK 51 or ZWO ASI 174). The 2400 l/mm holographic gratings are not blazed, giving a blaze angle equal to zero (cosine equal to 1). It would give:

1- The angular dispersion defined by Equation (4) is equal to:

A = [cos 0/(2400 x 10^-7 x1)] x π/180 = (1 x 100000/24) x 3.14/180 =

72.68 Å /degree

2-The linear dispersion:

The linear dispersion DL in Å/mm is defined by the relation:

$DL = \cos \theta 2/(r \times m \times F\ cam)$ (5) ;

where F cam is the focal length of the optics

r is the number of lines per mm of the grating

m is the spectral order

Therefore :

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

For 4.4 µm pixels:

$DL = 0.0069 \times 4.4 = 0.030$ Å /pixel

3 – The resolving power at 5000 and 6563 Å

The theoretical resolving power is given by:

$R = \lambda / \Delta\lambda$ (6)

Where:

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

where ΔLf is the width of the slit projected onto the sensor plane and DL the linear dispersion in Å per mm.

<u>For a 15 micron slit opening</u>

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

At 5000 Å

R = λ/0.10 = 5000 / 0.10 = 50000

At 6563 Å (Hα line):

R = 6563/0.10 = 65630

<u>For a 10 micron slit opening</u>

Δ λ = 0.010 x 6.94 = 0.0694

At 5000 Å

R = λ/0.0694 = 5000 / 0.0694 = 72046

At 6563 Å (Hα line):

R = 6563/0.0694 = 94567

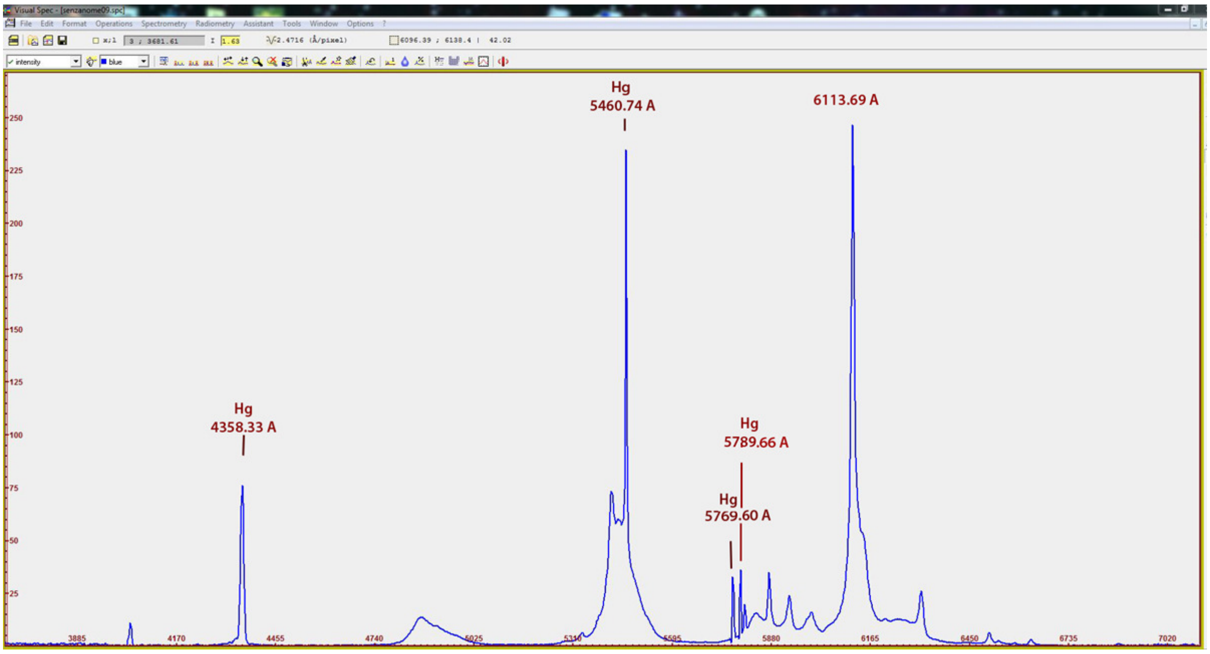
It is recognised, and verified by visual observation on any spectrum, that the closing of the slit has an immediate and important effect on the clarity and definition of the spectral image. Many times it has happened to me that I am unable to achieve good focus. Focusing and refocusing, having forgotten that the slit was too open and therefore end up obtaining a soft and undefined spectrum, even when I thought I had perfect focus.

The theoretical values of linear dispersion and resolution calculated previously agree in principle with those obtained by me (but the resolution measured in the field may be lower than the theoretical one). Using the VHIRSS spectrograph in digital SHG mode. The actual values in the field, measured with the Visual Spec software, of the linear dispersion compared to the theoretical ones are 0.02 instead of 0.03 Å /pixel with 4.4 µm pixels and an open slit of about 13-15 µm (in my cheap adjustable slit it is not possible to obtain the exact opening directly); it is good to point out, in this regard, that the lower the dispersion, the less the spectrum, spread along its lenght, and wider the appearance of the lines .

As regards the spectral resolving power, the calculated theoretical values are also significantly varied in practice for daytime seeing, focusing and slit opening. With VHIRSS I measured on average R= 43000 in the field with a slit gap of approximately 17-20 μm .

If you want to measure the resolving power of the instrument you can do it indoors, pointing it (with the slit closed to the working position, and as narrow as possible) towards a light source such as a low energy fluoro lamp or a neon lamp, obtaining the calibrated spectrum and measuring the FWHM of the thinnest line. It is also possible to measure atmospheric O_2 or H_2O on the lines, lines that belong to the Earth's atmosphere and are therefore stable.

Below is the spectrum of a low energy fluoro lamp obtained with my Spec 600 stellar spectroscope: the lines are easily identifiable.



Telescope parameters to use for the Littrow spectroscope

So far we have talked about the Littrow spectroscope, the one that appears black in the VHIRSS image, the heart of the system, let's now talk about the telescope that projects the solar image onto the slit of the VHIRSS spectroscope, the one that appears blue in the figure , and which makes it possible to use the spectroscope as a SHG.

Let's assume in this regard that we want to use a telescope at f 7-7.5 which at the same time gives an image of the solar disk on the slit no greater than 8 mm (or better still 7 mm), in the event that we want to use low-cost slits from SurplusShed appropriately modified as previously mentioned. The focal length must however be kept low both to contain the overall dimensions of the instrument and to accomodate the dimensions of the camera sensor in order to produce entire images of the solar disk without the need to create mosaics. A focal length of approximately 500 mm, with an image disk on the focal plane of 4.7 mm could be suitable for our purpose if coupled, as we will see, with a CCD sensor of adequate dimensions. This focal length is common to a certain number of lens instruments on the market, both achromatic and ED and apochromatic.Personally, for my VHIRSS SHG I used an excellent doublet of military origin with 62 mm aperture and 480 mm focal length which in numerous tests literally outclassed several ED refractors of the same diameter in terms of definition and contrast.

With some sensors, as we will see ,can accomodate the focal length up to 560 mm, and even further, always on the assumption of that we want to obtain full-disc solar images in a system that is not excessively long and cumbersome, but it can also be reduced to about 350-450 mm without appreciable decreases of overall resolution of the system. With Solarscan I used a Takahashi FS 60 C with 355 mm focal length. In this regard, the use of small ED refractors, perhaps purchased on the second-hand market, would be preferable, otherwise short-focus achromatic refractors, as long as they are of good quality and free of spherical chromatism.

The CCD or CMOS camera

The type of sensor

It is the last of the components considered for our digital SHG, but perhaps the most important. The key to the success of digital spectroheliography was precisely the advent and success of CCD and CMOS sensors, whose quantum efficiency (E.Q.) greatly exceeded that of the old photographic plates with which the first spectroheliography experiments were carried out, at the end of the 19th century, and that of the most modern photographic film of recent years.

Given that the quantum efficiency indicates the response of the sensors, i.e. the ability to convert photons into electrons across the spectrum, the EQ of the photographic film stood at a range between 4 and 10% (for hyper-sensitized films), furthermore this was higher in the blue part of the spectrum than in the red one, so much so that professional astronomical films were hypersensitized for red (Kodak 103 AO is famous). Modern CCD and CMOS sensors now reach EQ of 80, 90, and even 100%.

Here, however, we are not talking about CCD or CMOS cameras that provide single images, but about mono video cameras, therefore capable of recording video, i.e. the film of the passage of the solar disk across the slit. These cameras range from simple and inexpensive webcams to sophisticated and therefore expensive astronomical cameras such as the Imaging Source DMK in various versions with CCD sensors. Particularly the DMK 51, no longer in production today, but which can be found on the second-hand market. The ZWO ASI or equivalent with Sony CMOS sensors that are very popular, are also suitable as SHG cameras.

Very high performance mono cameras for our purposes are the 174 mm, the 174 MM the 178 MM and the 183 MM, obviously uncooled,working at 12 bit. The old DMK 51, which I still use successfully, has the characteristic of high contrast and high sensitivity in the near UV which makes it ideal for the spectroheliography of ionized calcium lines and uses a 8 bit. sensor.

Recently,there has been a real boom in the use of CMOS sensors for video cameras which, thanks to their high frame rate compared to CCDs, allows them, especially for planetary astrophotography, to obtain excellent results with bright objects for which binning of pixels, possible in CCDs but not in CMOS (apart from binning via software) is not necessary. In this field, CMOS have certainly surpassed CCDs.

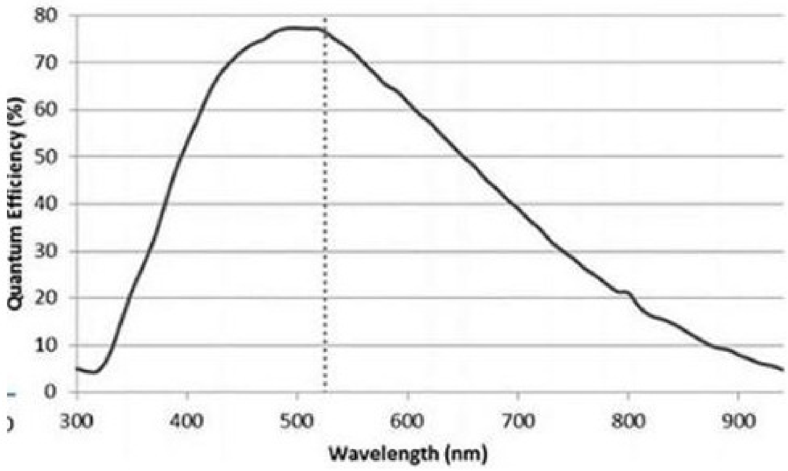
What about spectroheliography? Here the issue is complex, for a simple reason that despite the enormous luminous flux that arrives from the sun, the light that finally reaches the camera is modest, if not small. This may seem strange, but it is perfectly logical if you think about the fact that the definition and quality of the spectroheliographic images, everything else being equal, depends on the slit gap. With openings of 10-15 μ (or even smaller) and the possible use of filters the incoming light to the camera is significantly reduced and the greater sensitivity of the CCD can have the upper hand. On the other hand, the high frame rate of CMOS, in certain conditions, together with the smaller pixels, can be a winning choice.

Furthermore, it must be considered that many cameras with CCD sensors, dated or not, such as the DMK 51 have 8-bit dynamics, while modern CMOS work at 12 or 16 bits, and this constitutes an important factor for the better recording of some characteristics of the solar chromosphere. Then there is the factor of quantum efficiency, the sensitivity of the sensor in the various spectral regions, for which the latest generation CMOS, especially the backlit ones, are superior with a high EQ even in the near ultraviolet and infrared.

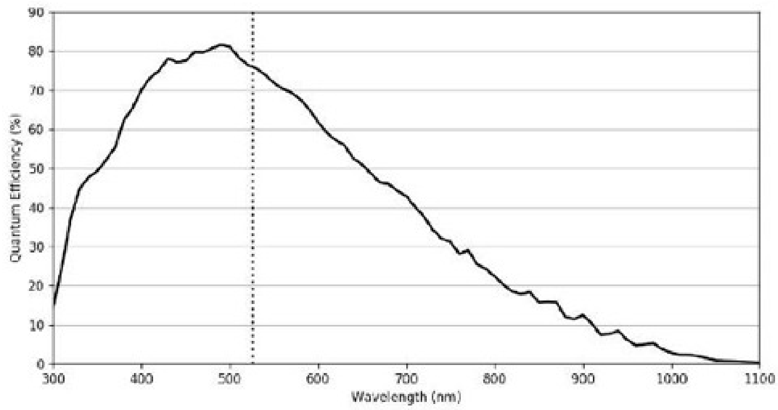
Here we also touch on a further point in favour of CMOS: the possibility of using backlit sensors at lower costs than those of CCDs. The latest generation of CMOS cameras, such as the ZWO ASI 290 and the 183 MM, both of which I own, are equipped with these types of sensors which have a higher sensitivity compared to others CMOS and similar CCDs.

Below are the quantum efficiency curves of some cameras with CMOS sensors suitable for spectroheliography. It goes without saying that <u>for spectroheliographic applications only cameras with black-white sensors should be used, due to the superior sensitivity in conditions of low light on the focal plane.</u>

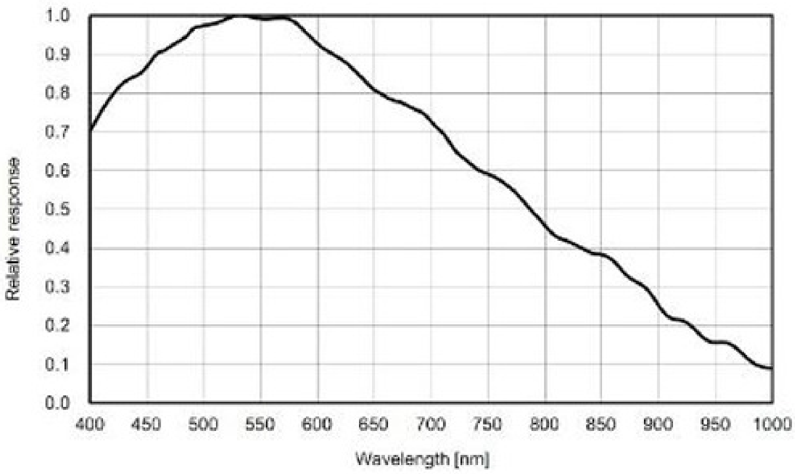
ASI 174 M Q.E



ASI 178 M EQ

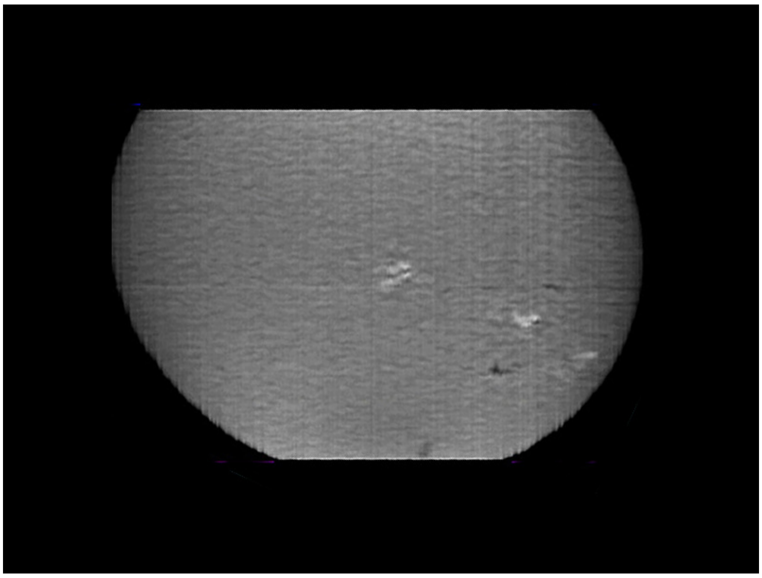


ASI 183 M Q.E



The size of the sensor

The physical dimensions of the sensor are important because they will determine (with the slit length) how much of the solar disk will be recorded by the camera. If, for example, I use a webcam with a Sony ICX 098 BQ 3.6 x 2.7 mm sensor and a 500 mm FL telescope that projects a 4.7 mm solar disk onto the slit, the recorded AVI file will have a coverage of 3.6/4.7 = 0.76, that is, it will cover about ¾ of the disk, obtaining a partial image, as shown in the following image, which was my first solar image recorded many years ago with a Philips Toucam webcam.



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

This applies in the case of Littrow spectroscopes with a single optic, where it is not possible to change the collimator/imaging lens focal lenght. However, in the case of spectroscopes that use both collimator and imaging lenses it will be possible to change the focal length of the latter to reduce the image of the solar disk to better match the dimensions of the sensor. Let's consider we have a 700 mm telescope that projects an image of the sun of 6.5 mm in diameter, a ZWO ASI 224 with a 4.8 x 3.6 mm chip, a classic spectroscope with a collimator of 200 mm focal length and a camera lens also of 200 mm (magnification ratio equal to 1) the solar disk will not fit within the chip, resulting in a partial spectroheliogram.

Let's now imagine changing the focal length of the camera lens from 200 to 100 mm: this will produce a reduction in the magnification factor of 100/200 = 0.5, and the solar disk will now have an apparent diameter of 6.5 x 0.5 = 3.2 mm and it will easily fit on the ASI 224 chip.

The dimensions of the pixels

The daytime 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 air masses at high altitude the cause of poorer daytime observation conditions compared to night-time ones.The 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 everyone has this opportunity. We can safely say in daytime solar observation, even more than in long-exposure night-time observation, that it is the seeing and not the diameter of the optics that determines the achievable resolution even with exposure times and integration closer to those of planetary imaging than to those of the deep sky. Assuming an average seeing of 4 arcsec, the necessary sampling, according to the Nyquist criterion, will therefore be 2 arcsec per pixel, and therefore the focal length of the resulting spectroscope imaging optics will be:

With 4.4 µm pixels (DMK 51)

F= (0.0044 * 206265)/2 = 453 mm

For 5.86 µm pixels (ASI 174)

F= (0.00586 * 206265)/2 = 604 mm

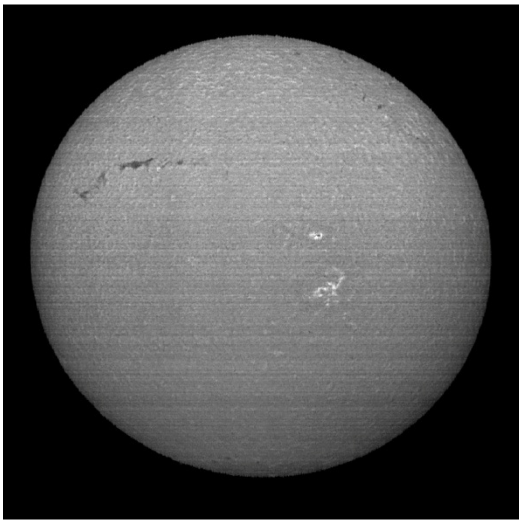
For 2.4 µm pixels (ASI 183)

F= (0.0024 * 206265)/2 = 247 mm

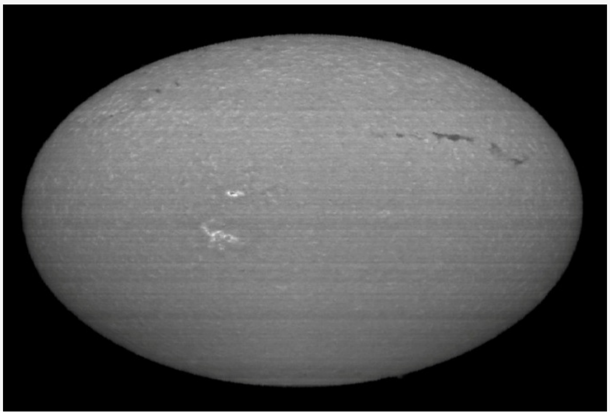
All this works well with a slit opening of 10-15 µm as previously mentioned.

The frame rate

The frame rate is important because the resolution of the image along the X axis (or Y, depending on the position of the slit and camera) depends on it. With a DMK 51m 1600x1200 pixel (oriented with the longer side of the chip along the AR axis, parallel to the spectrum) a scan of 160 sec and a frame rate of 7.5 fps I obtain an image that extends along the X axis of 160x7.5 = 1200 pixels including edges (not counting lost frames). Along the Y axis the size is the native one of 1200 pixels (in the absence of cropping of the video image). The appearance then looks like this:



With a frame rate of 12 fps I would get 160x 12= 1920 pixels for the full image along the X axis, with an appearance similar to the following.The distortion introduced between X and Y axis can be easy corrected with any photo editing program.

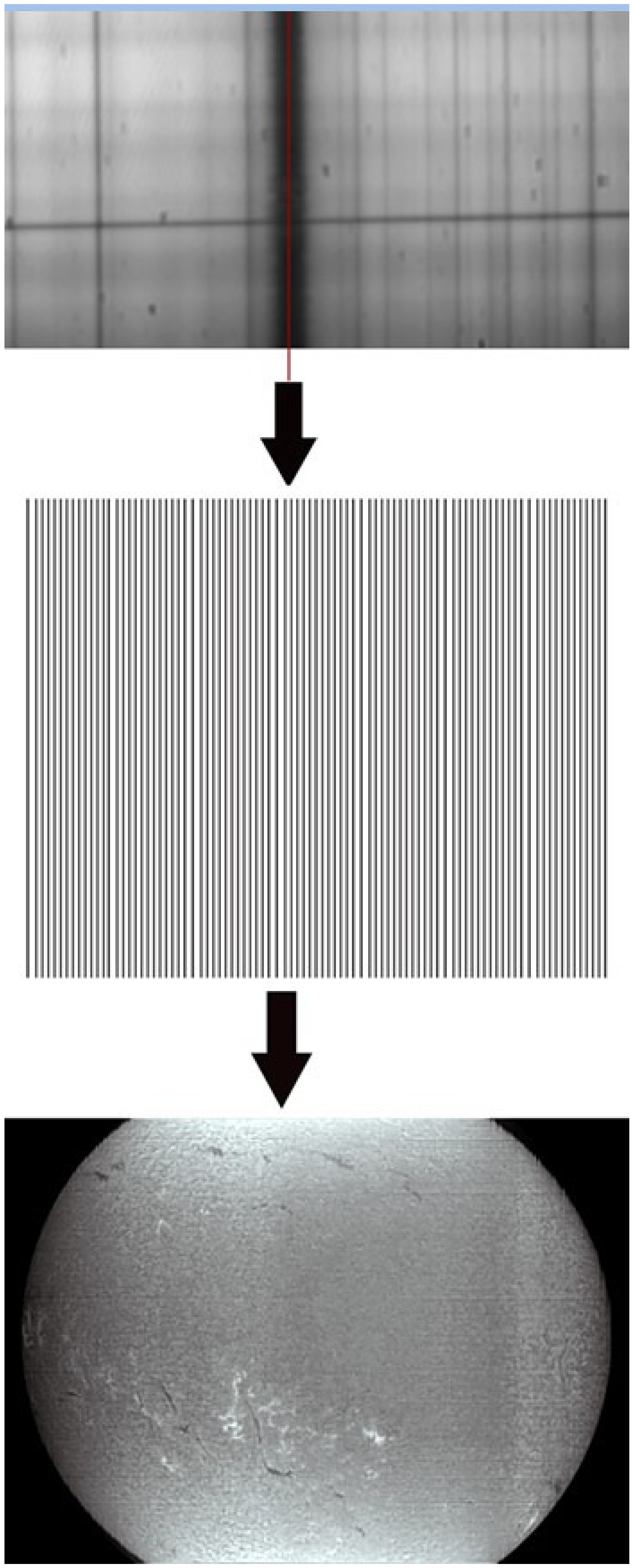


The aspect ratio problem has now been overcome by the latest generation software, which provides a squared image of the solar disk of given dimensions in pixels starting from any level of frame rate.A high frame rate can be advantageous at times when short scans are made on a mount driven rather than the classic scan of letting the solar disk drift across the slit due to the apparent motion of the sky.

However, the high frame rate with full-frame images can cause download problems on PCs and cameras equipped with USB 2.0. For the ZWO ASI cameras, which use an USB 3.0 bus, this problem is not an issue on the latest generation PCs.

At this point, I'd like to discuss the methods of video acquisition and the various programs for reconstructing the SHG image starting from the recording of one line of the spectrum.Once you have placed the disk of the sun on the slit and centered the target line on the video image using a camera acquisition program (Firecapture, IC Capture etc.), possibly by using a ROI (Region Of Interest) you use the mount motors to move the image of the solar disk to the upper edge of the slit of the spectroscope, you will see the line disappear on the PC screen, then start the acquisition of the video by immediately stopping the motors of the mount and letting the solar disk drift across the slit due to the earth's rotation.As the image scrolls on the PC screen, the line will gradually appear, become increasingly larger, and then disappear at the end of the scan, which lasts approximately 3 minutes at 7.5 fps (including downtime).

Once the video scan is obtained, image reconstruction software allows a pixel column from the video spectrum to be selected (generally the centre of the line, in red in the image).This column is then extracted and placed alongside the same pixel column extracted from all other frames to make up the final image.



Therefore, assuming for example that there are a total of 1200 video frames obtained with the scan, we will have an image width of 1200 pixels on the X axis and as many pixels as the native ones of the camera chip on the Y axis. Here the advantage of a lower dispersion (with a larger spread and larger lines in the spectrum) and a high spectral resolution comes into play.The lower the dispersion, there are more pixels in the width of a line, and the more times pixel columns can be selected.This then allows stacking the various images obtained during the scan.For instance, if the Hα line is wide 60 pixels, I will be able to obtain 60 images from pixel columns from the various points across the line, which can be added to obtain a better final integrated image.

Not only that, but, having the foresight to put a limit in the acquisition program on the number of frames you select, for multiple scans, images in the same format will be obtained which means that frames from many scans can be added together,based on line width of 60 pixels as per the previous example with 6 scans 60 x 6 = 360 images of one pixel column to be stacked.

This is one of the reasons why I designed and use high resolution SHG with medium-long focal lengths. The previous image illustrates the described sequence: from the spectral line (the Hα) to the selection of the single pixel column of interest within the line , to the combination of this column with the others, extracted from all the frames of the movie to obtain the final image.

In the latest generation software, which operates directly on the appearance of the solar disk in the image (inclination, shape, centring, and so on), as well as squaring the image itself, the processing is much more complex than the simplification described above, but the methodology remains more or less the same.

Final note: the exit slit

As we have seen, the original SHG designs had two slits, one at the input and one at the exit, for reasons linked to the synthesis of the images. With digital SHG this is not necessary, given that the synthesis is carried out via software. However, especially in the case of the Littrows, it is easy for scattered light to be created along the optical path. The use of internal diaphragms is rather complicated as, if not implemented perfectly, it risks creating obstruction to the input and return optical beams.

An alternative solution is to use an interference filter at the output of the instrument centered on the wavelength of the target line we want to use to obtain the image. This is helpful when recording the video, to suppress a good part of the scattered light and increase the contrast. This filter can be inserted into the 1/1/4" nosepiece of the camera. A second solution, at least with Hα imaging, can be to use a deep red rejection filter placed in front of the telescope objective, or along its optical path. Even the common 2" 35-12 nm bandwidth filters placed at approximately 30 cm from the focal point can be useful for this purpose. However, it is necessary to consider, in this last case, that in the long run have now UV radiation can be harmful to the coating of the filters themselves, which is why the use of UV-IR cut filters is recommended in front of these.

In conclusion:

We have now analysed the components of a digital SHG in detail, arriving at some interesting ideas that agree quite well with the practical experience carried out with my instruments, namely:

1-To reconcile portability, compactness, lightness and high spatial and spectral resolution, the Littrow configuration of the spectroscope presents itself as the best in terms of overall efficiency, i.e. the performance/size ratio, weight and relative ease of construction. As part of this configuration, the telescope, which sends the solar image to the slit, should have a focal length of around 500 mm and a focal ratio of f 7-8.

2-The slit, to accommodate the solar image of the 500 mm FL telescope, should have a length of at least 7 mm (better 10-15 mm), and close to a gap of 10-15 µm or less.

3-The spectroscope optics should have a diameter of 70-80 mm at f 7: 80 mm ED refractors at f 7-7.5 are ideal candidates.

4-The grating should be 2400 l/mm and 50 x 50 mm or less, in the case of smaller instruments.

5-The camera should have a large sensor and small-medium pixels between 4 and 5 μm, i.e. smaller pixels in 2x2 binning.

6- The telescope should have a FL compatible with the length of the slit,the dimensions of the camera and the F/D ratio of spectroscope optics, possibly of an f 6-7 F/D ratio.

Naturally 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 spectroscope optics (three 80 mm f 7.5 ED refractors) I used optics of different telescopes, although of excellent quality (a 60 mm f 8, a 70 mm f5, and a 60 mm f 6). I have not noticed, as yet, any particular differences in the performance of the three instruments in terms of resolution. Nothing prevents us, for example changing the size of the camera chip to give full disk imaging and slightly sacrificing size and weight, to adopt two 80 mm f 7.5 as telescope and spectroscope optics.

Instruments for spectroheliography

I created five Littrow projects, similar in layout, but different in size and weight, and each with different specific functions. Some might ask: but was it really necessary to build five similar instruments to ultimately perform the functions that only one of them could it have done? The answer to this question is very simple:

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

b) From my home in Rome I have an observation window of approximately 0.45-1.15 hours (after which the sun is covered by the ceiling of my balcony) which means that in this period of time I have to carry out the video recording. In this context, using an instrument already setup for the Hα and another on the Ca II K greatly facilitates operations and allows me to be more efficient by dedicating the little time available to the output rather than to the setup focus, centering on the line and other instrumentation setup operations. Obviously these problems do not occur with Solarscan whose operating procedures, controlled by PC, are very rapid and precise.

Naturally mine is a special case, but perhaps not too much, and anyway the pleasure of dedicating myself to such DIY activity has overcome any inconvenience.

Having said that, let's now look more closely the individual instruments, originally used as high-medium resolution spectroscopes and then converted into digital SHG.

1 **VHIRSS** (Very High Resolution Solar SHG). This was the simplest project, but also the best performing among those assembled at home with only having to resort to a mechanical workshop for the threading of the aluminium box. It is currently dedicated to digital imaging of the Hα spectrum.

2 **POSS2** (POrtable Solar SHG 2).An SHG Littrow now dedicated exclusively to imaging in the CaIIK and H ionized calcium lines and other near them (Al1,Cn, and so on) with the use of specific filters to isolate UV radiation.

3 **SOLARSCAN** is the main instrument from a construction point of view, as it was excellently manifactured to my design by Avalon Instruments of Pomezia (Rome). Initially used as a SHG, it was subsequently modified by me to capture the Zeeman Effect on sunspots and the measurement of their magnetic fields.

4 **HIRSS2** (High Resolution Solar SHG 2) is now used only for experiments of various kinds.

5 **UPS** (Ultra Portable SHG) given its very small size and weight (an Eq2 mount carries it without problems) is used for imaging the H beta and H gamma lines and for field demonstrations of the use of spectroscope and SHG.

The first four are high resolution instruments, with a spectroscope focal length of 600 mm and a 50 mm sq x 2400 l/mm grating, while the fifth is medium resolution, with a focal length of 300 mm and a 25 mm grating. To these, a low resolution solar Littrow was recently added, called **MILSS** (Mini Littrow Solar Spectroscope/SHG.

DIY high resolution digital SHG in Littrow configuration: VHIRSS

But let us now examine in detail a DIY digital SHG by the author: it is, as has been said, an auto-collimating or Littrow configuration. Making a digital SHG is certainly much less complex than the traditional SHG, but it still requires a good amount of manual skills, mechanical skills and, mainly, experience in the DIY field. Anyone who wants to test their skills should know that not only general theoretical preparation in astronomy and manual aptitude count, but also some knowledge of spectroscopy and its practical applications.

This is because, once the instrument has been built, it's necessary to interpret what it has captured, and some preliminary knowledge will make the task easier. In general the layout and schemes are, in principle, rather simple, but the problems of aligning the optics and spectra increase more than proportionally with respect to the focal length of the lenses or mirrors used, hence the suggestion is not to exceed focal lengths of the order of 600 mm for the spectroscope.

I would now like to talk about the instrument that has given me and still gives me the most satisfaction:the VHIRSS. The layout of the instrument is in principle extremely simple, and it is precisely this simplicity of construction, combined with its weight and small dimensions (8kg and 110 cm in length) that makes it the instrument

I use the most. I have currently dedicated it recording the solar chromosphere in Hα, but obviously it can be used in any wavelength.

Below is the layout, in which we see an Orion 80/600 ED refractor as the spectroscope's optics and a 62/480 objective of unknown origins but quality performances as a telescope, adapted into the blue tube of a SW 70/500.

<u>The initial project</u>

The Idea behind this project was to create a sophisticated instrument with almost professional performance that was simple to assemble, disassemble and transport, as well as being resonable in weight and size. I therefore decided on an assembly of five elements, each very easy to disassemble, thereby reducing overall dimensions and increasing ease of transport. The dimensions are approximately those of a refractor of 10 cm aperture and 1000 mm focal length.

The optical-mechanical elements are:

-The case containing the grating and its movement system, obtained from a simple lens hood from an old 102/500 refractor. I did not consider using the ED 80 lens hood itself as I had to drill it to accept the axis of the grating cell, and I preferred to make use of a piece that was no longer of use to me.

- The Orion ED 80 refractor tube.

- The square aluminium case 60 x 60x 3 mm containing the 20 mm square deflection mirror and the adjustable slit.

- The 62/480 surplus refractor telescope tube used to send the solar image to the slit.

- A square steel support tube with a side of 30 mm, a thickness of 3 mm and a length of 1 m used as a support for the rings of the two refractors, set up so that the optical axis of the 62/480 was aligned with the entrance of the slit and focused on it, and the whole assembly had absolute rigidity, without any flexure.

- A micrometric slide for macro photography was installed on the 62 mm refracting telescope allowing precise focusing on the slit with a longitudinal translation movement.

Having said that, let's move on to the details of the construction notes:

1- The grating

The grating chosen was a holographic, non-blazed, 2400 l/mm 50 x 50 mm grating purchased from Edmund Optics at the price (at the time) of € 250, now around € 360. It is the grating with the highest number of l/mm, and which therefore allows the maximum possible resolution to be obtained, provided, obviously, that its surface is entirely covered by the diameter of the optical cone from the collimation optics. This grating has proven to be of excellent quality, adequate for the not exactly negligible cost. After all, the diffraction grating is the heart of a spectroscope, and wanting to save on it is like wanting to buy a sports car with a 50 cc engine.

If you intend to use an optical tube with an aperture of less than 80 mm for the spectroscope, a 30 mm grating is also fine, costing significantly less (around €225). Obviously the grating must be handled with the utmost care, holding it from the sides, possibly with talcum-free rubber gloves, given that any finger marks or scratches on its surface are permanent and cannot be eliminated.

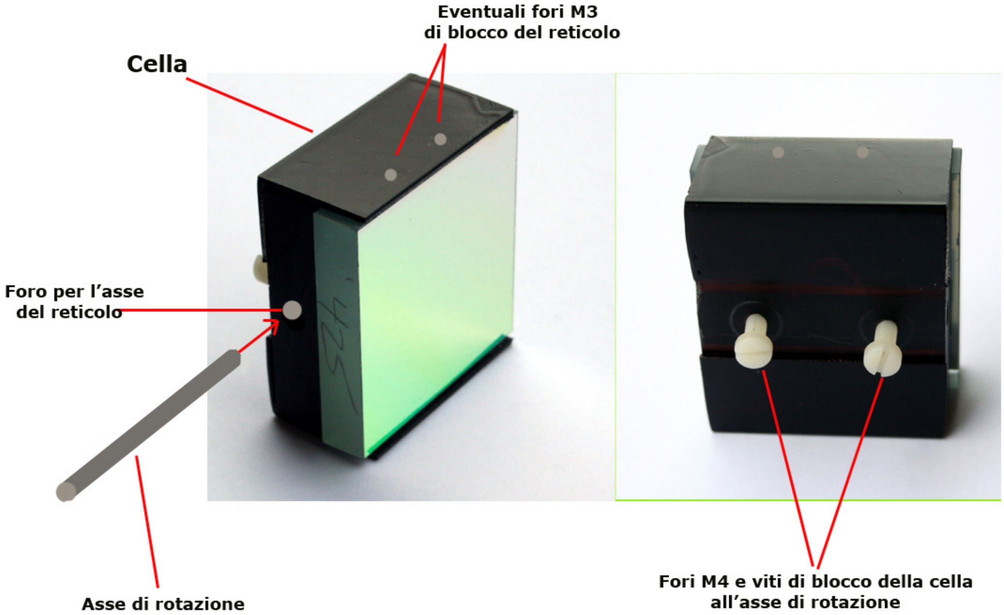
The grating must then be positioned in the cell in such a way that the arrow indicated on one of the sides is perpendicular to the rotation axis and facing in the direction of the collimation optics. This can easily be verified by holding the grating on the side with the arrow, pointing it towards a light source and rotating it: you must observe the bright band of the spectrum, from blue to red.

2-The grating cell

This is a critical element, as it must hold the grating perfectly without forcing it into place.

I had a 50 x 60 mm black PVC block which was milled to approximately 20 mm thick, to a depth equal to the thickness of the grating (9 mm) in order to accommodate it perfectly in its seat.The grating was held in place with a double-sided tape. However, I found it appropriate to secure the grating even better, by threading the two upper and lower parts of the cell M3, and fitting fixing screws. This fixing must be carried out with the utmost attention, given that excessive pressure could damage the grating or its performances (plastic screws are recommended).

The cell was then drilled longitudinally with a 6 mm hole to accommodate the rod used as the rotation axis. This rod was secured in place by two M4 screws blocking the cell onto the axis.

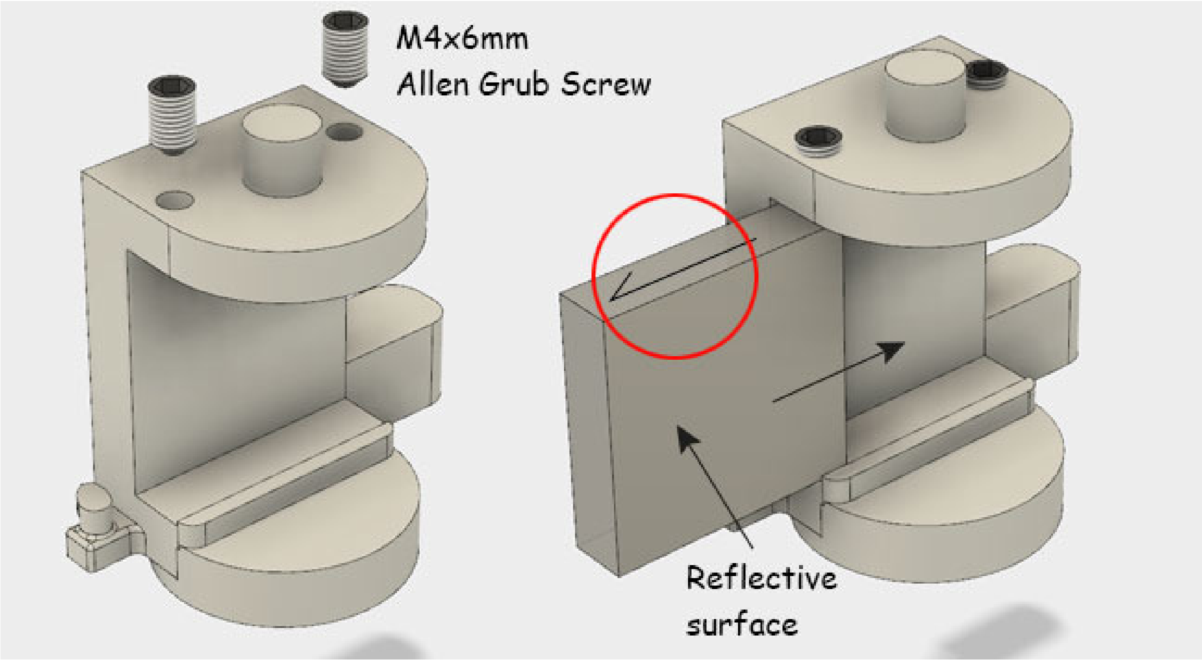


It is worth noting that with the increasing use of 3D printers, the grating cell (like other minor components) could now be conveniently printed in PLA or PVC with a good resolution printer, as per the "Low Spec" project by Paul Gerlach

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

3D printers with high resolution and technical capabilities useful for our purposes can in fact be purchased today at prices around € 1000, and greatly facilitate the creation of secondary components in plastic material, such as the grating cell just described, which are not subjected to excessive loads.

The following image shows a 3D grating cell printed in PLA



It is important to point out that the grating must be placed in the cell so that the arrow indicated on the side of the grating is perpendicular to the axis of rotation of the cell and pointings towards the optics of the self-collimating spectroscope. If placed the other way round, no spectrum will be seen Furthermore, <u>the rotation axis itself must be parallel to the slit along its length and to the relay mirror, otherwise some slant of the spectrum may occur.</u>

The material of the rotation axis can be chosen as desired, however, given the very low weight of the cell and the grating, a lenght of M5 or M6 threaded bar is more than sufficient. Mounting the grating in its cell (and therefore the holes in the box that houses the cell) must be positioned at a distance from the spectroscope objective which allows the complete rotation of the grating.

3-The collimation-imaging optics

the optics used for VHIRSS was an Orion 80 ED OTA (practically the same as the SW 80 ED) an ED refractor with 80 mm diameter and 600 mm focal length purchased on the second hand market for € 250, with excellent performance in terms of definition and contrast. Given its versatility, it was also adopted by me for the other two

Hires SHG, Solarscan and POSS2. Today the prices on the second-hand market are higher, but it is still not difficult to find these for 350- €400.

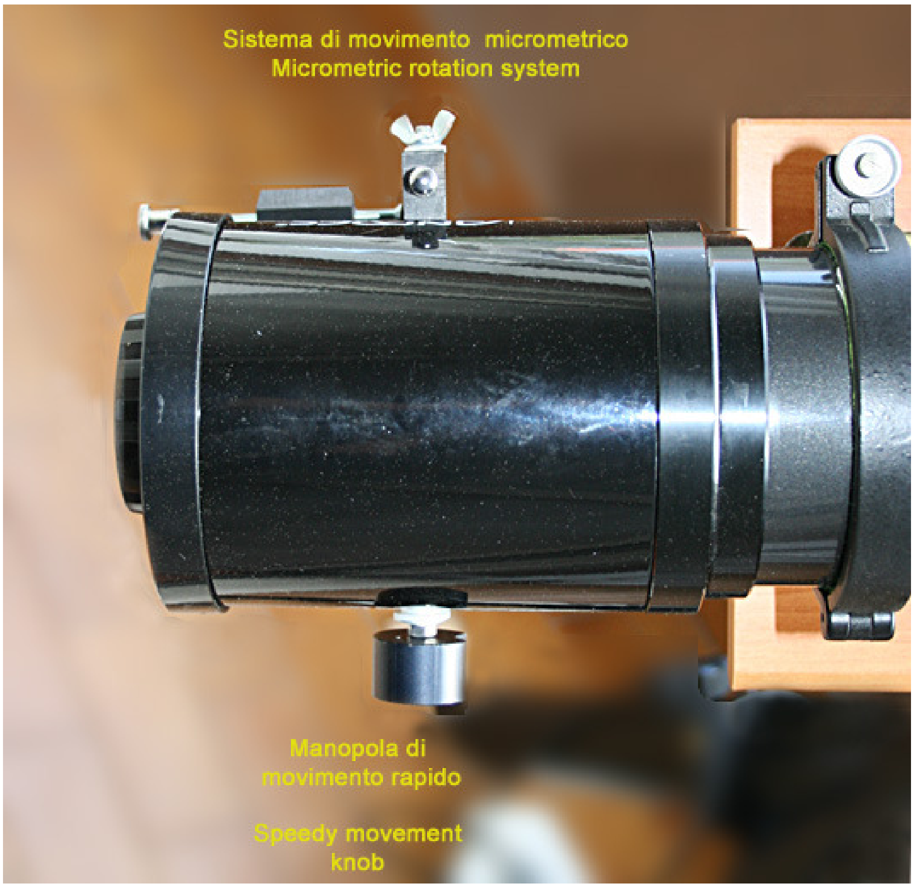
4- The grating box

The box in which the grating in its cell can be mounted can conveniently be made up of the lens hood of the telescope. In my case, not wanting to damage the original Orion 80 ED lens hood which constituted the spectroscope optics, I used the lens hood of a 100 mm Antares lens already in my possession. Regarding the drilling of the box (in my case the lens hood), it is necessary to ensure that the holes to locate the axis in the housing must be absolutely aligned.This is best obtained with a long drill bit and a column drill press. In the following image you can see the lens hood drilled with the rotation rod.

Regarding the rotation methods of the grating in its cell, which, as we know, serves to select the wavelength and the line of interest, I tried to combine construction simplicity with maximum efficiency in the rotation, which is fundamental for the purposes of use of the instrument.

In stellar spectroscopes, given the low resolution, the modest length of the spectrum and the very small rotation range, it is convenient to use a micrometer to select the wavelength. In solar ones with focal lengths over 5-600 mm, the length of the spectrum is considerable, and going from one end of it to the other with a micrometer becomes exhausting and annoying. I then thought of equipping the rotation rod with two movements: a rapid one, obtained by manually moving a knob fitted on one of the ends of the axis, and a micrometric arm on the opposite side, which is activated, again manually, by means of a special friction screw which engages 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 an electric motor and batteries exclusively to a basic task for the operation of a device can be a source of problems. I would therefore recommend, in any case , that the motor replaces the manual micrometric motion, while still leaving the fast one operable by hand in the case of motor failure. Naturally, for those who possess the necessary knowledge of electricity and electronics, the use of stepper motors for the fine adjustment not only of the rotation of the grating, but also of the focusing system of the telescope and spectroscope, perhaps controlled by a PC, would not pose a problem.

The following image shows the box and the two systems for controlling the rotation of the grating cell, the fast one and the micrometric one.

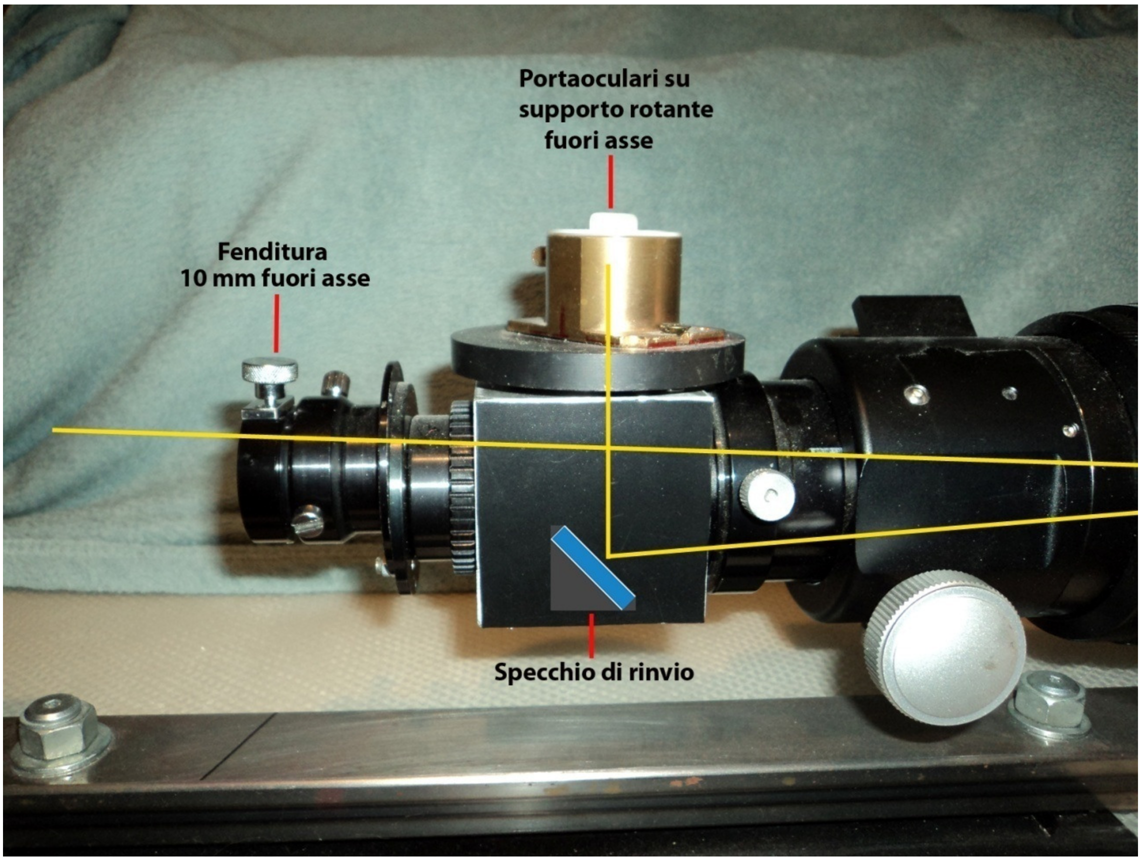


Below is the detail of the micrometric movement, extremely simple to achieve even with home-made means. The PVC arm inserted onto the axis but can be made of any material, preferably aluminium, as long as it is smooth and can slide. Once it is locked to the axis by tightening the friction screw, it can be controlled by a tangential screw with a tension spring. It's a system that may seem crude, but it works perfectly.

As you can see, by tightening the friction screw, the arm becomes locked to the axis and the rotation in one direction or the other is controlled by a tangent screw with knob and a tension spring.

5- The relay box

This is another important component of the instrument. In some cases it may be convenient to adapt an off-axis guider which can also be found on the second-hand market at affordable prices, possibly with a mobile prism of adequate dimensions. As a box I used a piece of aluminium square tubing 60 x 60 x 3 mm thick. This can be closed on the sides with closing caps secured with M3 screws (alternatively glued 1-2 mm black PVC is also fine). The box was then drilled on three sides and threaded T thread M 42 x 0.75 to allow, as seen in the figure, the attachment of the 1 1/4" eyepiece holder of the slit, the eyepiece, camera and also the attachment to the focuser of the spectroscope optical tube using a commercially available T thread to 2" male adaptor.



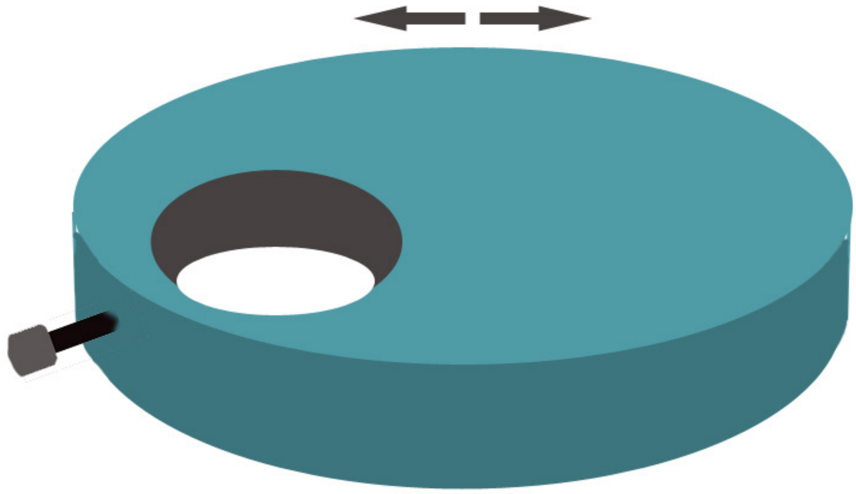
In the figure above you can also see that the eyepiece holder of the slit is placed off-axis with respect to the axis of the optical tube. One of the characteristics of VHIRSS and POSS2 compared to the other Hires spectroscopes I have built is the positioning of the slit off the optical axis. This variation was dictated by the intuition that a larger angle could allow for better resolution and scattered light reduction. The displacement of the centre of the slit with respect to the optical axis was approximately 10 mm, equal to just over 1 degree at the grating plane. From the use of the instrument in the field it would seem confirmed that this displacement can bring an improvement in the resolution and the final image, also due to the suppression of some internal reflections.

The relay mirror that redirects the return light beam (spectrum) coming from the grating via the objective towards the camera should have a size equal to the full light field of the objective (in my case an 80/600) necessary to cover the focus point at the camera sensor diagonally, measured at a distance of approximately 70 mm before the focus itself, i.e. 530 mm from the optics. Taking into account that the largest of the sensors mentioned measures 15.8 mm diagonally (ZWO ASI 183 MM), a mirror size of 20 x 20 mm would be sufficient in the example mentioned.

However, when choosing the lenght of this mirror, it is necessary to pay attention, when placed at 45°, it does not interfere with the light beam entering from the slit. Naturally, instead of an aluminized mirror, a prism of suitable dimensions can also be used.

Speaking of assembly, the cell of the mirror or prism should logically be mounted in such a way as to allow the adjustment of the optical beam on three points at 120°, similarly to the holder of the Newtonian diagonals However in practice I have noticed that this adjustment, which can complicates assembly quite a bit, is not absolutely necessary and in any case can be partially replaced by a 120° adjustment in the eyepiece holder of the camera.

Another particular feature of the instrument is the rotating off-axis 1 1/4" eyepiece holder. This allows you to centre the line of interest even if the spectrum, as is known, moves along its axis as the wavelength varies due to small imperfections in the grating grooves and/or its positioning in the cell. An alternative to this system could be to make a grating cell adjustable with 3 screws at 120° and therefore able to slightly decentralize and rotate the grating. However this solution does not excite me due to the suspicion that a grating placed obliquely with respect to the collimator optics can produce coma aberrations and astigmatism in the spectrum.



The rotating eyepiece holder with a 11/4" off axis hole

It is important to point out that, if you do not opt for the off-axis slit solution, the box with the slit and the eyepiece holder for the camera can be advantageously replaced with a good off-axis guider, however mounting it in reverse so that the prism faces the grating, rather than the telescope.

One of these, particularly suitable for this purpose (of which I have two examples), has the advantage of being able to retract the large prism at will, so as to be able to position it in the best point, as well as extract it completely and, as necessary in our case, direct it on the opposite side. However, it does require adaptors rings and, obviously, a 2" male connection to fit into the eyepiece holder of the spectroscope's optics focuser (see figure). Naturally, in principle, any off-axis guide can be used, as long as it has, as we have seen, a prism of adequate size for the optical beam it intercepts and the necessary mechanical connections.

Off axis guider with moveable prism

6-The slit

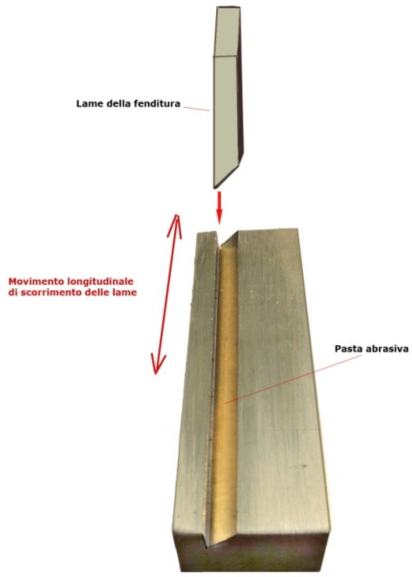
I have left the discussion on the slit for last as this component, together with the grating, are the decisive ones for the resolution of the system and the quality of the images. It is also the most problematic one from the point of view of the processing of the slit jaws and the general mechanics .A slit worthy of the name can cost considerable sums and would be overkill for the needs of an amateur instrument such as a digital SHG. Many amateurs recommend making the slit blades yourself, but this is not at all easy without owning and knowing how to use a mechanical workshop with cutters and grinding machines. Furthermore, not all precision mechanical workshops are able to work the blades to the required degree of precision, which is that similar to the manufacture of astronomical mirrors (1/4 λ) or at least approaching this.

For VHIRSS I adopted a hybrid solution, namely that of purchasing a low-cost commercial slit and improving the finishing of the slt blades myself.

The slit is the one produced in India and marketed in the USA by Surplus Shed

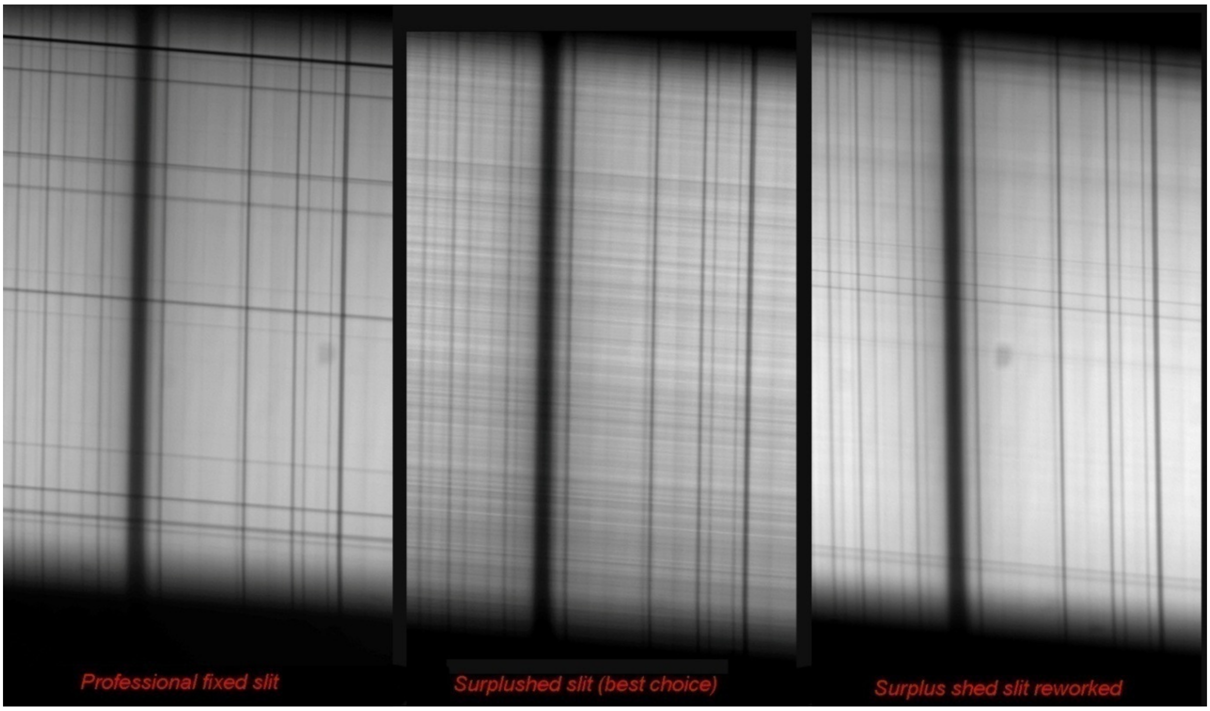
https://www.surplusshed.com/pages/item/m1570D.html.

It was dismantled and the blades checked under a microscope at X 400, after which the edges of the blades were worked by passing them over a specially made brass tool with a female slot similar to the blade male bevel, applying body repair abrasive paste (but also cerium oxide can be used). After a few passes, at medium pressure, the improvement was evident under the microscope, and they were reassembled.



Obviously the work of refining the blades can also be carried out without the tool shown, which in practice acts as a guide, by appropriately tilting the blades on a perfectly smooth surface of hard plastic or, better, glass, applying the abrasive body repair paste, if you don't have cerium oxide.

Below is the comparison of this modified slit (on the right) with one of the best ones from Surplus Shed (in the centre) and with a fixed professional one (on the left) on a spectrum of the Hα line. This confirms the usefulness of the processing carried out.The horizontal lines of the transversalium have in fact almost completely disappeared and the spectrum is more defined. All this obviously with the same opening of the slit jaws.



Recently an English amateur astronomer passionate about spectroheliography, Douglas Smith, has created a fixed slit on a thin layer of chromium oxide deposited on a base of fused quartz, all mounted on a 25 mm copper ring.

The author owns two of them, and they perform their task excellently, ensuring perfect uniformity of the luminous flux between the centre and the edges, However. since it is advisable to use a filter that eliminates IR and UV radiation, I inserted a 31.8 mm UV-IR cut at the end of eyepiece barrel that contains it.

Other 10-micron chrome on glass slits are marketed by the French spectroscopy instrument company Shelyak.

https://www.shelyak.com/produit/se0223a-fente-alpy-uvex-10-%c2%b5m/?lang=en

Based on my experience with VHIRSS I can say the following:

-The air-adjustable slits are, in some ways, equivalent in terms of performance to those made of quartz or glass as long as they can be closed to at least 10-15 microns without excessive transversalium and without losing the parallelism between the blades, which is unfortunately quite difficult without mechanical improvements like the one I carried out.Regarding the problem of the transversalium, if the lines are of slight intensity the final image will not be affected given that the latest conversion software, which we will talk about shortly, provides a routine for eliminating it, and in any case, in this regard, air slits have a slight advantage over quartz slits: that they can be closed to the maximum to visualize the transversalium lines on which to focus, and then open to the working aperture. Furthermore, they have the characteristic of being able to be adjusted depending on the light intensity and the F/D ratio of the telescope and of being absolutely resistant to the heat of sunlight concentrated on their surface.

With low-cost air-adjustable slits, such as those from Surplus Shed, the main problem was that of the poor parallelism of the blades to the working closure, so it is better to acquire a certain number of them and choose the best one from a mechanical point of view, then work to improve the edges of the blades, as previously mentioned.

As regards slits in quartz and glass, it is however in my opinion necessary to place a UV-IR cut filter in front of them to avoid overheating and possible breakage; furthermore, in order to regulate the luminous flux, especially in the case of fast F/D ratios and large telescope objectives sending sunlight to the spectroscope, these can only be used with ND filters of appropriate density.

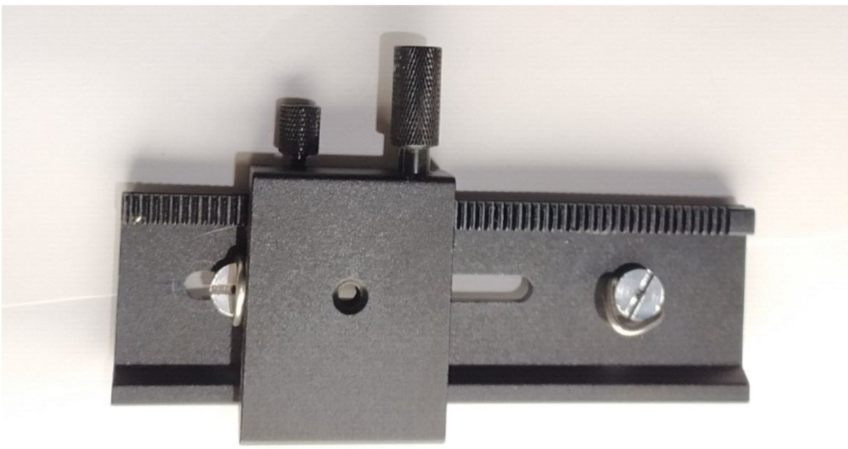
7 -The optics of the telescope

The VHIRSS telescope optics are, as I said, an excellent surplus doublet, probably of military origin.I paid at the time the ridiculous sum of € 10 and rehoused the objective in the tube of a Skywatcher 70/500 achromatic refractor. This, being separate from the spectroscope, operates, as can be imagined, with a separate focusing system, which makes it slide back and forth until the image of the solar disk appears focused on the slit and, more importantly, the longitudinal edge of the framed spectrum appears perfectly defined on the PC monitor, a fundamental thing as it will be the edge of the solar disk in the final image (spectroheliogram). The focusing system I used with VHIRSS is a micrometric system for macro photography purchased on Amazon for around € 20 (but can also be found on e-Bay), shown below. The refractor with the rings is fixed to the upper part of the focus. The rings are used to place the tube perfectly in axis with the slit; to check that this happens, simply aim at the centre of the objective or, if you want to be more precise, make a 1 1/4" objective diameter/eyepiece holder adapter and insert a laser collimator. This possibility also allows an overall check of the general alignment of the system's optics,with the warning that only low power lasers should be used, otherwise the grating could be damaged.In every case the laser beam cannot be observed directly with the eyes that could be damaged.

8-The focusing of the digital SHG

The focusing on a high resolution SHG such as the VHIRSS consists of two operations: the focusing of the spectrograph and also the telescope, which must be adjusted until the solar edge and the details on the disk of the spectroheliogram are both well defined. Focusing of the spectrograph, must be carried out on the Littrow collimating refractor by directly observing the chromospheric details visible within the line of interest (Hα, H beta CaIIK and H etc.), alternatively sunspots, which appear as a black line that cross the spectrum longitudinally , the narrowness and intensity depending on their size,can be used. However, this approach is often difficult, so it is possible to operate on the transversalium produced by the slit. By focusing on the transversalium ,we can achieve almost as good a focus as would be obtained using the detail within the line, eventually finishing later with greater precision.

It will obviously also be necessary to focus the telescope on the slit gap using a micrometric slide as that shown below, until the image of the spectrum on the PC monitor is perfectly focused on its longitudinal edge. Generally, by trial and error, adjusting both components, spectroscope and telescope until we obtain a well-defined solar image. However, I focus the spectroscope first and then the telescope.Once acquired, the focus is stable and can be maintained for a long time excluding small variations in the case of strong temperature variations or small bumps.



In conclusion, if the chromospheric details within the line, (or transversalium) and the edge of the spectrum are both in focus and clear, the final focus is correct. In any case, the most recent reconstruction software allows you to obtain within a few seconds the sun image from the scan video for a focus check.

9-Final checks on the correct assembly of the instrument

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

-Check that the slit is placed exactly on the focus point of the collimator and that the slit lenght is parallel to the grating grooves;

-Check that the grating to collimator optics distance is the minimum possible;

-Check the alignment of all the components (telescope-slit, grating, mirror or deflection prism). This can be done, as mentioned, with a laser collimator inserted in the lens hood or in front of the telescope objective with a special adapter (it is possible to make one make or have it made with a 3D printer with a round of PVC with an external diameter equal to the internal diameter of the lens hood and, in its centre, a 1 1/4"hole to accommodate the laser collimator with a blocking screw. Alternatively, you can insert the laser into the eyepiece holder of the camera to perform the opposite optical path. The warning remains not to use powerful lasers and not to observe the laser beam directly with your eyes.

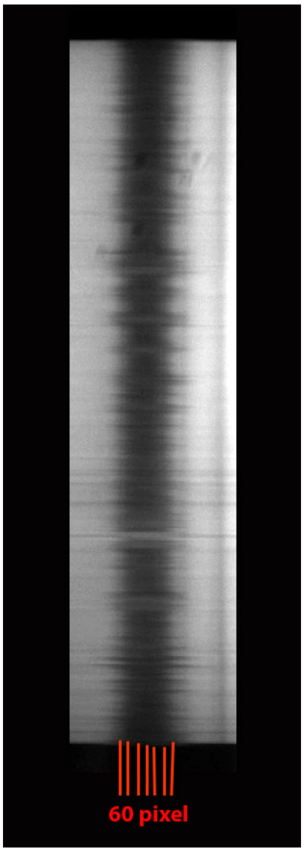
-Check the functionality of the instrument in the field by observing the lines of the solar spectrum (better the O2 lines) and focusing both the telescope and the spectroscope optics. Finally, check, indoors, with a Neon or low energy fluoro lamp (better) the dispersion and resolution provided by the instrument itself.Measure the FWHM of the lines and the R value at the related wavelength.

Difference between high and low spectral resolutions

I mentioned previously the difference between low and high resolution instruments, now it is time to review the situation. Today, thanks to the evolution of amateur astronomical spectroscopy in recent years, various types of spectroscopes exist on the market, with which,with the same high power grating, slit opening and camera, good spectroheliograms can be obtained, thanks to the latest generation software.

However, the focal length of the spectroscope's optics (in addition to the dimensions of the grating and the quality of the slit) plays in my opinion a crucial role in obtaining solar images in an SHG spectroheliograph. Let us therefore assume that we have, with the same grating, a spectroscope with 100 mm collimation optics (Littrow or not) and that it gives, with the pixels of that given camera (for example) an image of the Hα line of 10 pixels wide My VHIRSS, with 600 mm optics, will give, under equal conditions, a spectral image of the line of 60 pixel in width, therefore 6 times greater. Now, taking into account that the conversion software can generate, from the video scan (obtained by the drift of the solar disk across the slit with mount drives stopped) an image of the sun for each pixel column along the width of the line.

In the first case I will obtain 10 images extending across the entire line, in the second 60, which, joined together by stacking will give a better result. Not only that, but this happens for each scan. If, for example, I carry out 6 scans, and for each I take 60 images of one pixel column in the end I will have 60x6, 360 raw images of the solar disk to stack, with very good results in terms of both aesthetics and the quantity of visible details, superior to those of traditional solar filters due to the very narrow pass band, equal to the dispersion in Angstroms per pixel (0.02/0.03).



The importance of spatial resolution

Naturally, in addition to the spectral resolution given by the spectrograph, the telescope objective also gives a notable contribution to obtaining the final image. You can imagine the spectrograph as a normal commercial Hα filter, and the telescope as the element that sends the solar image to the latter. The better the optical quality and the diameter of the telescope itself, the better the quality of the spectroheliogram obtained. However, in an instrument like the one discussed the diameter of the objective should not exceed 80 mm and the focal length 500 mm, to minimize the penalty of excessive bulk and weight of the instrument.For small spectrographs, larger diameters can also be used, in practice by attaching the instrument to the telescope, thus gaining in spatial resolution, but losing in spectral resolution.

A little maths

At the end of this discussion on the construction details of instruments like VHIRSS, someone might comment “yes, okay, very interesting, but how much would it cost? Probably not all DIY enthusiasts can afford it".

The question of costs would be valid , so I will try to do a summary , even if approximate, of the costs, distinguishing two cases: that of purchasing a part of the components on the used market, as in my case, and that of purchasing each of them new, from traders in the sector. My VHIRRS cost around € 600, but in practice I purchased only the (new) grating and the Orion refractor (used) and making use of components already in my possession, but not everyone has this advantage.

1- Mixed purchase, new and second hand

The components of the SHG that can be purchased on the second-hand market are the refractive optics, the slit, and the transfer mirror case or, in its place, an off-axis guider.

Those to be purchased new are certainly the grating and the steel tube supporting the structure.

In detail, applying the costs of new and average used ones (All in Euros, prices in Europe):

- Refractor 66/400 ED or similar used as a telescope (used)…….€ 200

- SW 80 ED refractor or similar as spectroscope optics € 300

-Off-axis guider (used)
………………………………………………………………………………… € 100

-Edmund holographic grating 2400 l/mm (new)
………………………………………………………………………………….. € 360

-1 m steel tube 30x30 or similar (new)…………………………€ 10

- Small metal parts and small accessories………………………………………..
………..…………………………………………………………………………..€ 40

Surplus Shed air slit……………………………………………………€ 30

Total…………………………………………………………………………….€ 1040

Obviously, the purchase of another kind of slit, new or used would add to the above cost.

2 – <u>Purchase new only</u>

-Refractor 66/400 ED or similar to use as a telescope……………………………………………………………… € 400

-SW 80 ED refractor or similar as spectroscope optics
…………………………………………………………………………………..€ 500

-Off-axis guider
……………………………………………………………………………………. € 200

- Edmund holographic grating 2400 l/mm (new)
……………………………………… …………………………………………...€ 360

-1 m steel tube 30x30 or similar (new)
………………………………………………………………………….………. € 10

-Small metal parts and small accessories……………………….€ 50

-Surplus Shed slit……………………………………………………………€ 30

Total……………………………………………………………………… .... € 1550

This is based on using ED optics (which I recommend). We could purchase commercial achromatic optics for the spectroscope, for the telescope or both, the prices indicated could decrease by between 10 and 30%, depending on the type and quality of the optics. The cost of any accessory filters it was not considered, on the basis that almost all amateur astronomers who deal with CCD imaging possess some of them.

Let's weigh up the cost to benefit. With a figure around € 1000-1500, or similar to the cost of a low-end Hα filter, we would get an instrument potentially capable of imaging the sun not only in Hα light, but in all the wavelengths of the elements of interest (Hβ, Hγ, Na1 and 2, Mg, Fe 1, CaII K and H , etc), this without considering the other uses of the instrument (Solar spectroscopy, measurement of solar magnetic fields, differential spectroheliography, etc). Furthermore,it has the ability to show details of the chromosphere equivalent to that of a commercial triple stack filter.Like having an instrument from a professional solar tower in your home or observatory.

I have deliberately neglected, here, to provide the construction details of my other instruments, POSS2, a Littrow similar to VHIRSS dedicated to spectroheliograms in the UV area of the spectrum (CaII H and K, Cn, Al1 etc) and Solarscan, dedicated to the measurement of solar magnetic fields. I refer the reader to the first edition of this text. For POSS2 I insert a photo, which shows its construction layout which can be compared to that of VHIRSS. Regarding Solarscan, I will prepare a report later.

POSS2 Digital SHG on a Losmandy G11 mount

Here I report the innovations and projects that have occurred in the last 4 years in my spectroheliographic instrumentation.

MILSS

I have often wondered if the auto collimating Littrow configuration would also be applicable to small spectrographs, so I began to develop a project whose characteristics inspired by maximum simplicity of construction and use while maintaining strong robustness and all the adjustments necessary for a serious instrument. Therefore, no plastic or PVC, but only aluminium. The idea was to create a high resolution spectrograph-SHG measuring approximately 30 cm in length and 1.5 kg in weight. I simply used the material in my possession, without purchasing anything.

The essential component was an Edmund Optics 30 mm 2400 l/mm holographic grating, inserted into a simple 6 cm square box of 3 mm thick aluminium threaded M 42x0.75 on three sides, with a knob for the rotation of the grating itself on its axis.

The micrometric positioning of the grating itself is ensured by three 4 mm dowels placed at 120° on the rotation knob. The aluminum box is connected to another of the same dimensions and layout which holds the eyepiece holder, the relay mirror and the slit. The 11/4" eyepiece holder is off-axis so as to always centre the spectrum and avoid the small, inevitable positioning errors of DIY assembled components and the inevitable difference in centering of the spectrum depending on the wavelengths. The collimator was an achromatic doublet with 30 mm diameter and 160 mm focal length derived from a vintage 6x30 finder. The 20x30 mm flat relay mirror is placed on the base of the second box and is adjustable with three screws at 120 degree.A non-rotating helical focuser 45 mm long and with 25 mm travel is inserted between the two boxes.

As a slit I used a fixed 9 micron slit chromium lithographed on a quartz support.

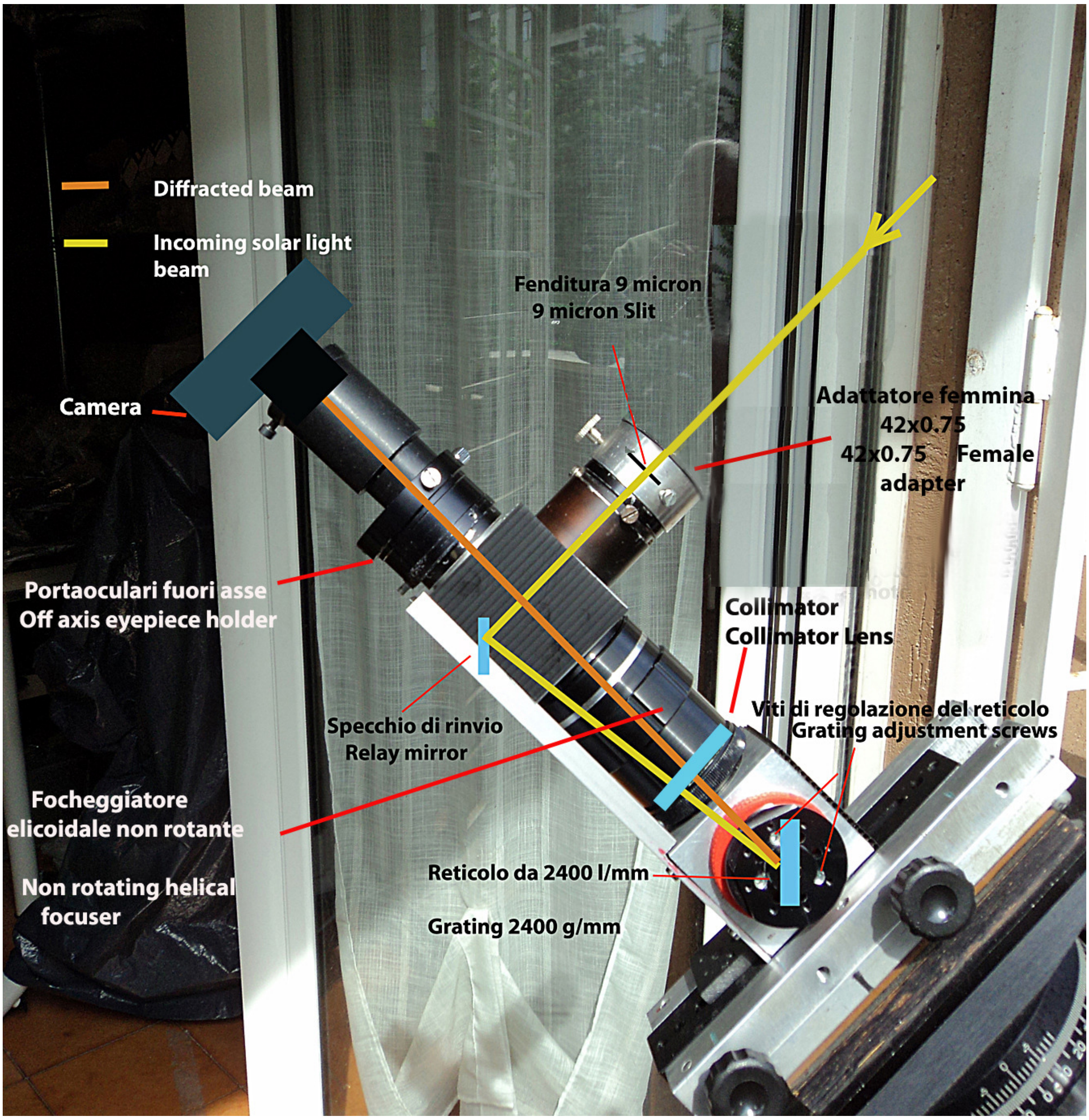
It has been positioned in the direction of height for reasons of collimation of the optics, so that the relay mirror is perpendicular to the grating and the eyepiece holder, and receives the light beam for the grating from the slit located at 90°.All in a small instrument measuring 30 cm in lenght and weighing 1.2 Kg.

The result was more than satisfactory. The stand alone spectrograph provided a dispersion of 0.057 Å/pixel with 4.65 micron pixels of my DMK 51 at 5890 Å and a resolution R = 33600 at 5884 Å, very respectable values for a small instrument such.

I called it MILSS, an acronym for **MI**ni **L**ittrow **S**olar **S**pectrograph-SHG.

The image below shows the layout of the spectrograph only.Note the off axis eyepiece holder,while its small size and weight allow it to be applied to any refractor or even catadioptric telescope, as long as it is equipped with a means of filtering solar heat.

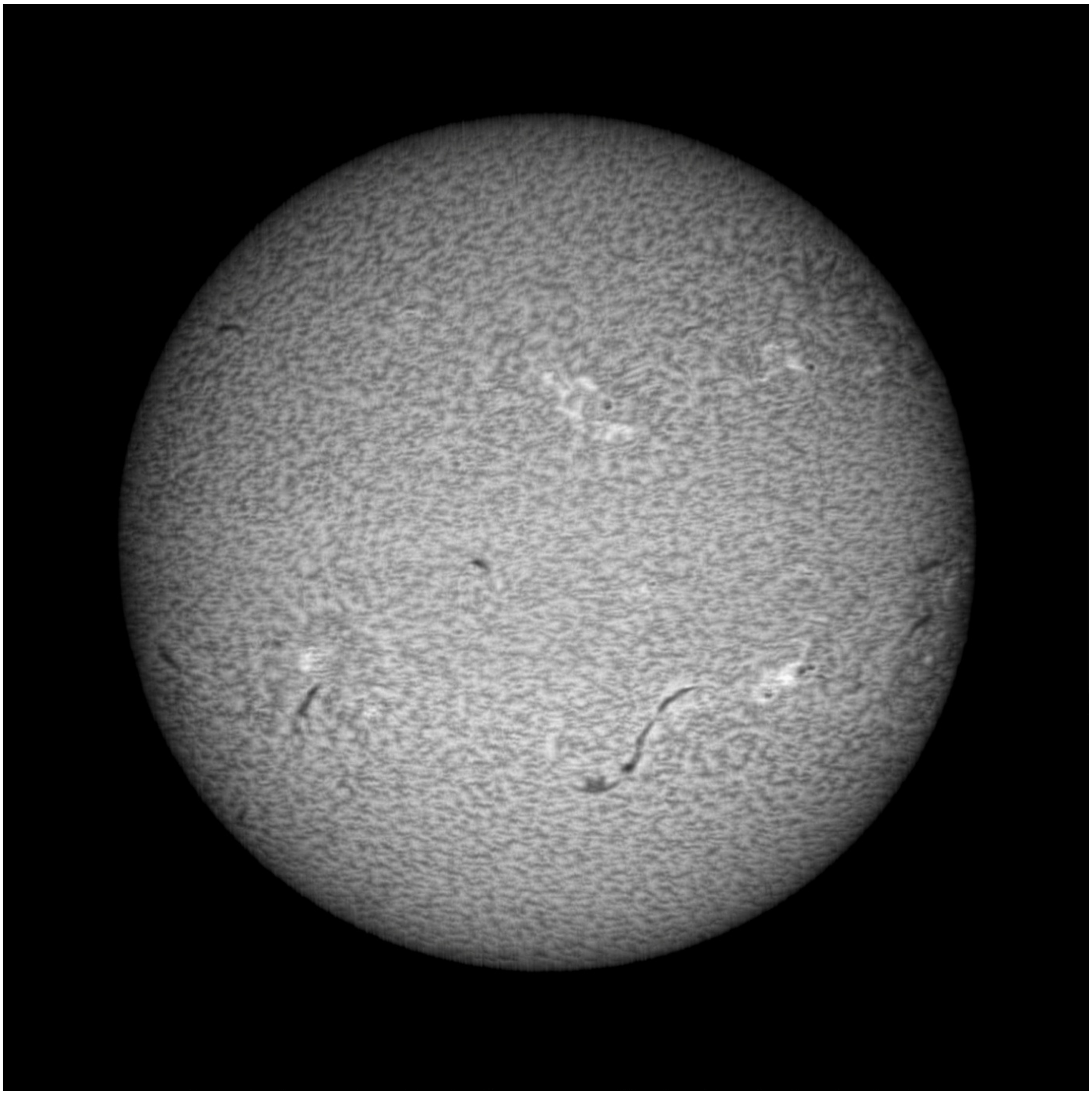
In the case of common use with refractors, an Astronomik IR UV cut L1 filter can be used in front of the slit, which has a passband capable of reaching the ionized calcium CaII K and H lines, and even deeper, for any other near UV lines.



The following figure shows the spectrograph's performance on the sodium doublet at 5889.75 Å, with a dispersion of 0.057 Å /pixel and a resolution of R= 33.622 at 5884 Å, very respectable values for the type of instrument.

Shown below is the MILSS at the focus of a 80/560 Tecnosky apochromatic refractor, acting as digital SHG and its first H alpha spectroheliogram.


80/560 ED
80 Refractor
MILSS



HIRSS2 upgrade

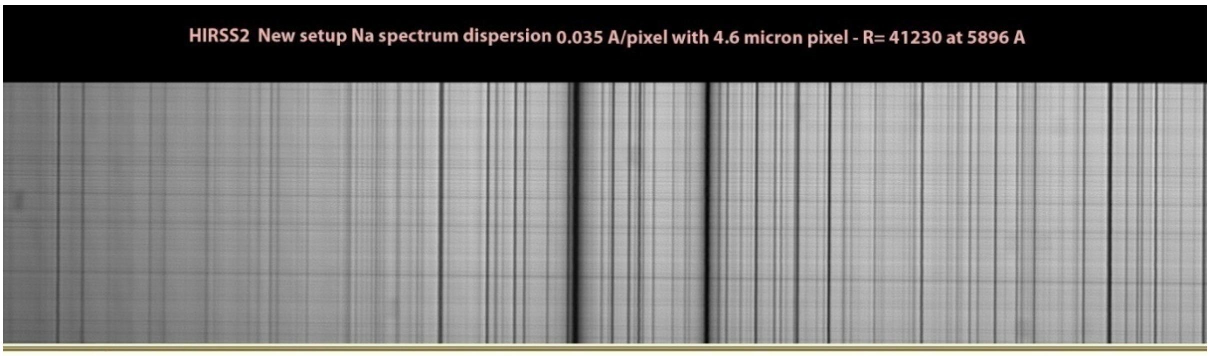
Recently decided to repurpose my HIRSS2 spectrograph (one of the 4 DIY high resolution spectrographs in my possession).I had purchased a William Optics 90/600 apochromatic refractor some time ago for a ridiculous sum (€ 60). It had a 5 mm chip on the edge of the front lens. Once the chip was covered with a permanent black marker, the instrument performed well, enough to replace the old

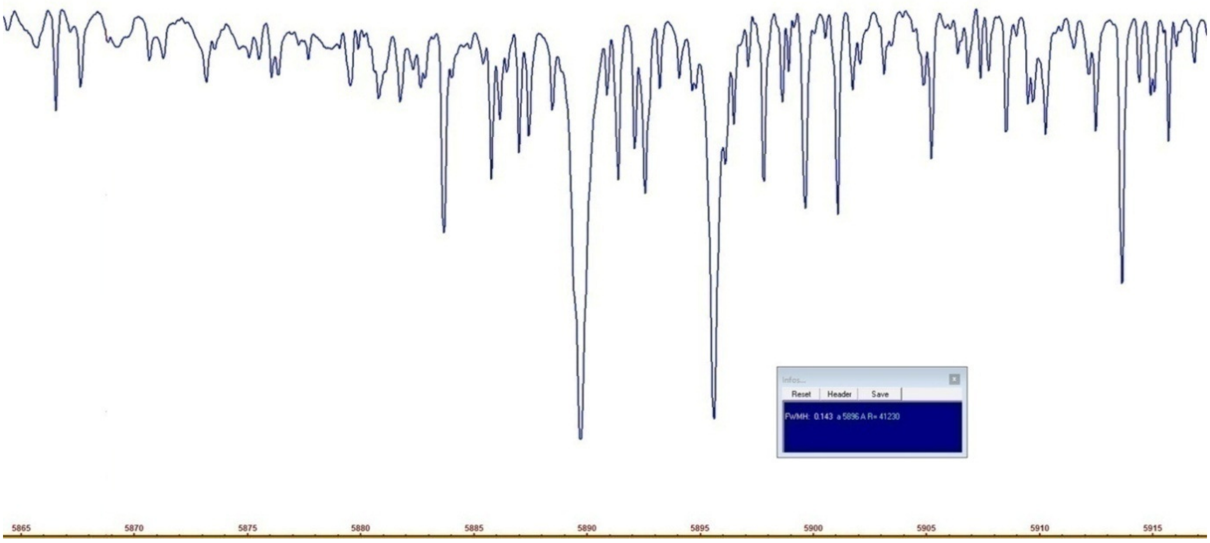
Achomatic Antares 100/500 refractor that I used as the optics of the autocollimating spectroscope. However, I had to also mount a new focuser, an old, but very precise and robust non-rotating Italian made helicoid capable of recording 1/10 of a mm. The telescope used is now, in place of the old vintage 60/420 achromatic refractor, from the 70s, (a real little gem), a 68/600 achromatic, branded Mizar, also from the same period and of Japanese production. This excellent refractor performed well , on comparison tests carried out, with the 90 mm apochromatic ED that I used for the spectrograph .

From the test carried out on the sodium doublet spectrum with a DMK 51 camera, the dispersion was 0.035 Å/pixel and the resolution of R 41230 to 5896 Å. I then switched to using it as a digital SHG with a Hα image, using a ZWO ASI 183 MM and FireCapture software for the acquisition .For the conversion of the SER video files I used INTI Avi recon V 3.7. The first spectroheliography test (carried out with the old 60/420 refractor) satisfied me quite well, I think it is still there further margin for improvements.

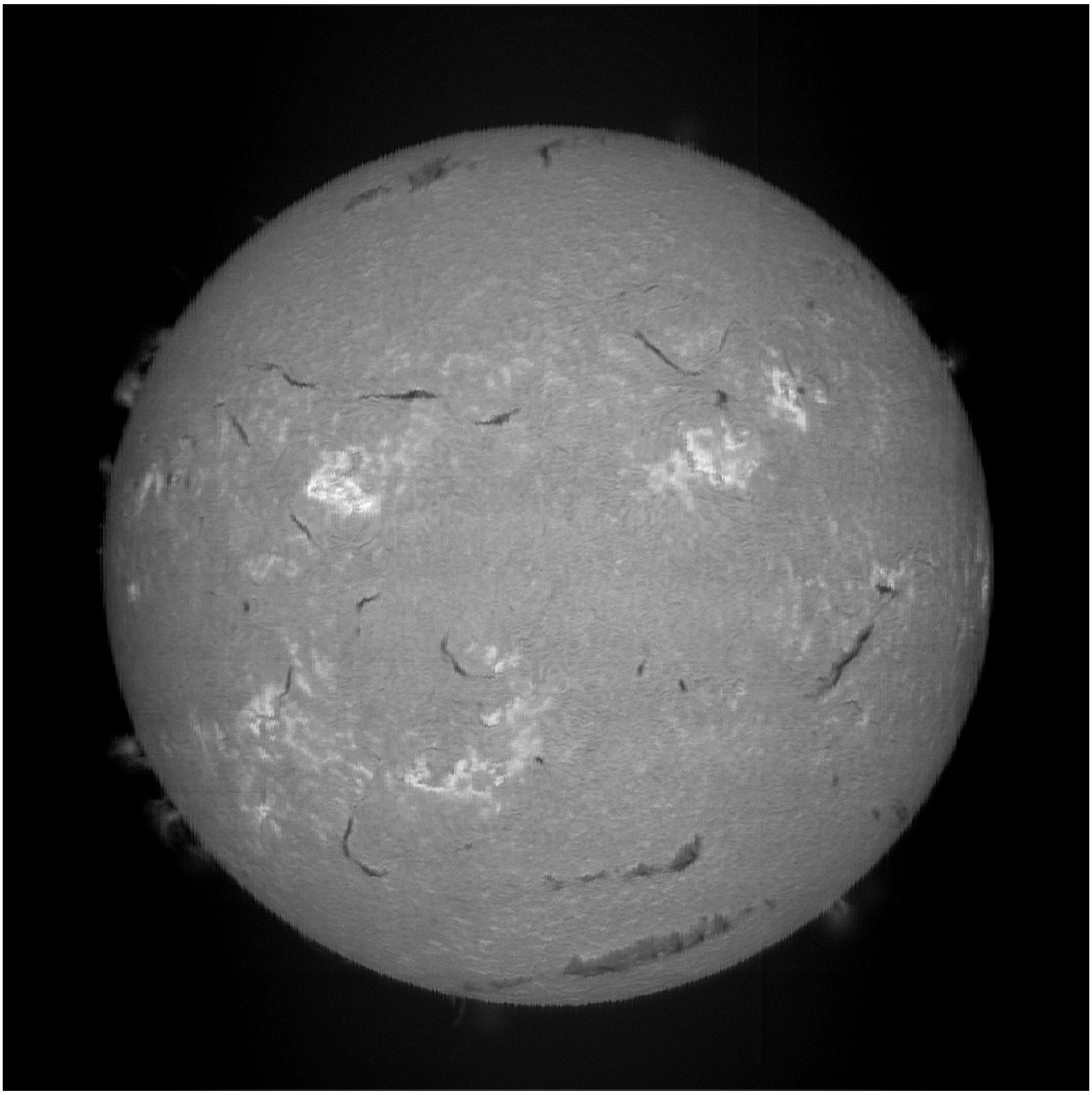
Below is the layout of HIRSS (**HI R**esolution **S**olar **S**HG)2, similar to VHIRSS and POSS2, the only difference being the slit placed on the optical axis.


Rufrattore acroMizar 68/ 600
Mizar 68/60 acro refractor
ZWO ASI 193 mm camera
Obiettivo ED apo 90 mm x 600 mm FL
RD Apo objective 90mm x 600mm FL
Specchio di rinvio
Relay mirror
Focheggiatore
elicoidale non rotante
Non rotating helical focuser
Reticolo Edmund
ruled 500 nm 1800 l/mm
Edmund ruled 500 nm
grating 1800 g/mm





The spectrum and spectral profile of the sodium doublet at 5890 Ǻ with the dispersion of Ǻ 0.035 /pixel with the 2.4 micron pixels of the ZWO ASI 183 MM and a resolution, measured in the field, of R= 41230 at 5896 Ǻ.



A Hα spectroheliogram with HIRSS2 and a ASI 183 MM camera.

The instrument, as we have seen, gives good performances, but, nevertheless, a little inferior to those of VHIRSS, despite the use of a camera with 16-bit dynamics and pixels of a size equal to half those of the DMK 51, which I use previously with the spectrograph.

I then asked myself why this is so?. Given that the optics used for the spectrograph and the telescope were similar both in quality and in focal length and diameter. The only differences of HIRSS2 compared to VHIRSS, are the type of grating, is 1800 l/ mm ruled, with blaze angle for 500 nm instead of a 2400 g/mm holographic grating and the position of the slit, on the optical axis for HIRSS2, while in VHIRSS it is off the optical axis being 10 mm above this.

Another factor of difference is the pixel sampling of the camera, 4.4 micron in the DMK 51 that I use with VHIRSS and 2.4 micron in the ASI 183 MM.I always use the ASI 183 MM in 2x2 binning, (but this isn’t a real binning as in the case of CCD cameras) leaving 1x1 binning only for high resolution spectroheliograpy.

At this point it was necessary to reassess things.

In the Littrow or autocollimating configuration, as has been said, there is only one optic which acts simultaneously as collimator and camera optics. In it the incident and diffracted light ray 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 or the angle of the grating engravings for engraved or "ruled"gratings. However, as regards non-blazed holographic gratings (with rounded grooves), considering that they convey the maximum light energy towards the 0th order, a blaze angle equal to zero is considered. In the Littrow configuration, furthermore the anamorphic factor, that is, the ratio between the angle of the diffracted outgoing ray and the incoming one is equal to 1, i.e. the angle is the same. It was therefore by pure intuition that I tried to physically increase the entry angle of the light ray into the spectrograph,in the hope of better illuminating the grating and increasing the spectral resolution.

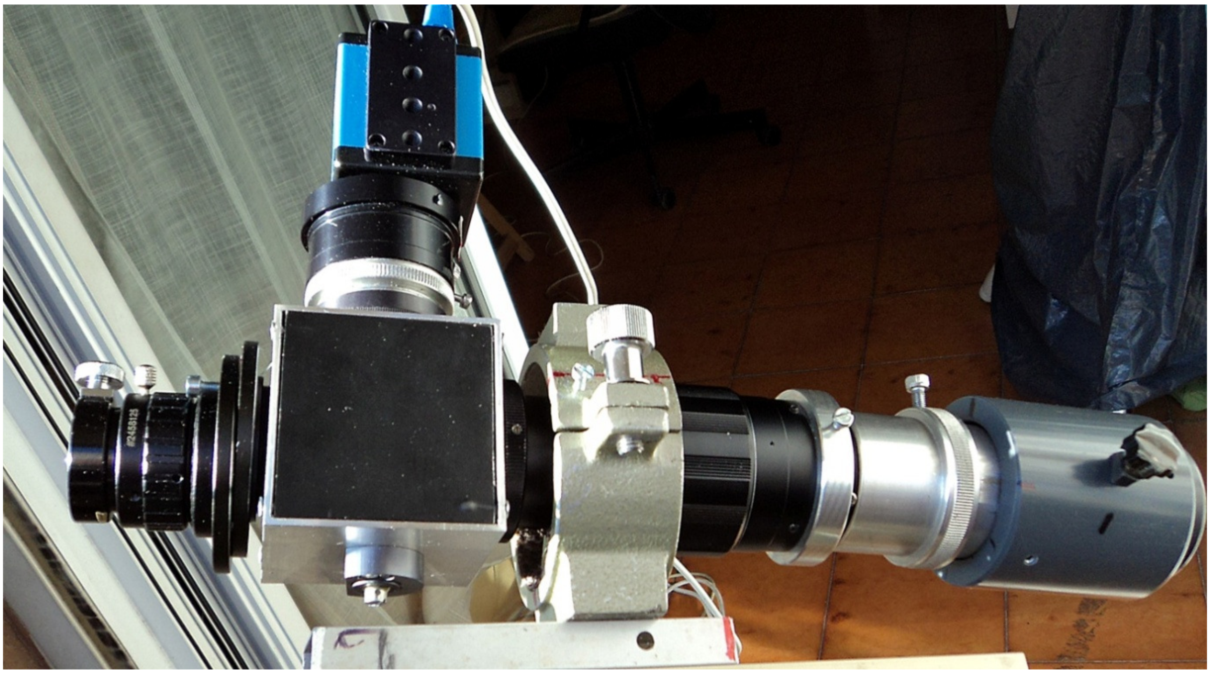
This result seems to have been achieved, without, however, being able to reduce the scattered light which is the only negative characteristic of Littrow configurations and which also depends on small irregularities in the grating, and the relative position of the slit-optics-grating and the relative angles of incidence. This inconvenience could be eliminated with the positioning of diaphragms in the optical path which, given the very limited dimensions involved, is very difficult on non-professional projects. It can be controlled with the use of narrowband filters placed possibly before or after the slit. In the case of VHIRSS and POSS2 it does not produce any loss of performance given that these SHG are used in spectral bands such as Hα and near UV in which the quantum efficiency of the cameras, CCD or CMOS (excluding the ASI 183 M) is modest. The question, however, attracted my attention to the importance of the position of the entrance slit in Littrow spectrographs.

UPS (Ultra Portable SHG) Upgrade

I had recently thought about dedicating this instrument to recording in H beta light at 4861 Å and H gamma at 4340 Å , spectral areas in which the EQ of the sensors is high. I realized that, with the original slit on the optical axis, the images showed gradients due to infiltrations of light and/or scattered light. I therefore thought of disassembling the spectrograph to find out the cause. Now, the (surplus) optics of UPS is a 36 mm doublet in diameter and 300 mm focal length, practically half the size of my other Littrow spectrographs, with a 25 mm 2400 l/mm holographic grating and the alignment of the system (slit-collimator-grating-return mirror) in the littrow of short focal length is quite demanding. So I tried and tried again, but the output of the instrument did not convince me. After numerous checks, however, the situation did not improve and the spectrum appeared undefined and not central to the the field due to misalignments between the grating, relay mirror and slit. I then adjusted the relay mirror, I tried to align the grating better, but nothing. An idea then came to me, given that the eyepiece holder was rotating and placed off-axis, why not do the same with the slit and align everything by adjusting both?

No sooner said than done, I chose among my accessories a male/female T threaded fitting M 42 x0.75 mm with 3 screws at 120° normally used to adjust the tilt of the camera, I added a 11/4 "eyepiece holder, loosened the screws so that the two disks of the fitting could slide on themselves, and the off-axis eyepiece holder for the slit was done!

Then, through trial and error, oriented the slit and camera until I obtained a centred, well-defined spectrum with the minimum amount of diffused light, then locking the two adjustments.



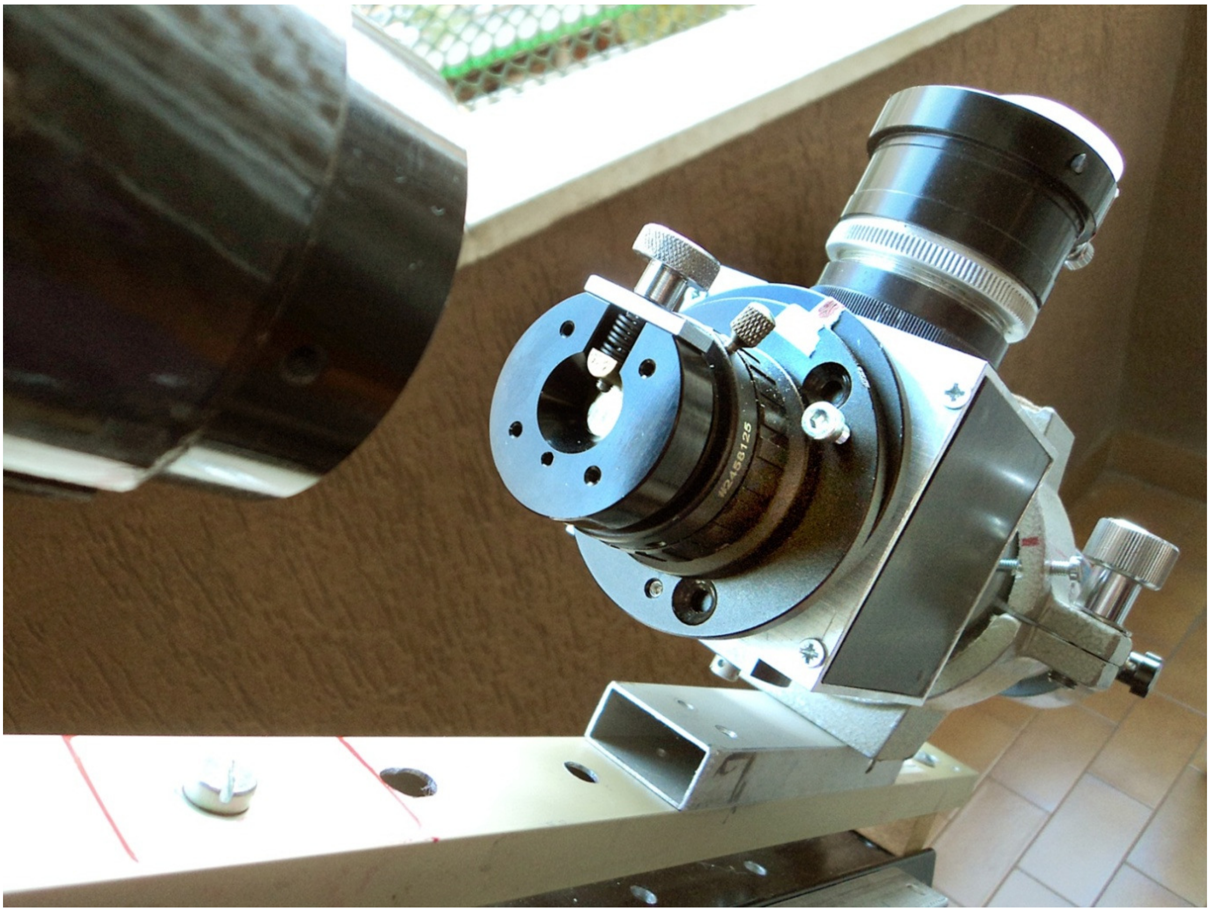
UPS stand alone spectrograph

As can be seen in the following images, the two off-axis components allowed:

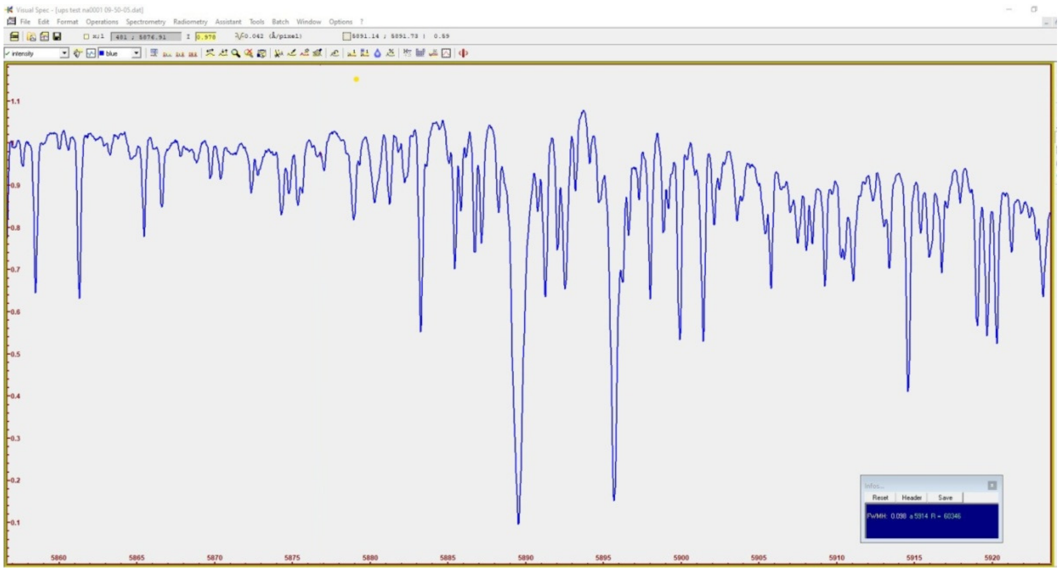
1- Placing the grating, relay mirror and camera perfectly on axis, which is quite difficult in a DIY short focal length Littrow.

2- Control and minimizing the scattered light in the system, achieved by positioning the slit off-axis almost perpendicular to the axis of rotation of the grating, at the point furthest from the camera.

the image below shows detail of the off-axis slit and the off-axis eyepiece holder



After adjustment, the Littrow showed excellent performance, as can be seen in the following spectral profile of the sodium doublet at 5890 Å, obtained with VSpec, showing a dispersion of 0.043 Å /pixel with 4.4 micron pixels.



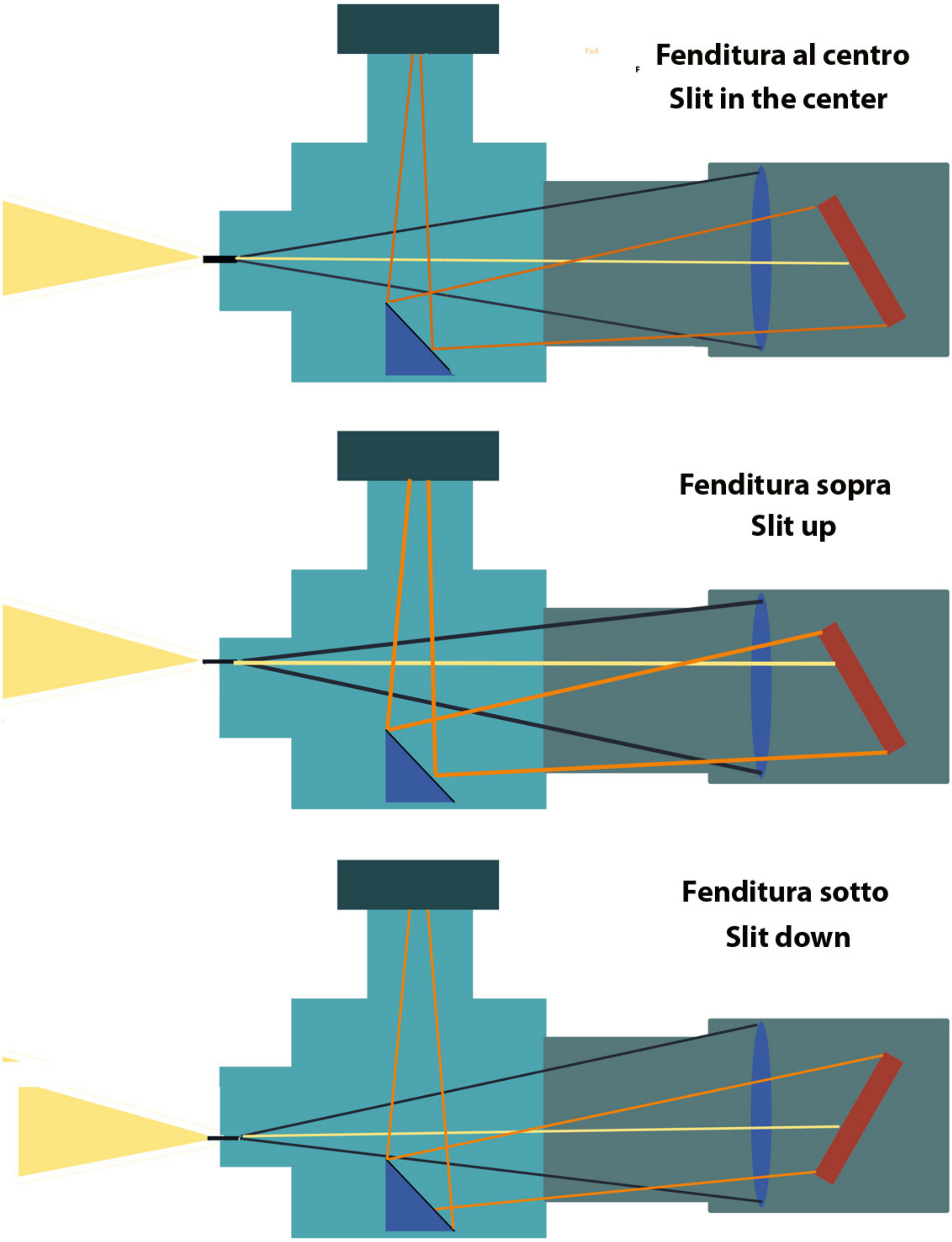
The alignment between slit, optics and grating in DIY Littrow spectrographs.

The spectrograph constitutes, as we have seen, the heart of a digital SHG. In self-built Littrow configuration spectrographs, the alignment between the slit, mirror or deflecting prism, optics and grating may seem easy, but this is not the case. Often small assembly errors of the components, especially in DIY instruments, affects the collimation of the various components. A system to overcome this is to place both the slit and the eyepiece holder of the camera off-axis, so that their position is adjustable. This is even truer for instruments, such as those with high resolution and long focal length in which the spectrum is very long and moves slightly, due to small imperfections in the grating and the wavelength. This solution allows:

-to adjust the initial collimation between the components of the spectrograph

-to centre the spectrum in the camera when moving in wavelength, e.g. from the Hα line to the CaIIK.

- to improve the scattered light and (slightly) the resolution of the system when the slit is placed in a position opposite to the direction of the diffracted ray of the grating or upwards when the grating is inclined downwards by about 20-30 ° and the diffracted ray points downwards) as for VHIRSS and POSS2 and the opposite case for the UPS. Below are the possible positions of the slit.



Possibility of increasing the spectral resolution in Littrow configurations.

After having discussed some types of SHG, all in the Littrow autocollimating configuration, I'd like now to share some experiments I carried out with the first model of the HIRSS2 SHG, relating to the increase of the spectral resolution .

The instrument, in its configuration at the time, was composed of a Littrow spectroscope made up of an Antares 100/500 achromatic refractor and a 50 mm square and 1800 l/mm grating blazed for 500 nm.The slit used was from SurplusShed. The telescope that illuminated the slit, with sunlight or otherwise, was a Carl Zeiss Jena 62/420 achromatic lens. The camera used was a DMK 51 AS.

We know that a barlow lens is normally used to increase the focal length of the telescope to which it is applied.In the case of the Littrow,when placed behind the lens it should create an enlarged virtual image of the slit both in the length and width direction.Two GSO Barlow lenses, one X 2 and one X 5, were placed between the spectroscope optics and the slit, at a short distance from the slit itself, maintaining a slit gap at around 30 microns in all cases.

A 700 frames AVI video of the solar spectrum was then taken in the areas of the sodium and the Hα line of Hydrogen and averaged with Registax.

The result, measured using the FWHM of the thinnest line with Visual Spec, was the following:

Barlow X 2 and X 5

Sodium area

1) **Without Barlow** or other optical components added:

at 5883.73 Å <u>R= 20572</u>

2) With **Barlow X 2 at 57** mm from the slit

at 5883.73 Å R =25806 (+27%)

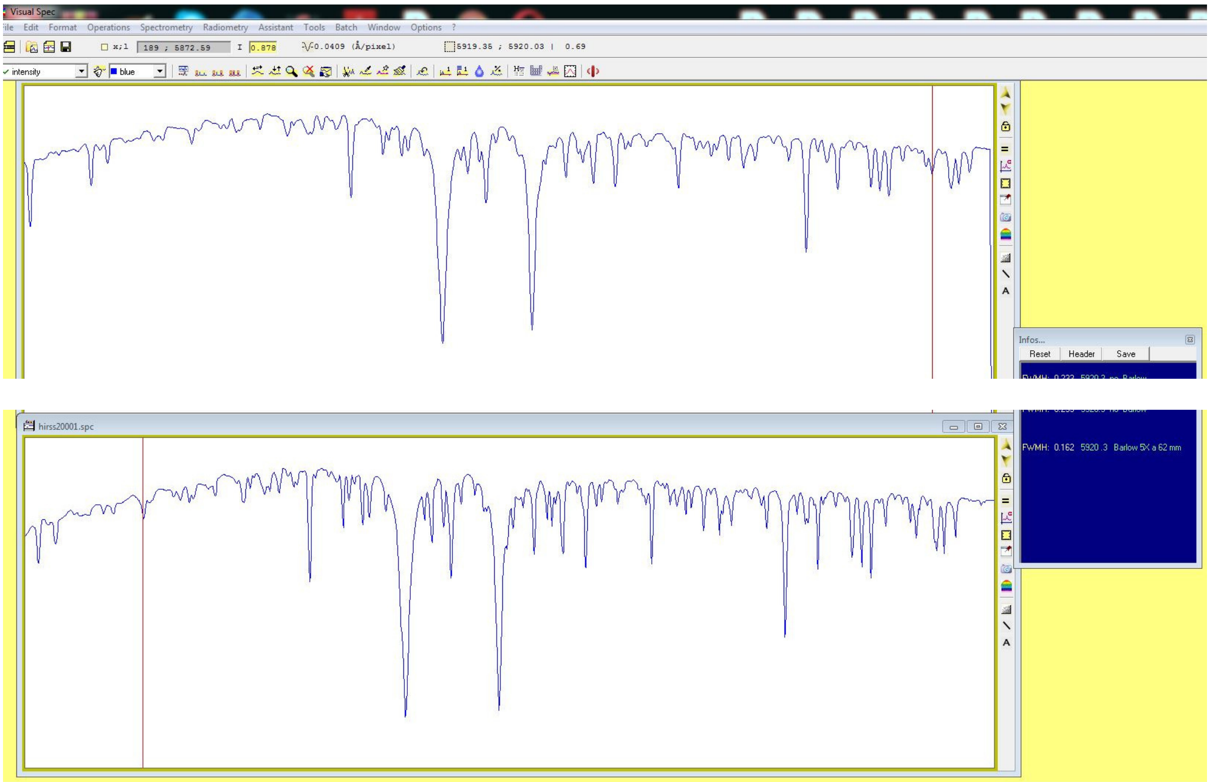
3) With **Barlow X 5** inserted between the slit and the spectrograph optics and the grating: **15 mm** from the slit itself

at 5884.17 Å R= 34411 (+69%)

4) **Barlow X 5** inserted between the slit and the spectrograph optics (and the grating) at **62 mm** from the slit:

at 5920.3 Å R= 36545 (+75.6%)

The following image shows the comparison between the spectral profile in the sodium doublet area without added optics (top) and with the X 5 Barlow (bottom). The difference is also appreciable to the eye, despite the low resolution of the image.



In the Hα zone, for the same configuration, (**Barlow X 5 at 62 mm**) we obtain, as shown in the following figure:

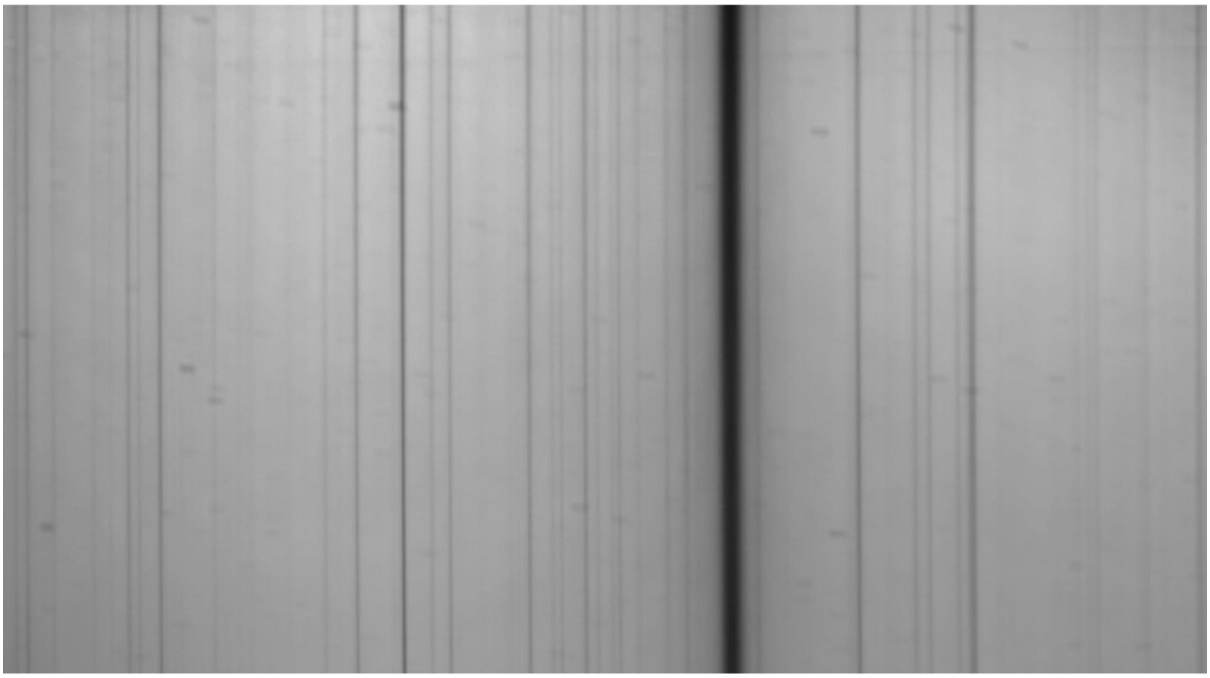
R= 52594 at 6574.3 Å

Using 25 mm FL cylindrical lens

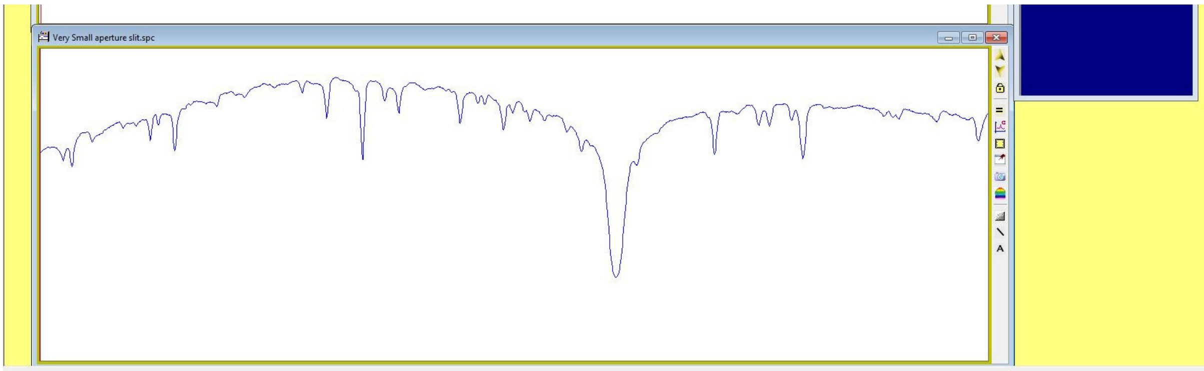
1) With a **25 mm FL cylindrical lens 52 mm from the slit**

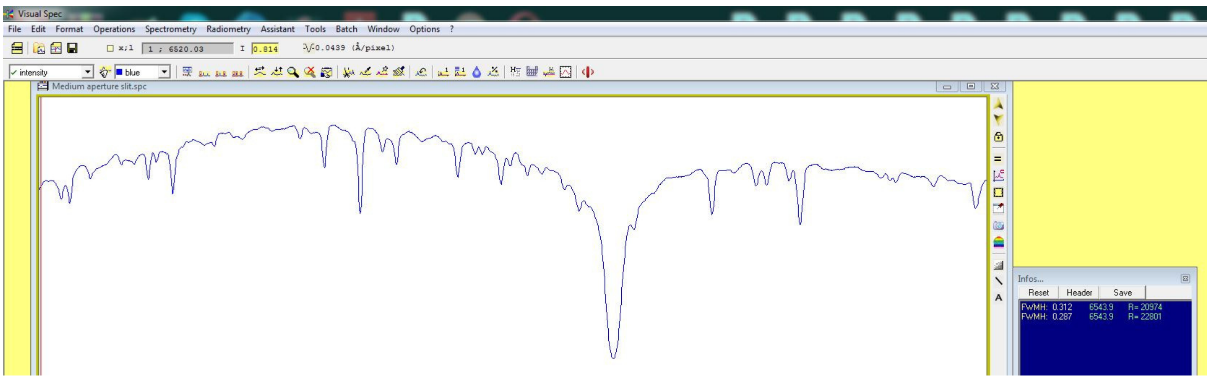
Hα zone

The resolution in the Hα zone was equal to or slightly lower than the normal one with a gap of 30 microns and improves slightly by closing the slit to the maximum possible, (from R= 20900 to R= 22800) but the interesting thing is the almost total elimination of the transversalium, even when the slit is almost completely closed, (10-15 microns) as can be seen in the image of the Hα line below.



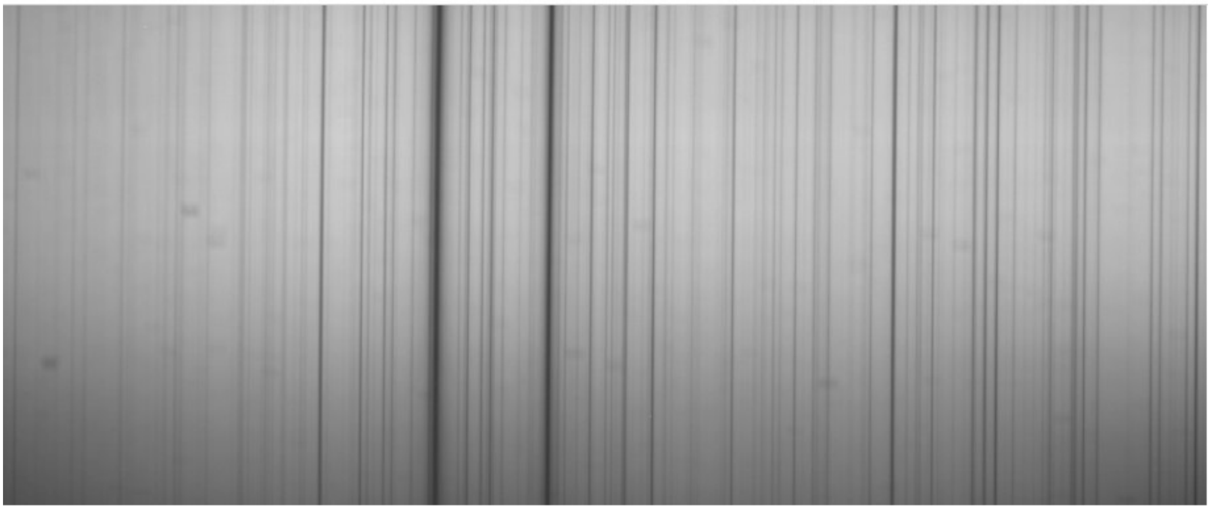
The following spectral profile shows the comparison between resolution R measured at 6543 Å with the slit open at around 30 microns and one open at around 15 microns.

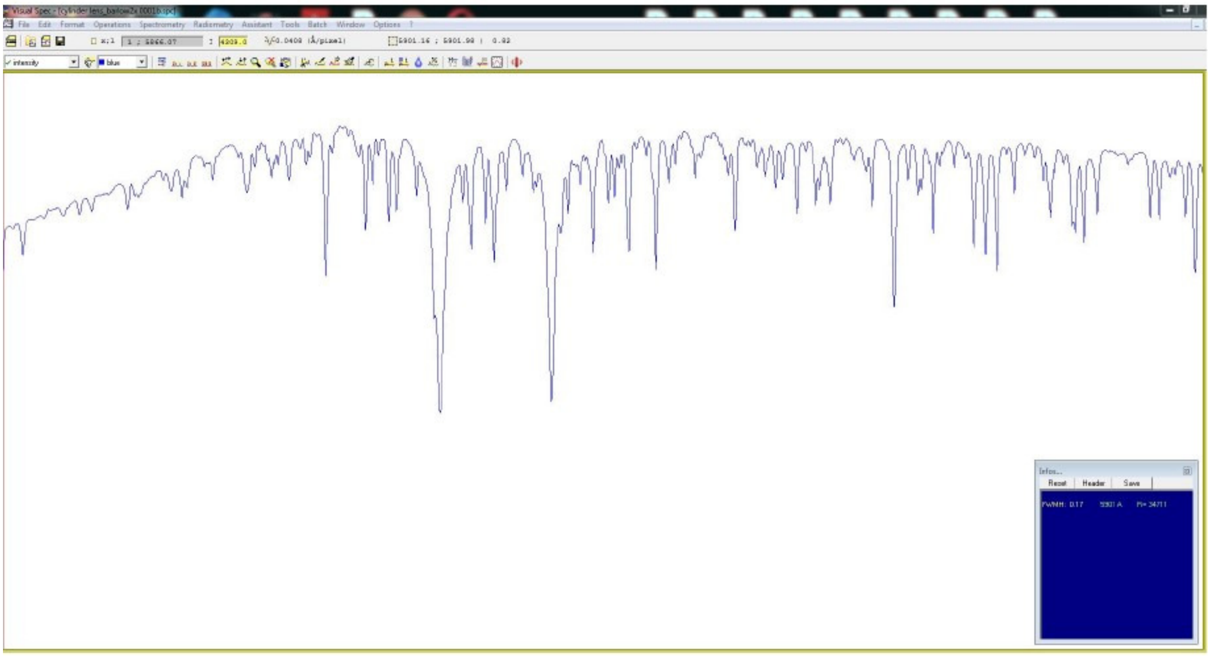




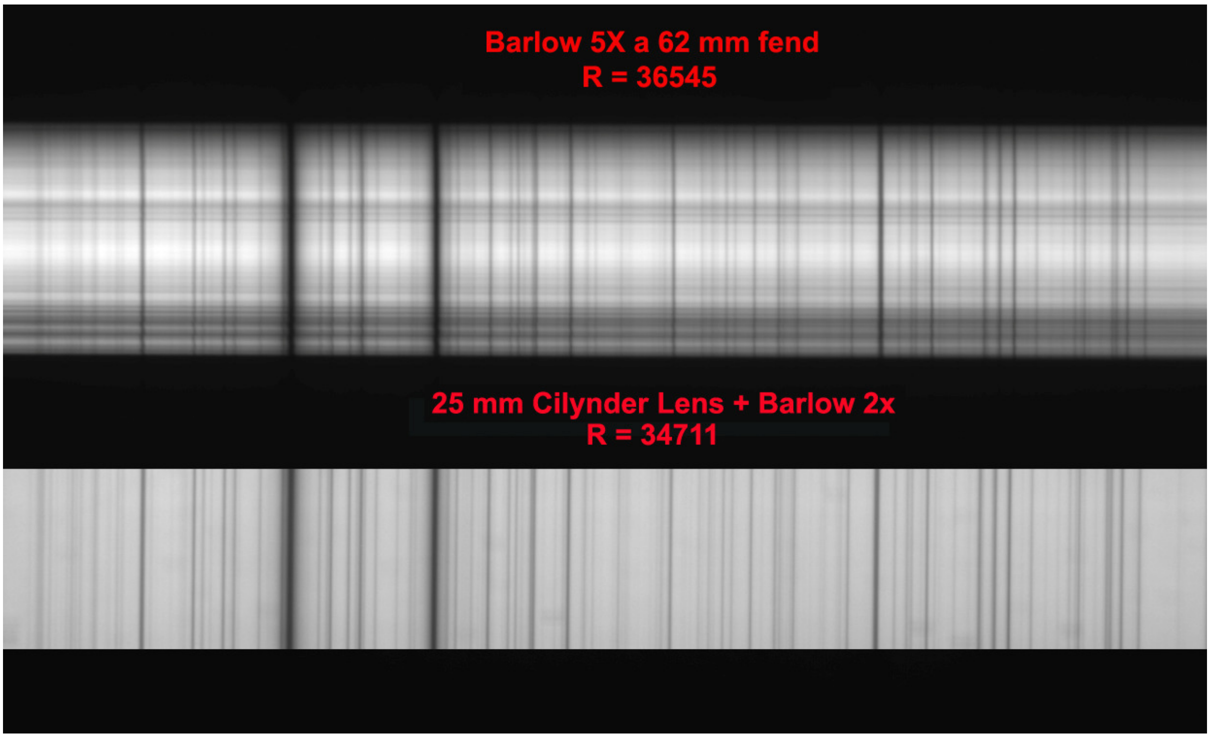
Na area

2)With a **cylindrical lens placed 52 mm from the slit and a X 2 barlow 6 mm from the cylindrical lens**, the following spectrum and spectral profile was obtained. The resolving power at 5901 Å is equal to <u>R= 34711</u>





Below is the comparison, in the sodium area, of this last solution with that of the X 5 barlow used previously.



In conclusion, the application of a X 5 barlow at 62 mm from the slit leads to an improvement in the spectral resolving power of approximately 75%. Obviously this is "in the field" and not theoretical resolving power, which, although not particularly high, can be decisive in some applications such as Zeeman line splitting.

The result is different with a cylindrical lens, which, as we have seen, involves only a negligible improvement in the resolving power, but an enormous one in the definition of the spectrum with very closed slits due to the absence of the transversalium. The cylindrical lens coupled to a X 2 Barlow instead, in addition to the practical absence of transversalium, gives a significant increase in the spectral resolving power of approximately 68%.

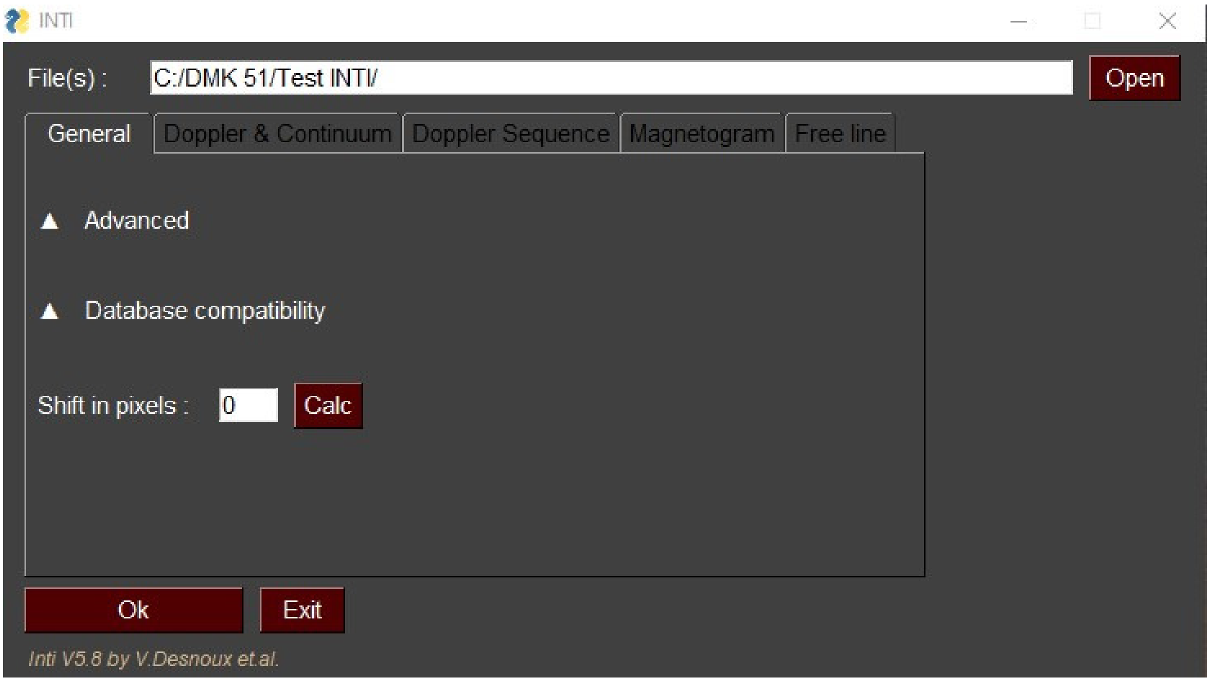
Another, easy solution to increase the spectral and (slightly) spatial resolution is to insert a x 2or x 3 Barlow before the camera, doubling and tripling the focal length of the collimation optics. This can be useful when you don't want to record a full solar disk and instead want to just capture details on the solar disk.

The Software

Four years have passed since the publication of my spectroheliography book in 2019. In this period, new freeware software for the reconstruction of spectroheliography images has appeared, which give surprising results comparable with those of "stacked" commercial filters.

The first of these in chronological order was the INTI software, specifically dedicated to spectroheliography with the Sol Ex spectroheliography system by C. Buil, created by the French amateur Valerie Desnoux and freely downloadable from her website.

http://valerie.desnoux.free.fr/inti/



It is a simple and complete software,with Doppler continuum, Doppler sequence,Magnetograms and much more, which however can only be used with SER files. From this it follows that those who still use 8 bit cameras with AVI files cannot use this program.

Some programmers have responded to this situation, among which I quote "The Smiths", that is Douglas Smith and his son Andrew, English amateur astronomers, producing excellent software, a modification of INTI, (Solex Avi Recon) which also works with AVI files and allows you to modulate the transversalium elimination routine and many other useful options.

The software in question, in the original or modified version, is very sophisticated and complex; in summary it carries out the following operations:

1-The first step is to create an average spectral line: this in turn averages all the frames of the scan video in the same way.

2-The program finds the centre of the darkest line, defined and identified by the darkest point in the line itself.

3-The line is modelled as a polynomial, some use a parabola (2nd order polynomial) others a cubic.

4- The video is read a second time and the polynomial is mapped frame by frame and projected onto a Cartesian grid.

5-The next step is to identify the edge that is used to make a geometric correction, transforming an ellipse into a circle.

6-The removal of the transversalium is then carried out, eliminating the lines parallel to the scanning direction.

7-Finally, a level adjustment (for example CLAHE) is applied to define the contrast and dynamic range of the image data.

The Smiths' SolEx Avi Recon software is now, at the time of writing, up to version 4.3, which features a remarkable number of commands and functions for optimizing spectroheliographic images.

This release can be freely downloaded at the link:

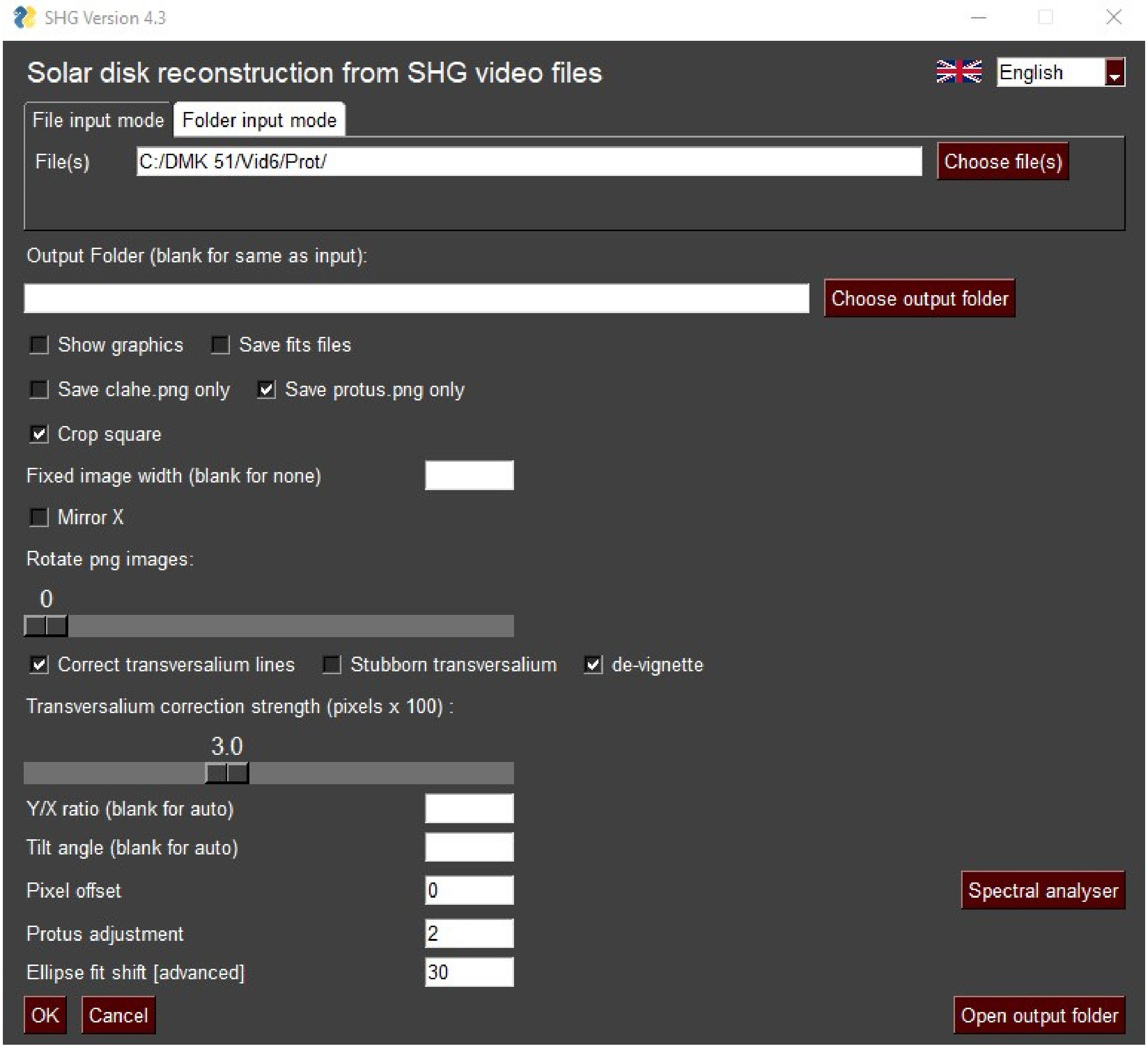
https://github.com/thelondonsmiths/Solex_ser_recon_EN/releases

The program consists of two versions, one for Windows executable, and another that requires the installation of Python software.

As mentioned, this software allows the elimination of the transversalium with various degrees of strength depending on the definition of the lines, it allows modifications to be made on the output images, to obtain them squared and inverted and to select them for each pixel of the line, i.e. obtain images from the sum of multiple pixels and much more.

Once the video file has been opened, the program takes a few seconds to produce an image, not only of the solar disk, but also of the visible prominences on a black disk, and therefore allows you to control the focus of the SHG almost in real time as well acquisition and other software settings.

An installation and how file to use can also be downloaded. Below, a screenshot of the program.



Examples of spectroheliograms

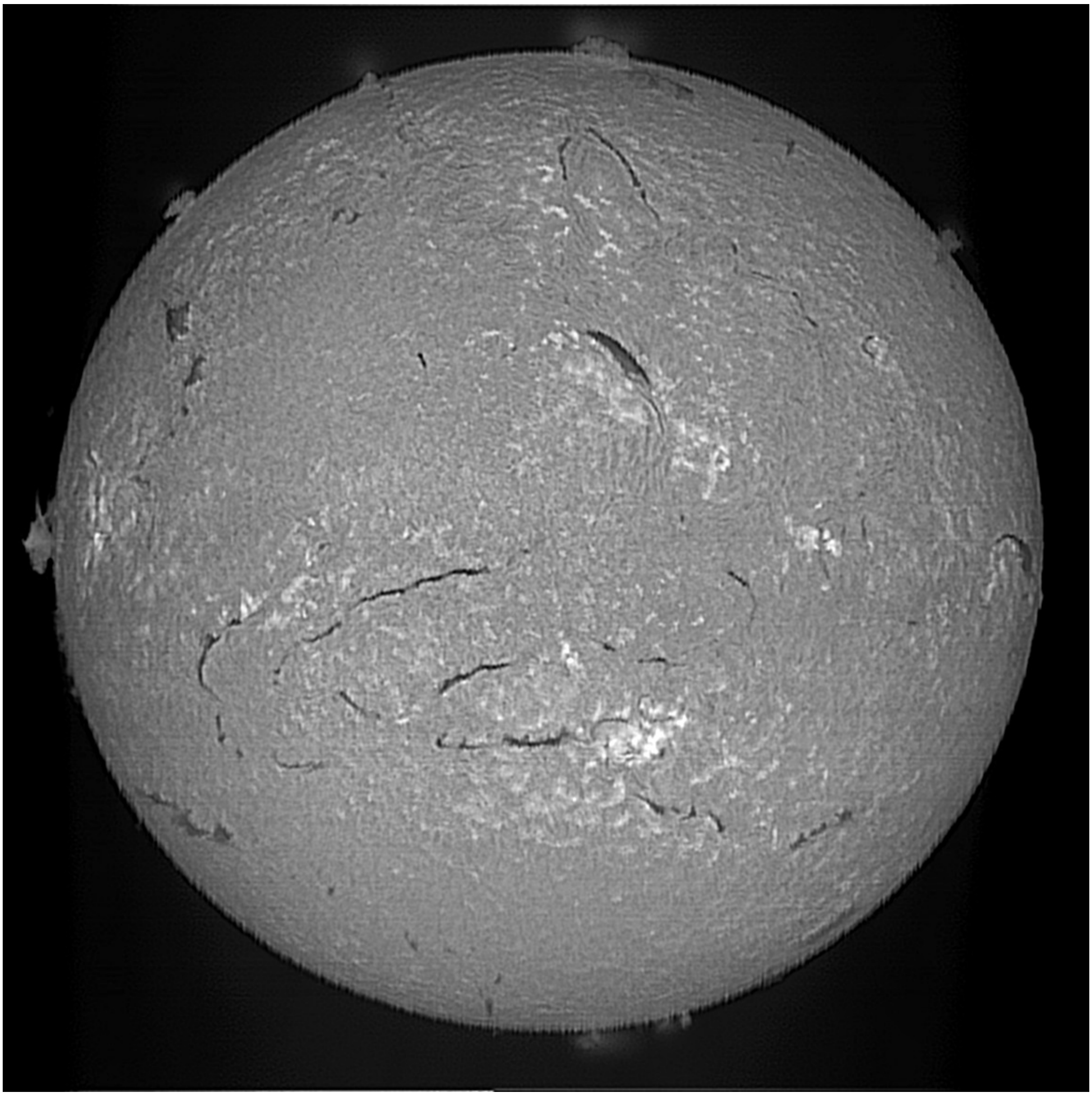
The instrument whose layout I showed, VHIRSS, is currently used by me exclusively for Hα imaging, while the others are intended for imaging in other wavelengths, such as CaII K and H,Al1, Cn, H beta , H gamma and Fe1, while Solarscan, the most sophisticated, is used for measuring the magnetic fields of sunspots via the Zeeman Effect.

As for the processing of spectroheliograms, by processing I mean applying some cosmetic steps to make the images more pleasing from an aesthetic point of view. It is useful to remember that such modifications to the files (Fits, PNG, BMP) make them unusable for any scientific analysis.

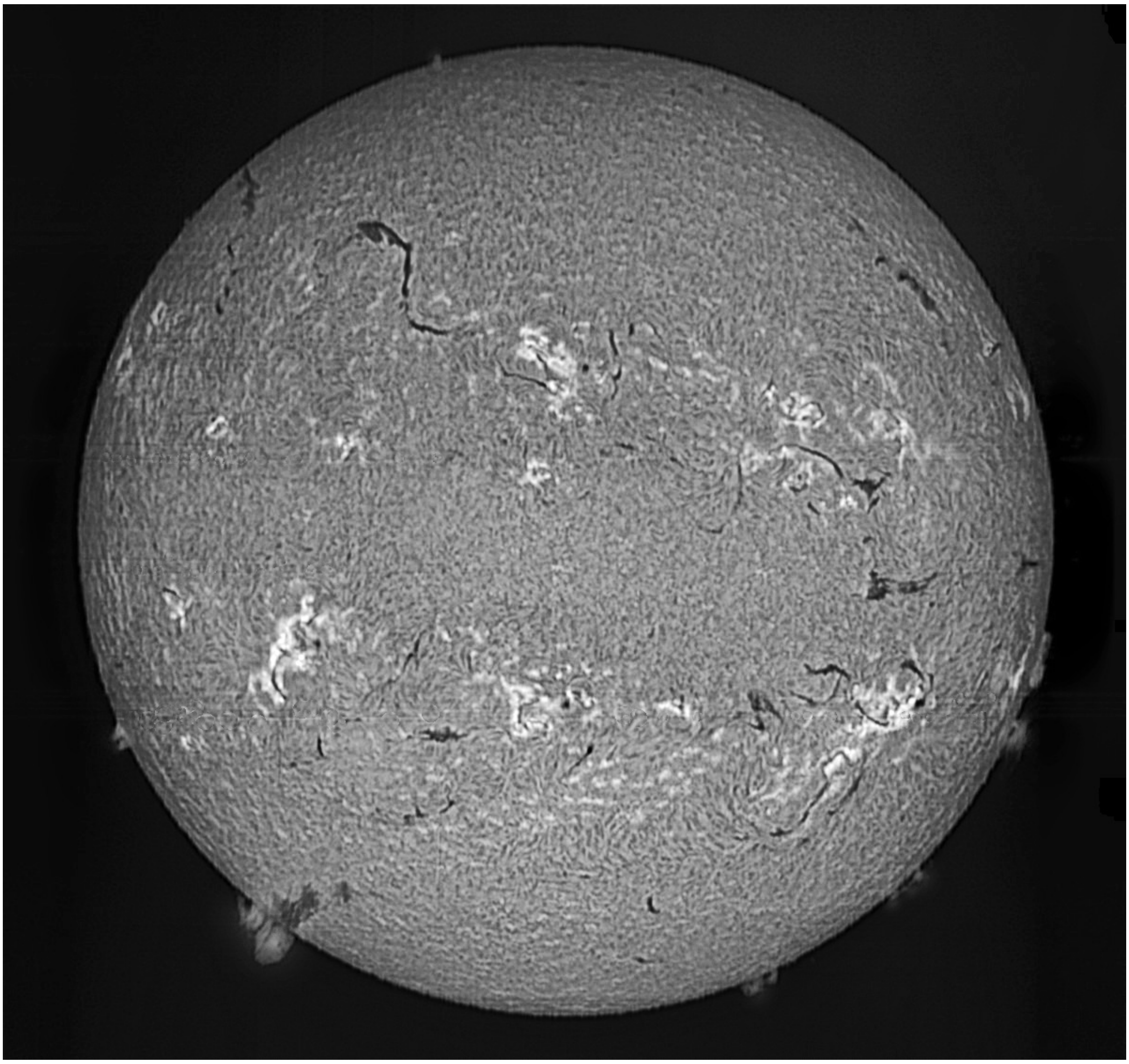
I generally use Registax 6 or Autostakkert for stacking of multiple raw frames and finally I apply a Wavelet filter.The final result can be further processed with Photoshop to combine prominences to the final image.

Here are some examples of H alpha spectroheliograms obtained with VHIRSS, all from last two years.

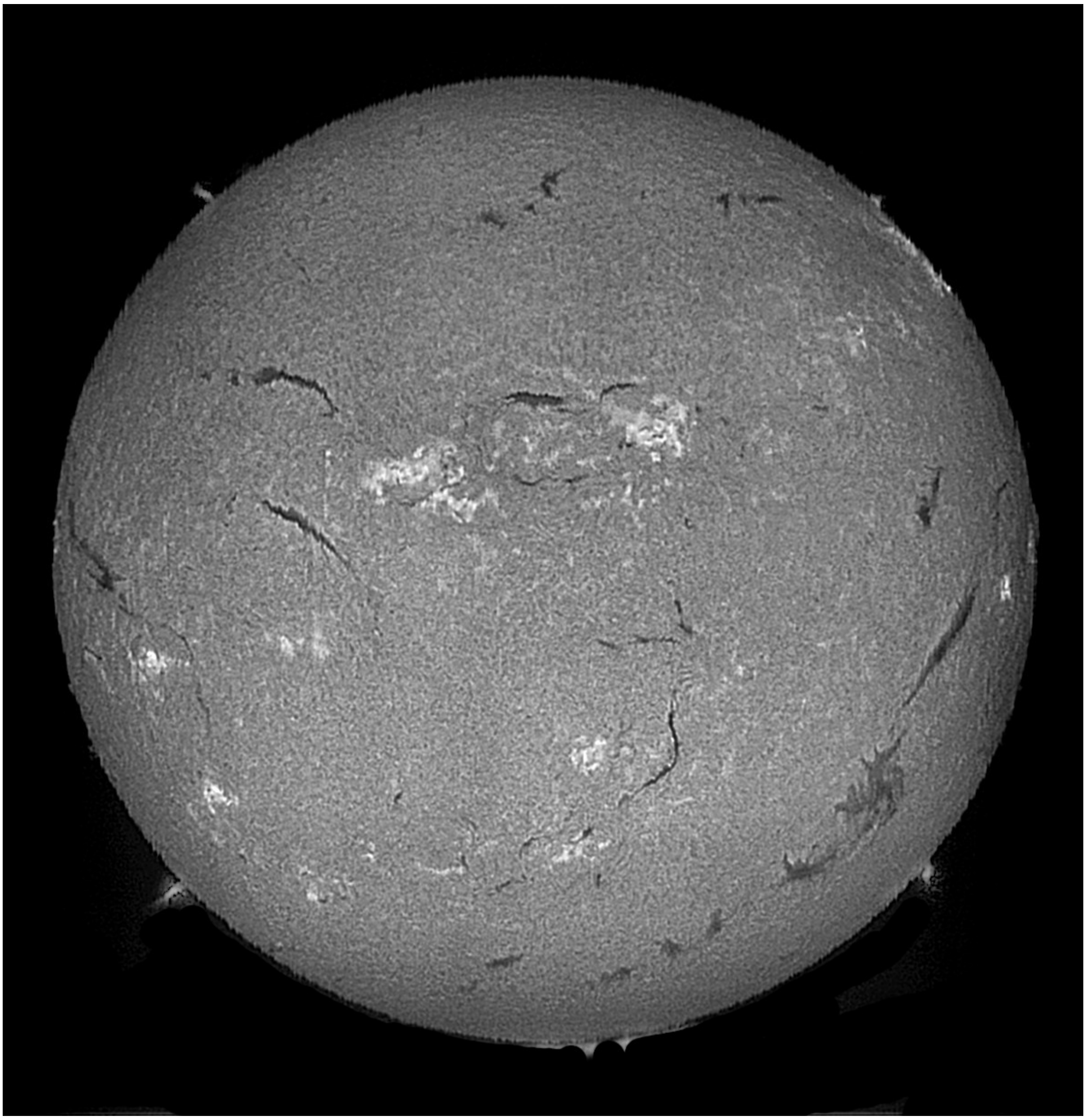
The quality of the images, as can be seen, is now light years away from that of just four years ago, and tends to surpass that of commercial filters and equal the output of professional observatories with solar towers tens of meters high. This being achieved with a DIY instrument,costing few Euros, with its limitations and defects.



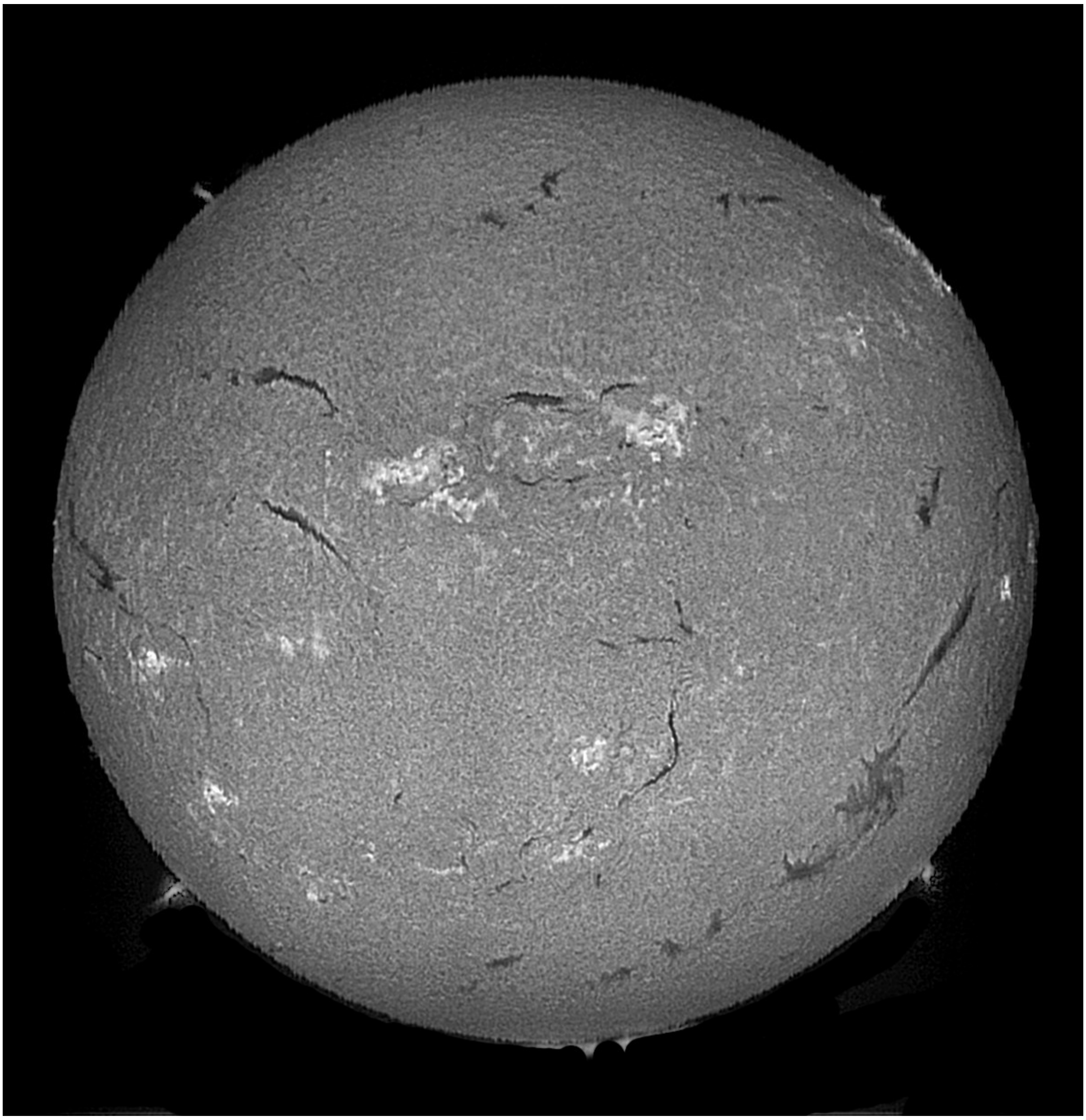
Hα spectroheliogram of April 4th 2023



Hα spectroheliogram of June 23rd 2023

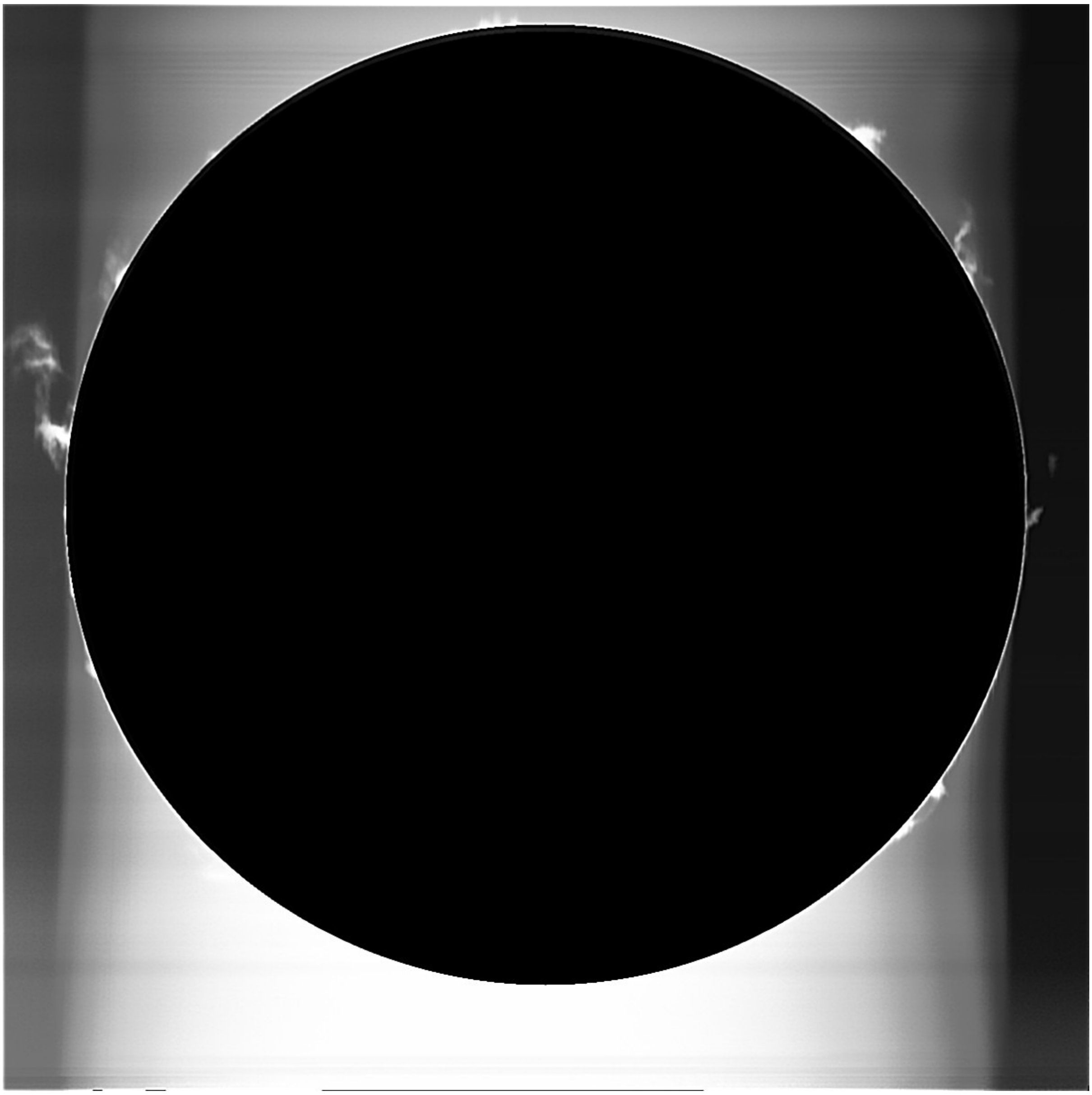


Hα spectroheliogram of September 11th 2023

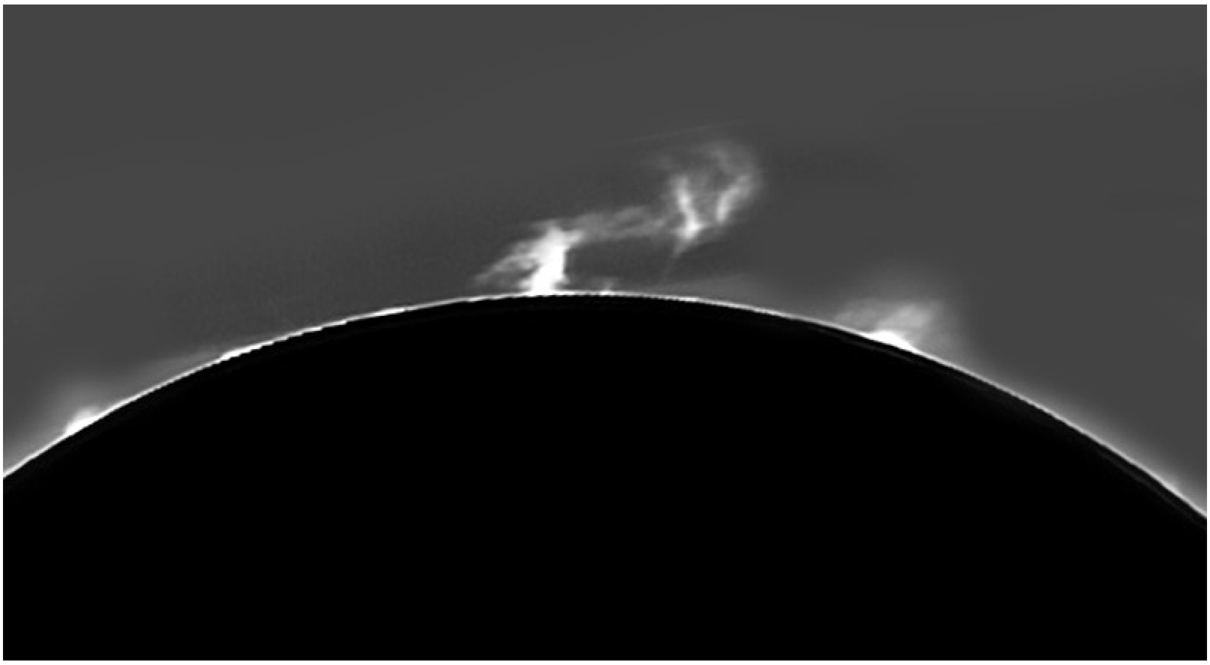


Hα spectroheliogram of October 4th 2023

Spectroheliograms can cover the entire solar disk, but they can also record details on the disk, such as this filament, imaged in September 2023. Note the three-dimensional, classic appearance of the spectroheliographic images.

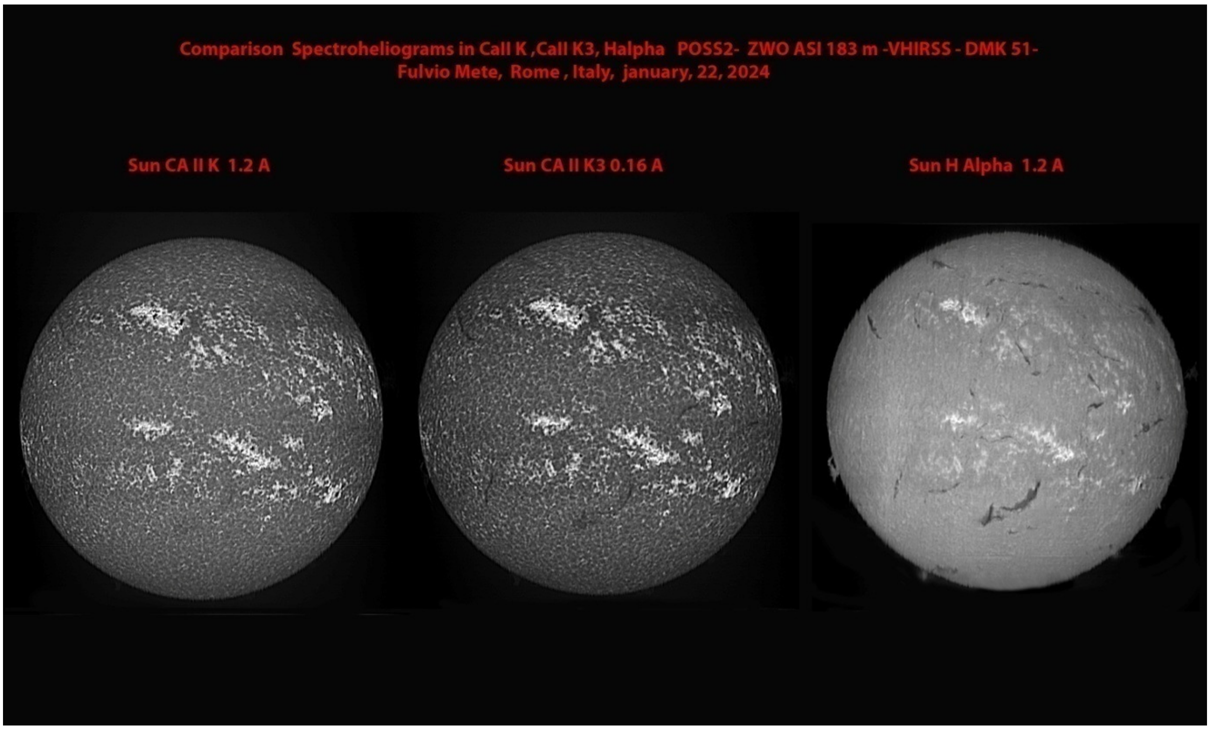


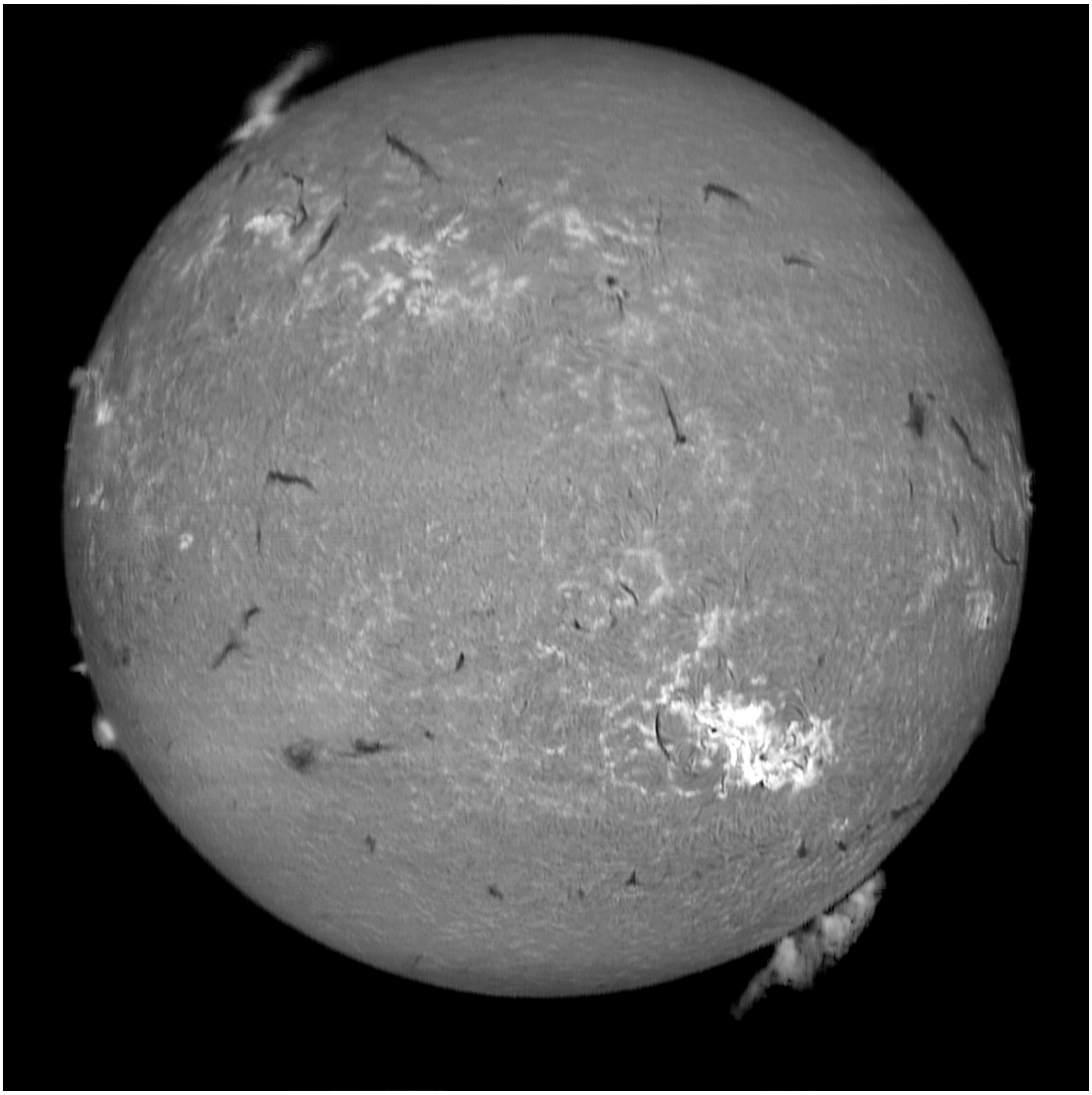
Solar prominences visible in the spectroheliogram of October 4th 2023



Detail of prominences visible in the spectroheliogram of October 4th 2023

A recent work of comparison between CaII K, CaII K3 and Hα spectroheliograms dated January, 22 2024, that was awarded Solaractivity Facebook Group “Picture of the Day”.

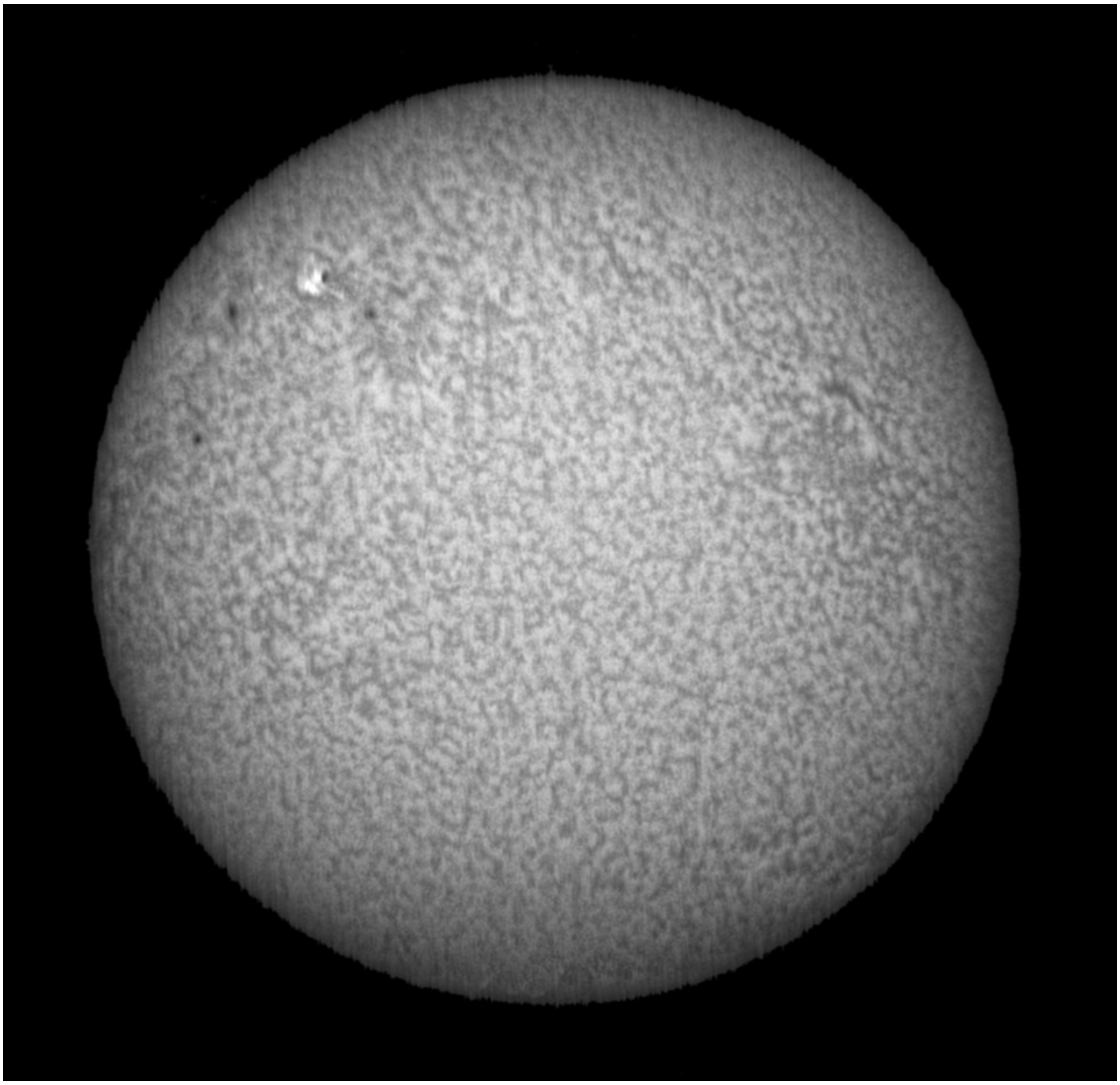




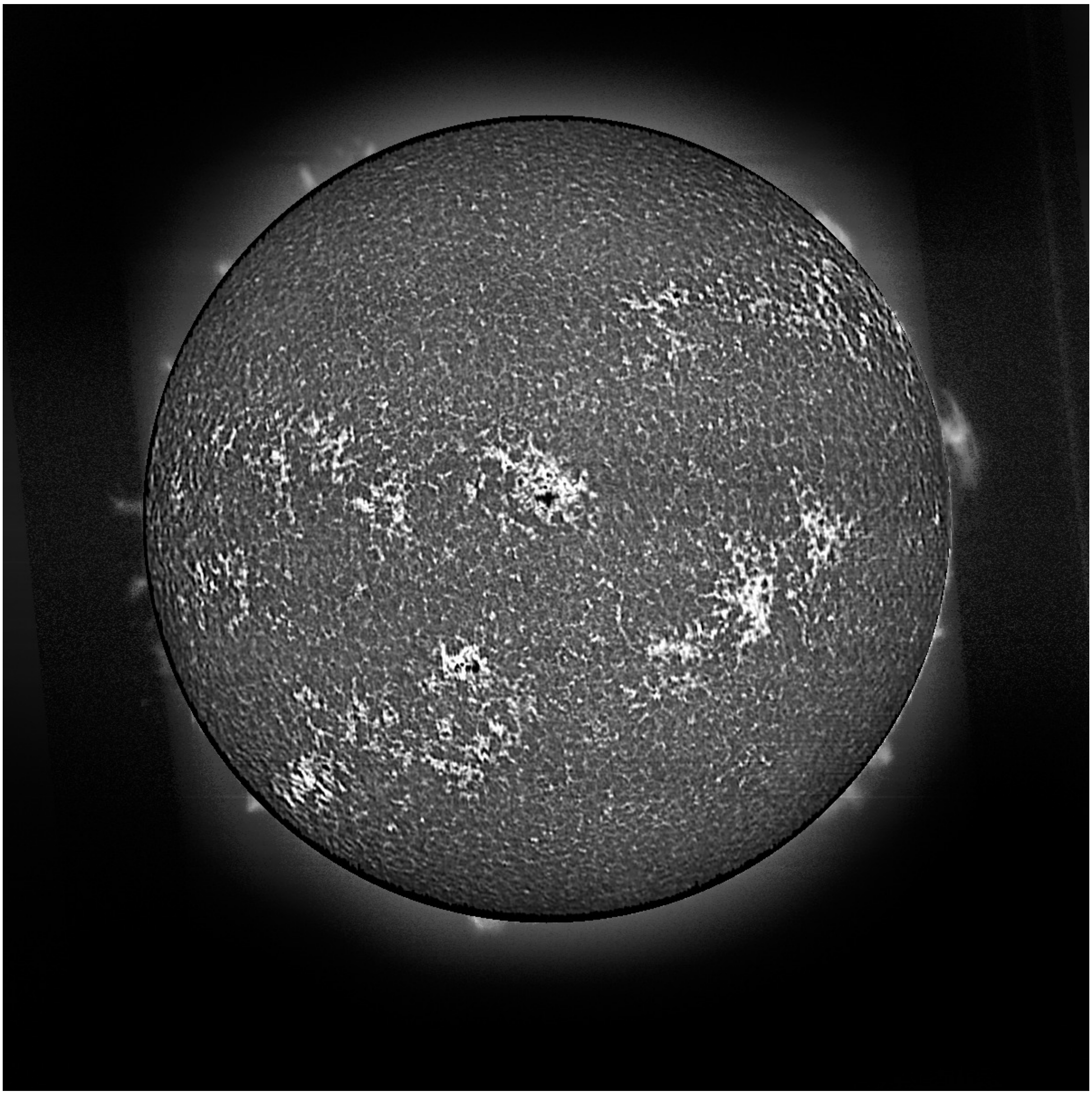
A recent Hα spectroheliogram on May, 10, 2024

As can be seen, the quality is high, and the clarity of details is excellent, with added ability of also capturing prominences in the same scan.

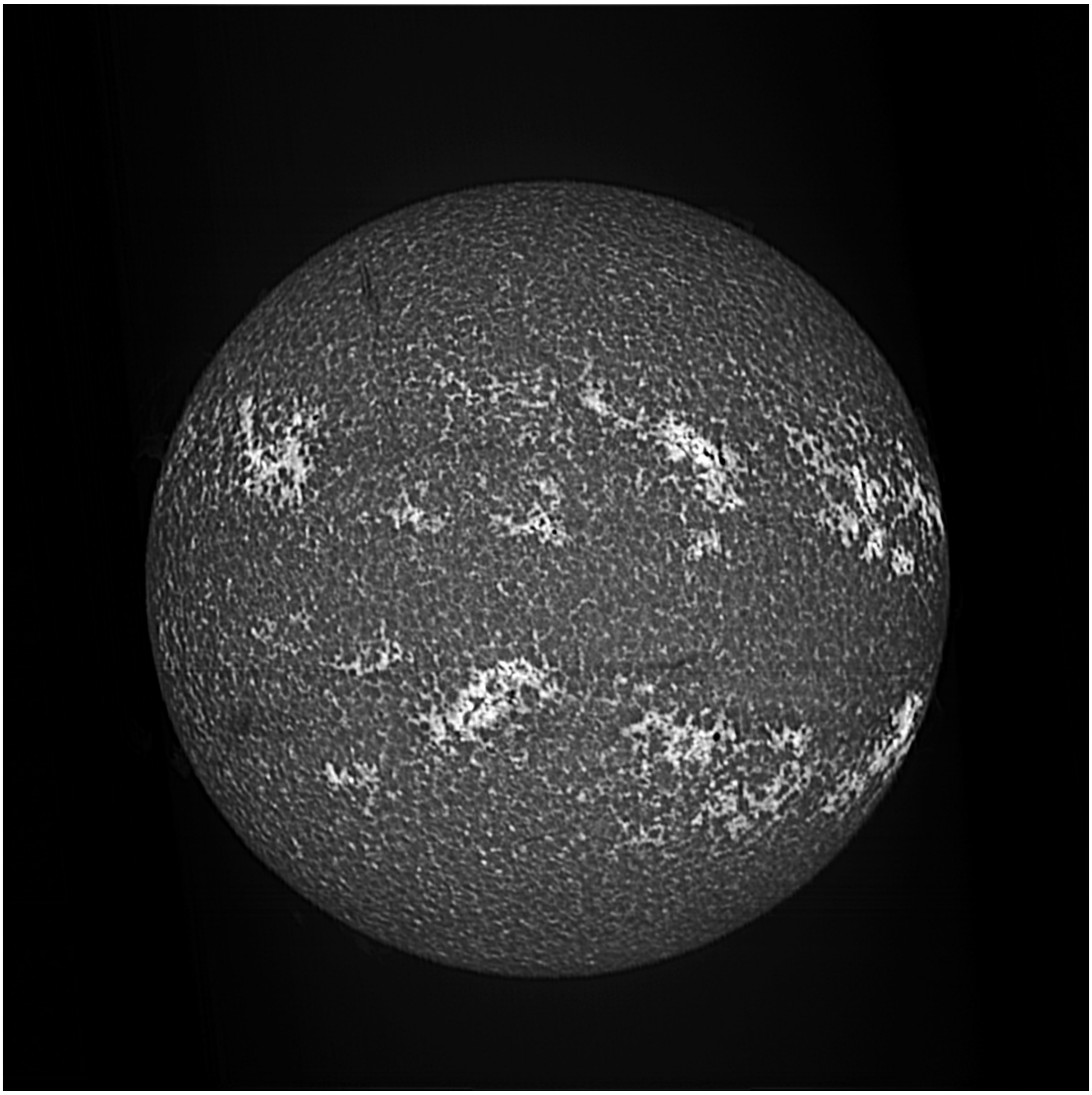
But it is not only Hα which lies within the reach of amateur SHG. In reality, any line of the visible solar spectrum can be imaged and thoroughly investigated. Below are some examples.



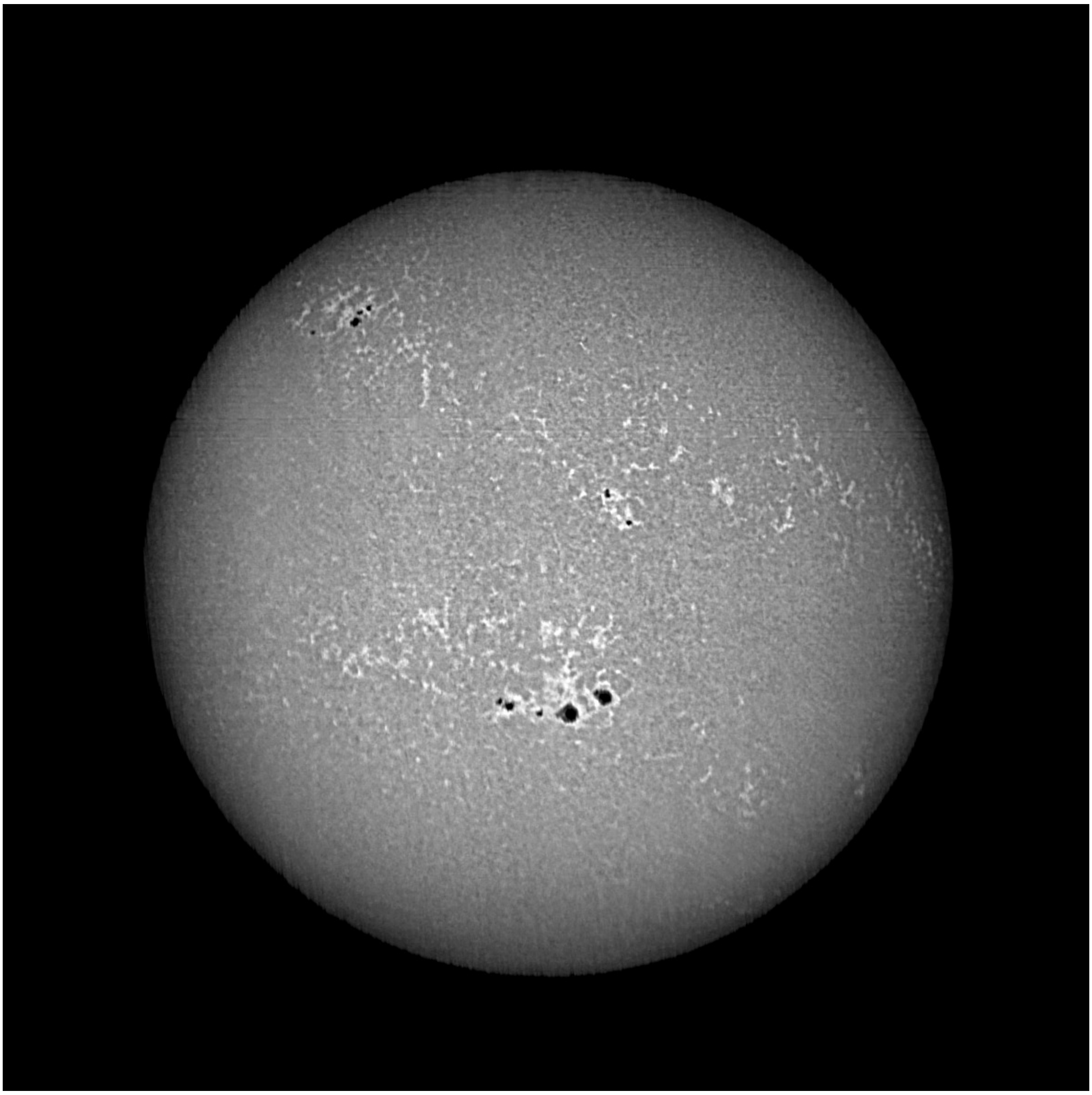
An H Beta spectroheliogram at 4861 Å taken on May 4, 2023 with the UPS SHG.



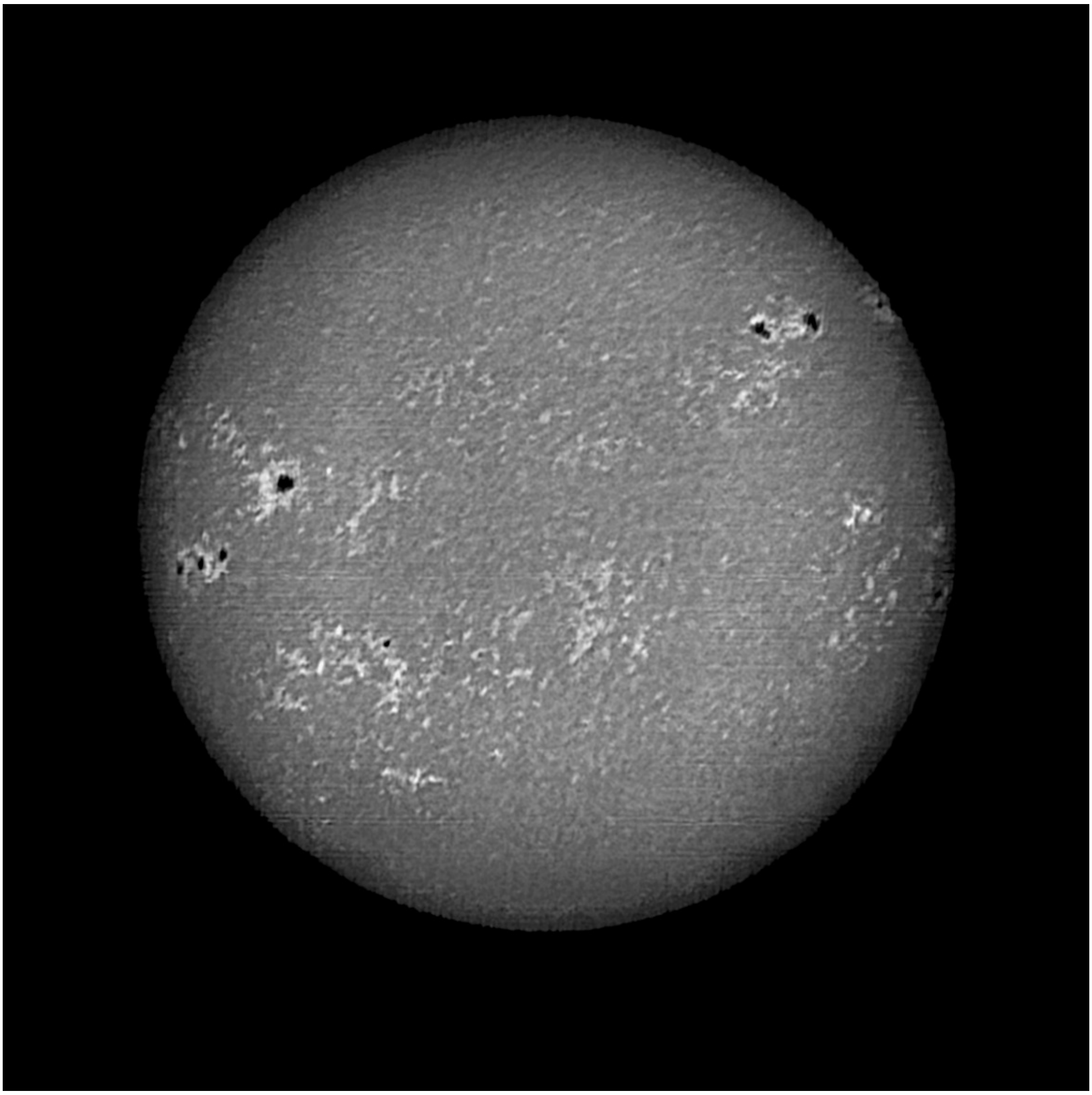
A CaII H spectroheliogram at 3968 Å taken with the POSS2 SHG on August 27, 2023. Note the image of the disk with the prominences, the result of a composite of two different spectroheliograms.



Spectroheliogram in CaII K light at 3933 Å obtained with POSS2 on June 25 2023.



Spectroheliogram in the light of AL 1 (aluminium) at 3961 Å, of April 28 2023.



Spectroheliogram in the Cyanogen (Cn) molecular band at 3883 Å taken on June 2 2023 with POSS2. Not an easy job due to the thinness of the band lines and only possible due to the high dispersion and resolution of the instrument used.

The images shown above constitute just brief example of the potential of spectroheliography, once a field of astrophysics exclusively reserved for professionals, and today within the reach of amateurs eager to advance their knowledge of the star closest to us, with enthusiasm and practical ability in astronomy, one with the very powerful driver that all amateur astronomers have in common: the curiosity of discovery.

What to observe with the digital SHG

It seems time to listen to the reader interested in this topic ask: but what can be observed with spectroheliography?

The immediate answer is: the main characteristics of the chromosphere, the solar atmosphere. The areas relating to the spectral lines of the elements present in it (hydrogen, calcium, etc), taking into account that lines of different elements and different aspects of the lines provide information on layers of the chromosphere at different height and temperature.

The observation of the solar atmosphere is of great interest, even for the amateur, as it is the site of complex phenomena, such as flares, and has always been an object of study in the professional field.

The main chromospheric characteristics and structures are:

-The "Plages", bright structures around the sunspots in the photosphere, due to the concentration of magnetic activity in these "active" areas. In CaII K and H light the bright areas, generally corresponding to the active regions, are called faculae.

-The Mottles, which constitute the elements of the chromospheric supergranulation, and appear dark or dimly bright in Hα light (absorption) and bright in CaII K and H light (emission).

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

-Filaments, dark coloured streaks, are nothing more than the same prominences projected on the disc, and appear dark by contrast.

-The "Spicules", "the grass of the chromosphere", small plasma ejections at the base of the chromosphere that are observed on the solar edge.

-The Flares. In some conditions, in the chromosphere, near active regions, particularly intense energy phenomena called flares develop, reaching up to the equivalent of 160 billion megatons! They take place due to magnetic reconnection phenomena which accelerate charged particles and bring them into collision with the plasma and can be associated, although not always, with coronal mass ejection (CME) phenomena. Their study constitutes one of the points of interest of solar physics.

The chromosphere lines of the solar spectrum best known to the amateur, due to the availability of solar filters,are essentially two, that of ionized hydrogen at 6563 Å (Hα) and those of ionized calcium CaII K and H at 3933 and 3968 Å. It must be said, however, that while the observation in Hα light can also be carried out visually, that in the calcium lines is an almost exclusive prerogative of CCD or CMOS imaging due to the poor sensitivity of the eye in the violet.

Many solar enthusiasts, however, do not fully understand the differences between the two different types of observation of the solar chromosphere, in a Hα and CaII K and H light, nor the physical differences between the two lines and the related atomic populations in the atmosphere of the sun. Here we briefly clarify the importance of solar observation in Calcium light, and in the entire near-UV band accessible to amateur instruments.

In this regard, it should be noted that the observation of the lines of the solar spectrum is not an end in itself. It provides us with valuable knowledge and information on:

1-The chemical elements present on the Sun, given that the lines associated with a given wavelength constitute actual fingerprints characteristic of each individual element.

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

3- The temperature at which the elements relating to the line or their atomic transitions are found, given that the transitions at different atomic levels occur at different temperatures. The temperature is also derived from the width of the line concerned.

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

5-The motion of the solar plasma with respect to the observer due to the Doppler Effect.

Why to observe CaII K and H in the UV

But why observe the Chromosphere in the UV band instead of the usual and all in all convenient Hα, for which there is a plethora of dedicated filters and telescopes at reasonable prices, and which also allows visual observation without problems?

In the paper by Vernazza et al (Structure of Solar Chromosphere-1981) the diagram below is published which summarizes in a simple and straight forward way the differences in height and temperature in the quiet sun between the observations in the different spectral lines of the atomic populations present in the chromosphere.

No. 4, 1981 QUIET SUN EUV BRIGHTNESS COMPONENTS 637

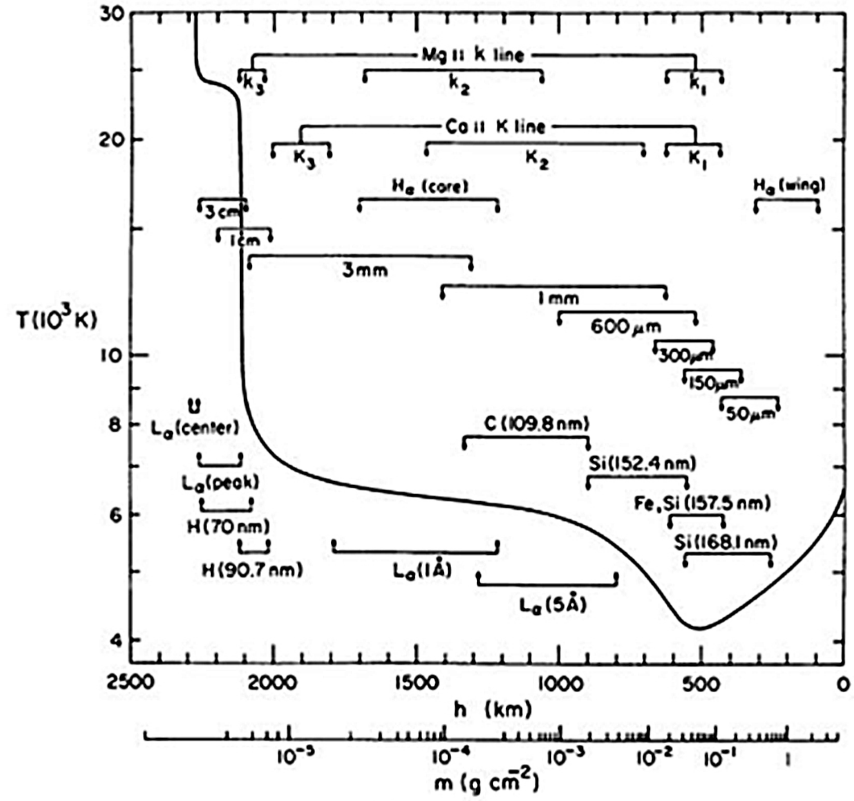
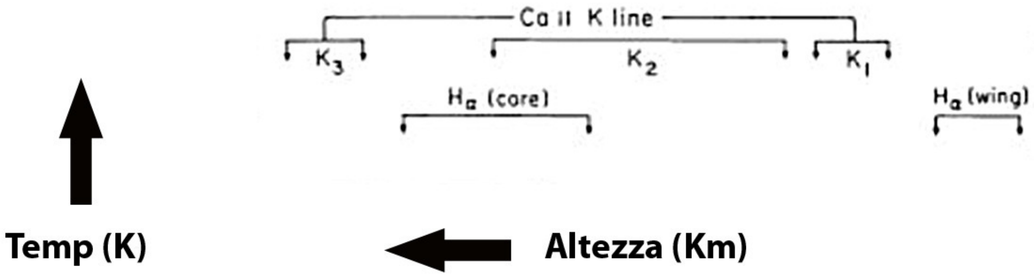


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

The first thing that catches your eye in the diagram is that, going from the wings, to the centre of the most important lines in the chromosphere, such as Hα and Ca II, you go from the high photosphere to the high chromosphere, that is, you go up in height , from approximately 200-300 km in the wings of the Hα to approximately 1800-2000 km in the central part of the CaII K line, the CaII K 3: at the same time the temperature rises on the basis of the curve.

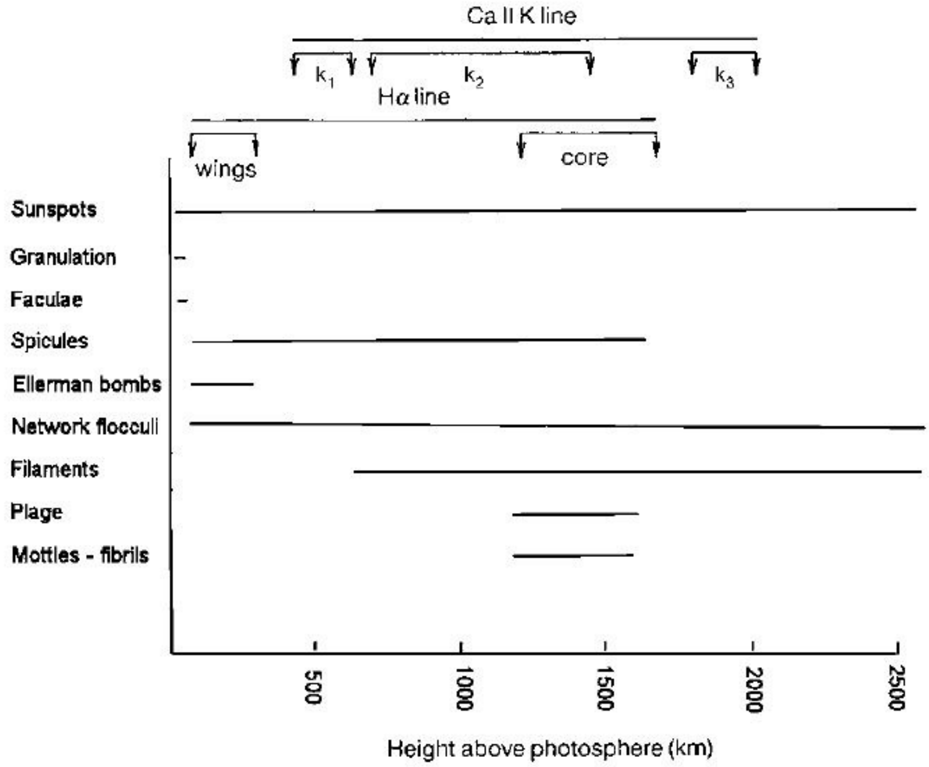
It also explains another thing to us, that the centre of the CaIIK (K3) line is located a little higher and at a higher temperature than that of the Hα.



To further clarify the concept, the following diagram shows us how certain physical phenomena present on the sun (spots, faculae, filaments, plages, etc.) present a different appearance not only depending on the element in whose light they are recorded or observed (for example example hydrogen alpha or ionized calcium) but also if the observation is made at the centre of the spectral line of the elements or on the wings. Since going from the wings towards the centre of the line means going towards the upper part of the chromosphere and rising towards higher temperatures .On the other hand, if we go from the centre towards the wings we move down towards the lower chromosphere and the photosphere.

For example: in the CaII K3 area, at the centre of the CaII K line only spots and flocculations are observed, but, given the sensitivity of this K line to magnetic fields is maximum, these features are observed in emission, with a brightness much more evident than in Ha , but the filaments are less evident.

In the example shown in the diagram, referring to Hα, we observe how, moving from the centre of the line towards the blue wing (which can be achieved with some solar telescopes with a front etalon by tilting it) we go from the more important chromospheric characteristics,granulation, flocculations, spicules ,being easily visible , to viewing an image of reduced details. Even the definition of the spots loses intensity.

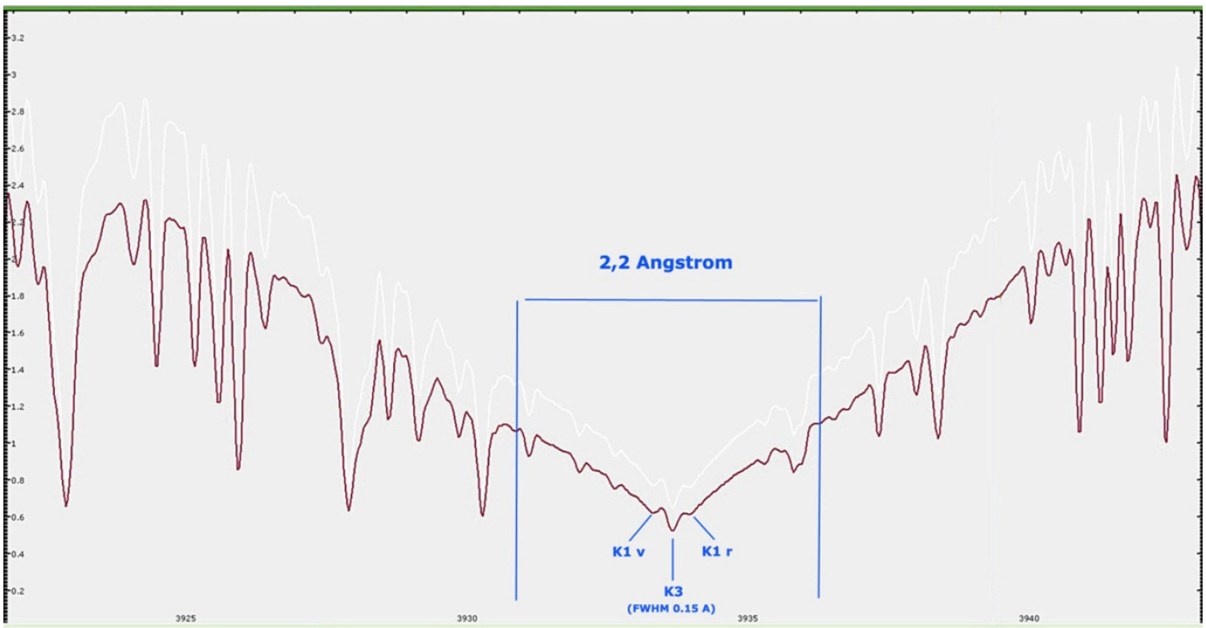


The Calcium lines, and in particular the CaIIK can be considered reliable indicators of the density of the magnetic flux in the line of sight, and have been used for the identification of the plages through the solar cycle and the historical series of the solar cycles, as shown in the article I.Ermolli et al "Comparison CaII K spectroheliograms time series with an application to solar activity studies" The Astronomical Journal, May, 27 2009.

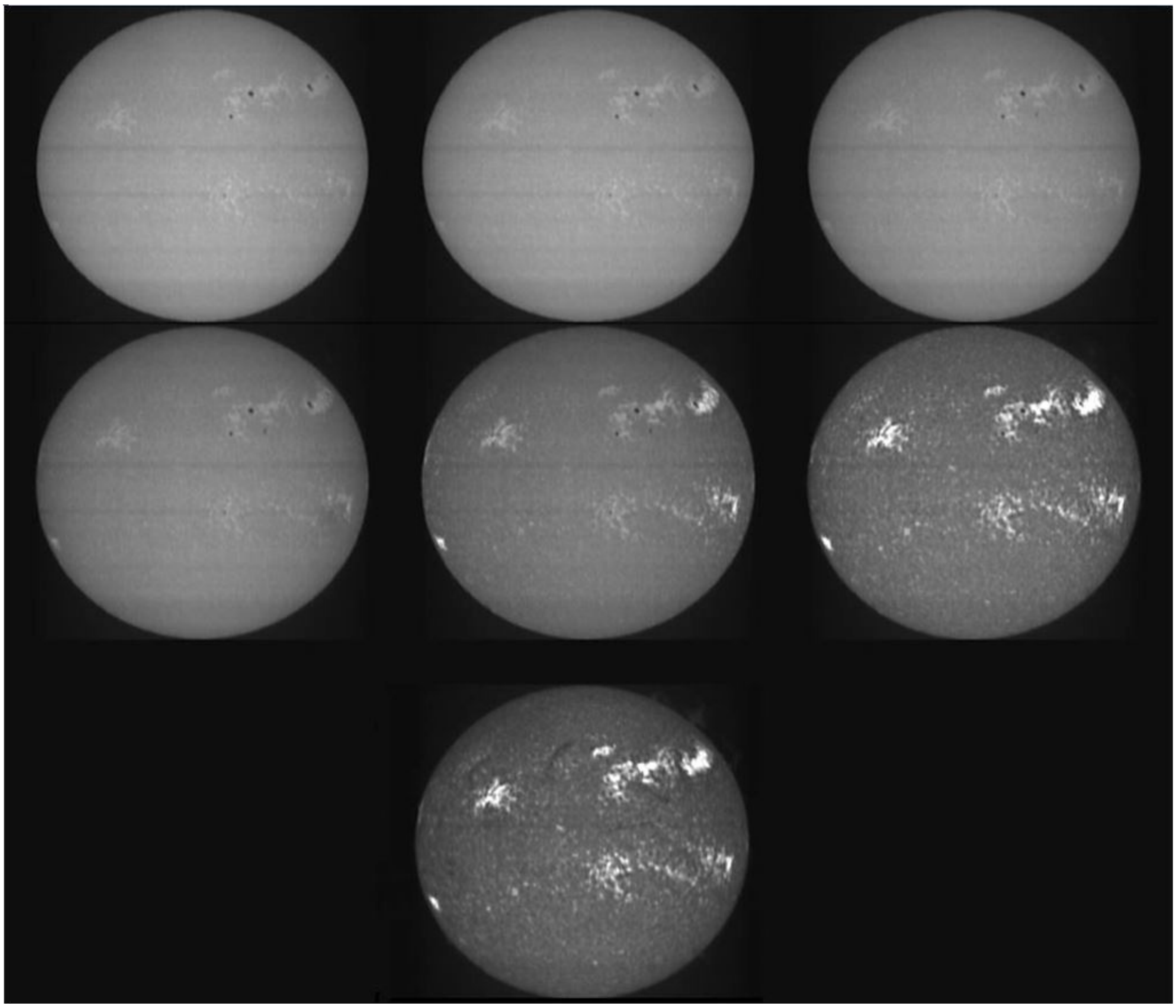
The CaII K line is very important in the study of solar activity and the chromosphere in particular. The NSO (National Solar Observatory) of Sacramento Peak in New Mexico (USA) carried out a monitoring activity of the line, evaluating, among other things, the parameters of the emission index (EM) corresponding to the EW (Equivalent Width) of an interval of 1 Å centered on the line, and the intensity values of the core K3 (0.15 Å) of the line itself. Since October 2015 the Sacramento Peak monitoring program has been suspended, as data from the SOLIS – ISS (Integrated Sunlight Spectrometer) project, active at the NSO – Kitt Peak is now being used, with a spectrograph capable of resolution R= 300000 and a wavelength range from 350 to 1100 nm. Monitoring also now extends to the CaII H line.

We therefore have two good reasons to observe the CaII K and H lines: the strong emission component which causes the bright areas coinciding with the plages, (which in turn coincide with the active regions), and the so-called. Chromospheric network, which outlines the supergranulation cells. But the emission component (plages) is closely linked to the magnetic fields, and its intensity is sometimes relatively proportional to the magnetic intensity. The supergranules in the upper photosphere and chromosphere have dimensions of approximately 30,000- 35,000 km and a duration of approximately 24 hours, while the granules observed at the level of photosphere have dimensions of 1000 km and an average life span of 8-10 minutes.

The spectral profile and bandwidth of the CaII K line is considerably higher than those of the Hα, more than double, and is around 2.2 Å, including the K1 points and the centre of the line K3 which has a width of 0.15 Å. From a certain point of view, the filters used for ionized Calcium light do not, unlike the Hα, need particularly narrow bands to give contrasted and visually pleasing images of the solar disk. The bandwidth of the CaII H line is very similar to that of CaII K.



In conclusion, digital spectroheliography allows access to a series of observations in Ca II K, some of a scientific nature, not possible with common commercial filters. For example, going with a sub angstrom precision from the wings of a line towards the centre and therefore increasing in height and temperatures in the chromosphere , observing its different structures and physical condition, as shown by the following image series made by the author of spectroheliograms of the CaIIK line from the blue wing to the centre of the line.



Not just imaging

After this overview of the possibilities offered by spectroheliographic observation in recent years, in my opinion of extreme interest both for the advanced amateur and for the beginner eager to learn, I would like to draw attention once again to an almost unknown aspect of high resolution solar spectroscopy: the measurement of the magnetic fields of sunspots through the Zeeman Effect. This is an application of exclusive professional expertise in past years, and today carried out by sophisticated equipment in observatories and on satellites. Achieving this objective with modest means can therefore be considered a source of great satisfaction for the amateur astronomer.

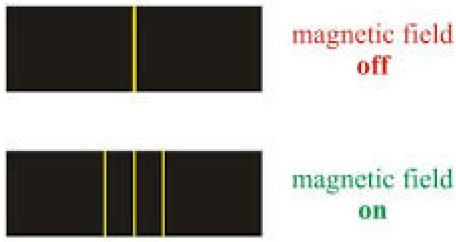
The method I followed, which I will illustrate shortly, is in principle the simplest, the observation of the magnetic fields of sunspots in non-polarized light which does not require further additional instrumentation, and additional expenses compared to those incurred for the construction of a SHG. The use of polarizers and ¼ λ glass retardant blades entails a complication in the layout of the instrument and a considerable expense (about € 700) which I decided to avoid, at least in an initial phase of this great adventure. In any case, the error attributable to the failure to use retardant plates and polarizers is, based on my experience, around 6-7%, all in all acceptable for amateur observations.

A quick reminder about the Zeeman Effect

The Zeeman Effect consists of the broadening or division into several parts of a spectral line due to the effect of a magnetic field. More specifically, the Zeeman Effect can be defined as the physical phenomenon connected to the breakdown of atomic energy levels or spectrum lines due to the action of an external magnetic field. Pieter Zeeman, the Dutch physicist who won the Nobel Prize in 1902 for the discovery of the effect that took its name from him, he noticed experimentally that, in the presence of a magnetic field oriented perpendicularly, some spectral lines broke down into three different lines (orthogonal Zeeman Effect) while with a magnetic field oriented parallel to the object there were two lines of decomposition, and the central one disappeared (longitudinal Zeeman Effect).

Subsequently it was realized that the decomposition was much more complex than it appeared and, in relation to the spin of the electron, it was called the anomalous or normal Zeeman Effect. In astrophysics, the American astronomer George Ellery Hale was the first to observe and officially report this effect on the magnetic field of sunspots in his 1908 article even though other astronomers, including Lorenzo Respighi, had observed the phenomenon many years earlier. Today the same effect is exploited to obtain magnetograms of the solar surface with highly sophisticated instruments such as the SDO HMI or other instruments.

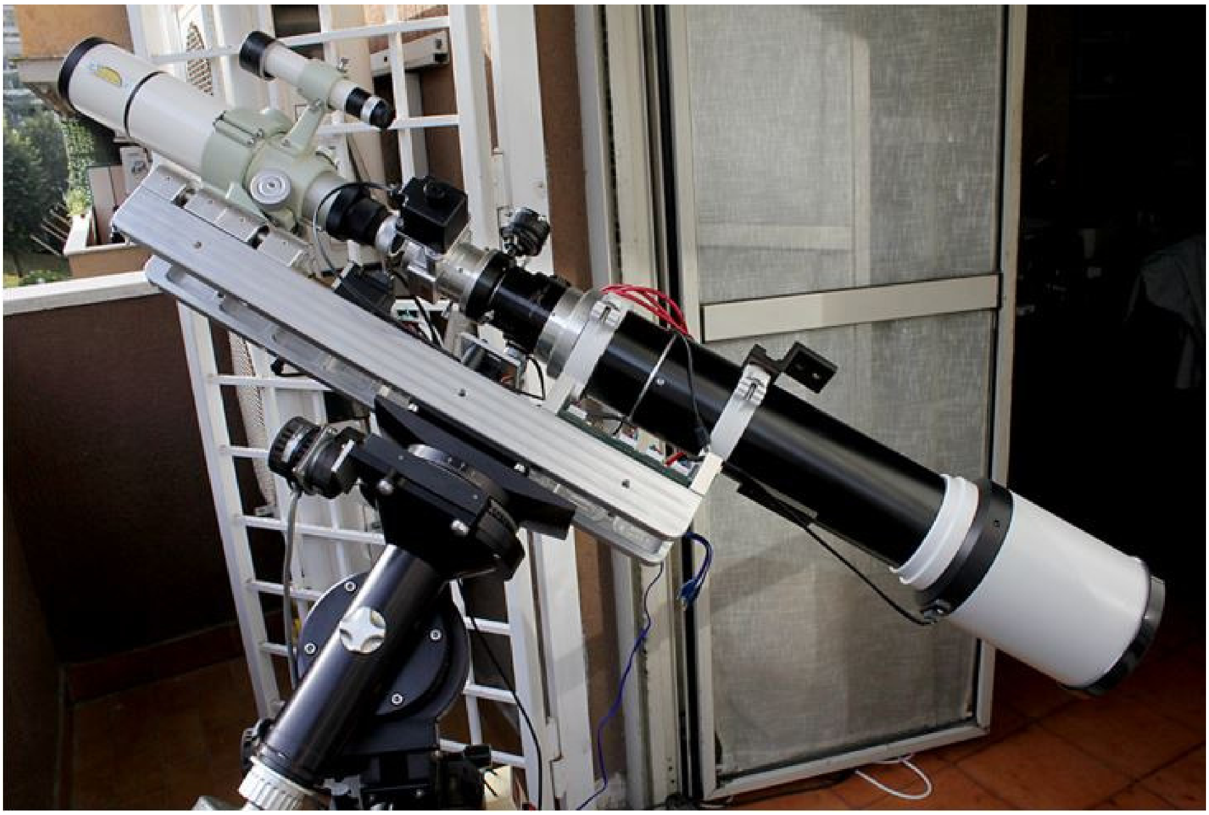
*) Hale, G. E. Publications of the Astronomical Society of the Pacific, Vol. 20, No. 123, p.287



If the line is emitting, it is called a direct effect, while if it is absorbing, it is a reverse Zeeman Effect. From the point of view of amateur astronomy, the phenomenon in question is very difficult to observe due the simple fact that it requires very high spectral resolving powers (in my opinion > 60,000) and a certain familiarity with the lines of the solar spectrum for identification of the iron lines involved in the phenomenon, including primarily those FeI at 6173 and 6302 Å. The recording of the Zeeman Effect on the lines of the solar spectrum in the presence of the strong magnetic fields of the spots therefore constitutes a real challenge for the amateur who deals with spectroscopy and its instrumentation.

My first experiments were carried out with the Hires Solarscan SHG in spectrograph mode and a DMK 41 camera, with a 1280 x 1024 Sony sensor on a Losmandy G 11 mount. This instrument, despite being practically equivalent to VHIRSS in terms of design (Littrow configuration, 2400 l/mm grating, ED 80/600 optics), was professionally built and is excellent in all aspects, even even down to the use of a small Takahashi 60/355 fluorite refractor, the instrument's functions can also be controlled directly from a PC. However, for such a difficult task it was necessary to further enhance its characteristics and potential.

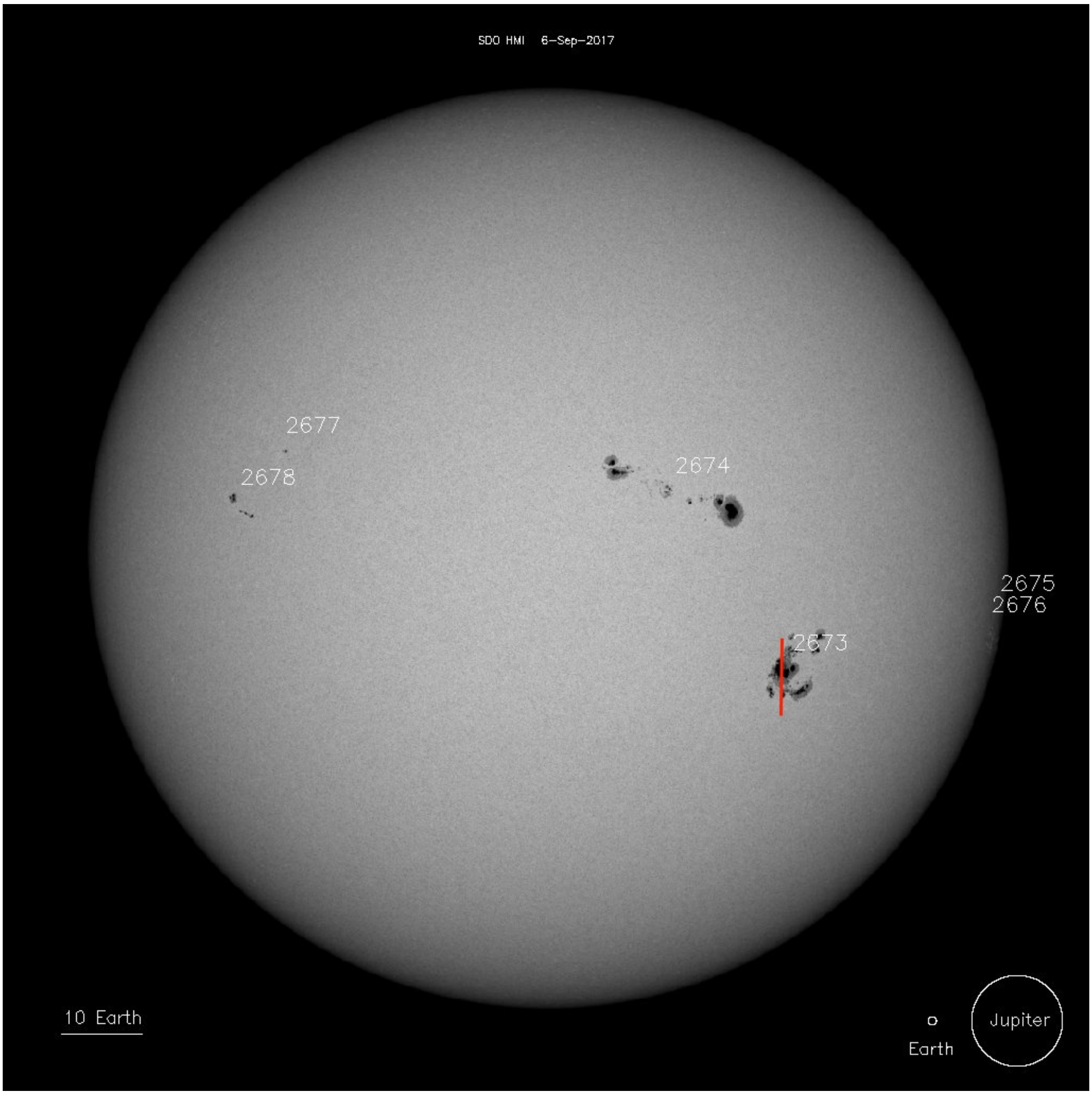
The original slit was therefore replaced with a fixed 5 micron air slit, purchased from Edmund Optics, which proved to be of excellent quality. This proved to be a winning choice, as it allowed me to obtain a notable gain in spectral resolution, which exceeded R = 100000 with the application of the usual wavelet filter to the spectrum. Honestly, one could not expect more from an instrument of such size and weight.



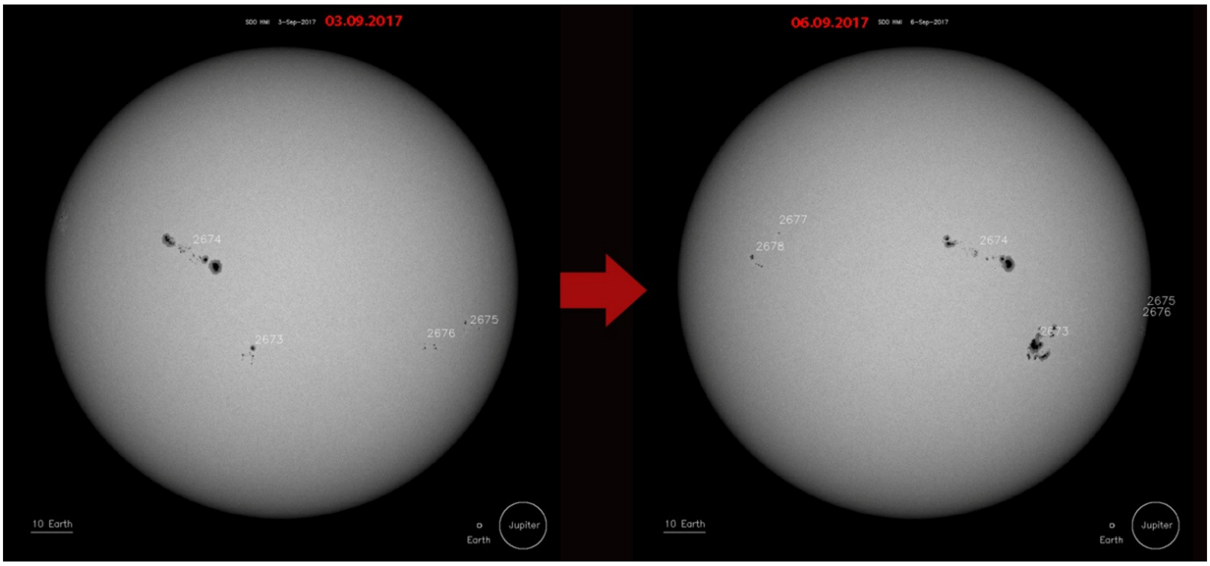
Solarscan remote controlled SHG

An example of Zeeman Effect detection

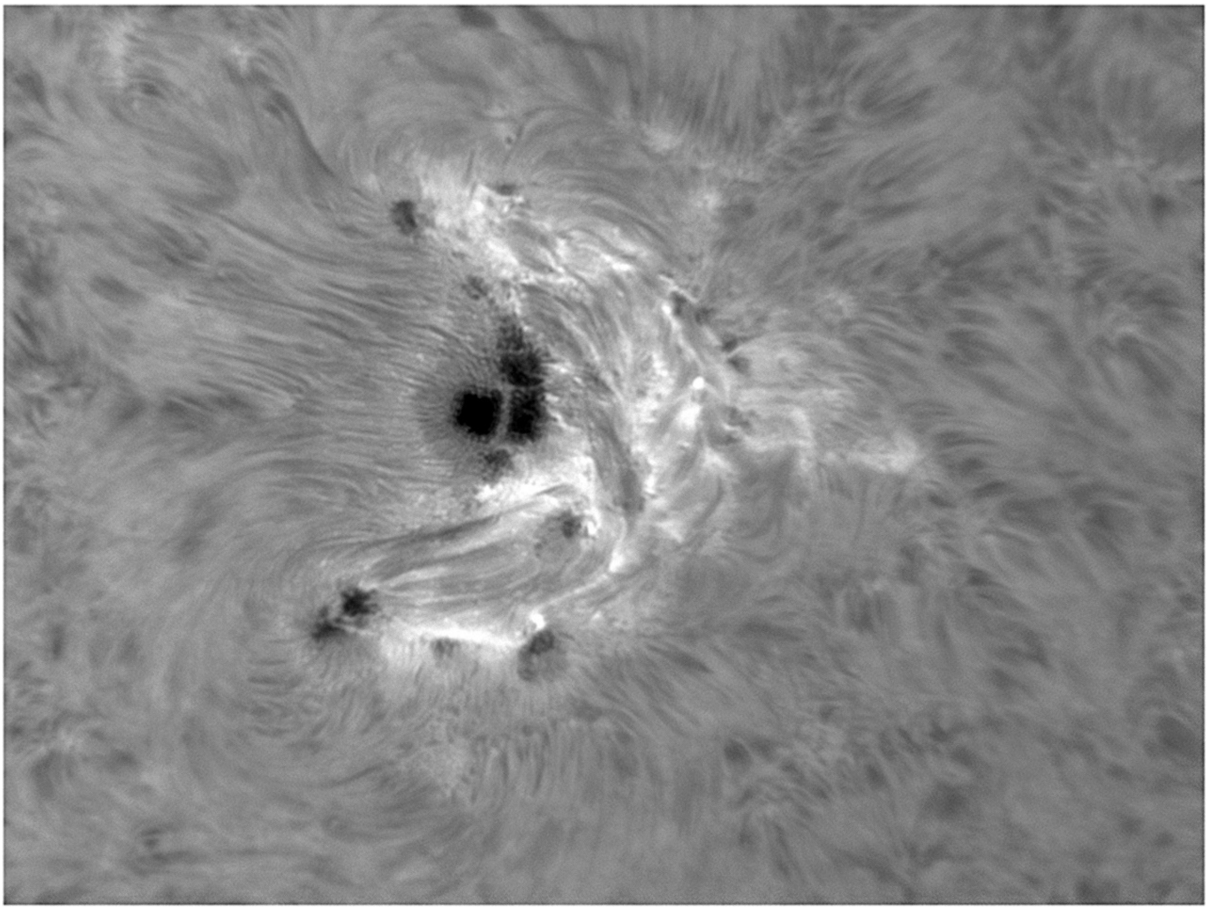
I remember what turned out to be the most intense sunspot of 2017, AR 2673, whose observation was carried out on September 6 2017. This spot, part of a rather complex active region as can be seen in the figure below (SDO - HMI) in which the position of the slit during the observation is also shown.



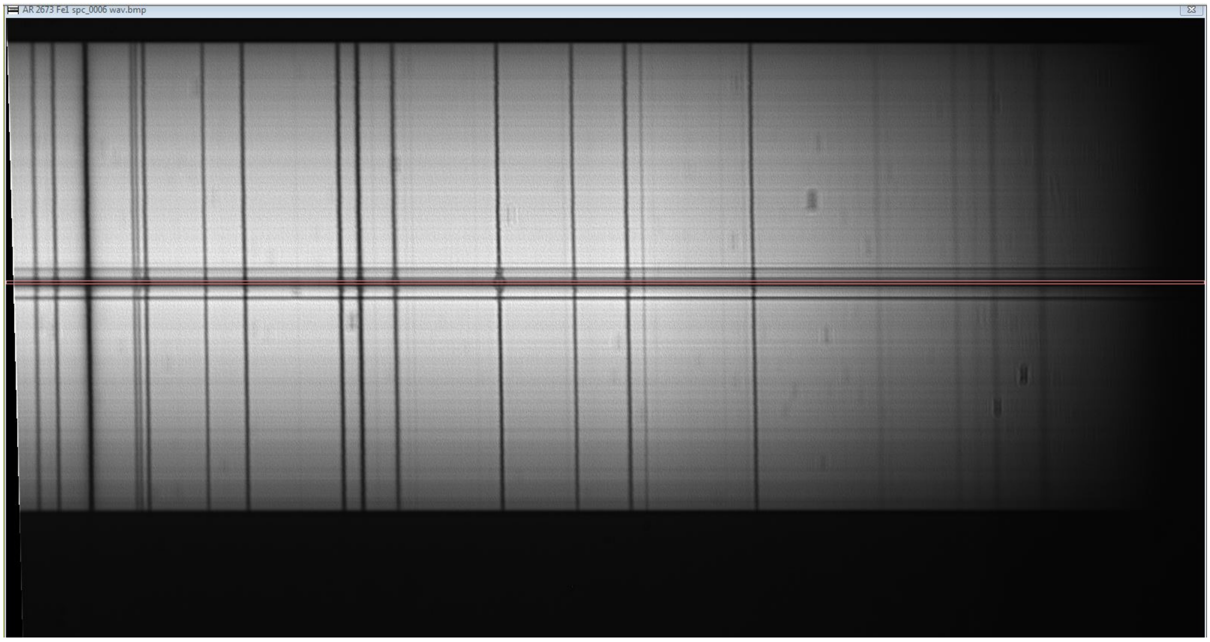
The characteristic of this sunspot was that of a truly remarkable development in just three days, as can be seen in the following image (Source SDO -HMI). However, at the time of the recording it was not in the centre of the disk.



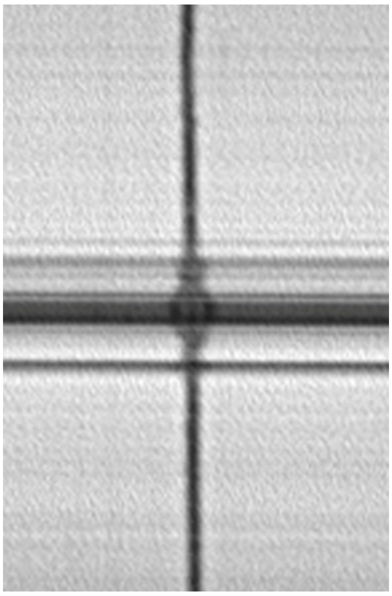
Above:The evolution of AR 2673 in the three days from 3 to 6 September 2017. Below: the complex activity around the sunspot AR 2673 in Hα ,photo by the author.



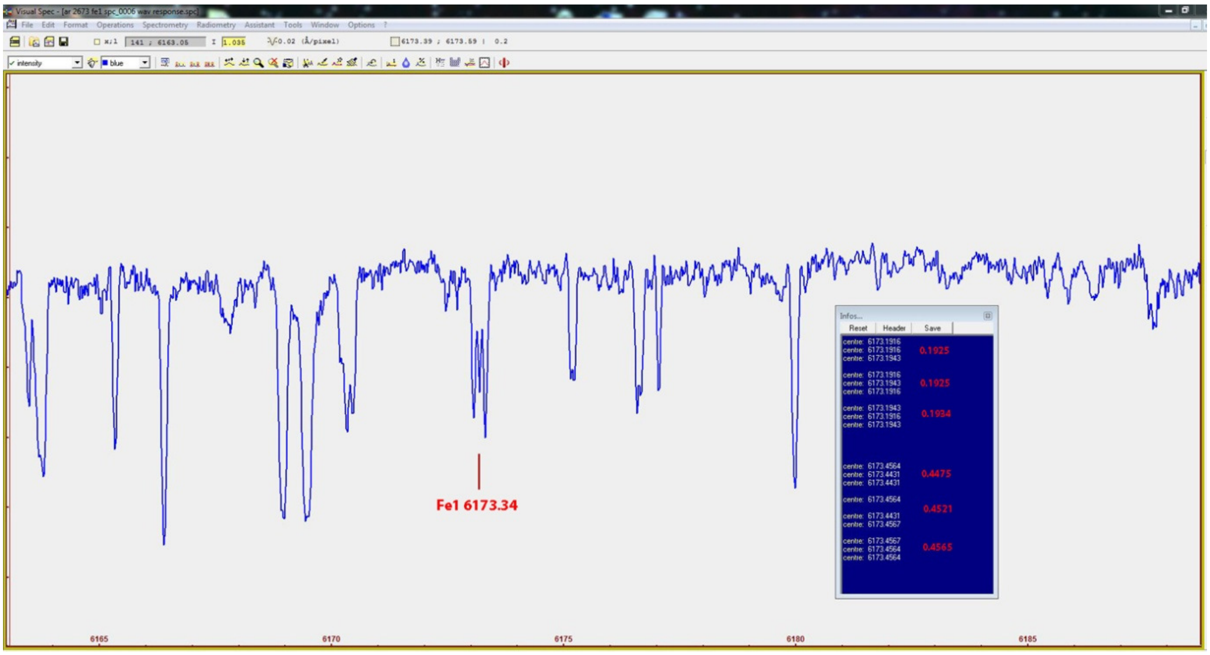
The spectral line chosen was FeI at 6173 Å. For the acquisition of the videos, a DMK 41 camera was used, with 1280 x 1024 pixels, and the dispersion was 0.019 Å /pixel. The most intense central transversal line is the appearance of the central spot on the spectrum, while the thinnest lines above and below were the other spots in the group: The double orange line indicates the position of the binning, i.e. the area of the spectrum on which the measurement of the magnetic field was carried out.



Enlarged detail of the previous one, in which the Zeeman splitting into three distinct parts of the central spot (larger transversal line) and also that, of lower intensity, of the other spots of the group (smaller transversal lines) can be clearly seen.



The Visual Spec spectral profile used for the calculation of the magnetic field, in which clearly appear the three lines of the orthogonal Zeeman splitting of the Fe1 line at 6173 Å.



Below is the theoretical formula used to determine the magnetic field.

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

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

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

dove:

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

λ è la lunghezza d'onda della riga;
is the wavelenght of the line

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

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

c è la velocità della luce
is the speedy of light

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

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

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

For the line at 6173.34 Å with a Landè factor of 2.5 (values rounded to 1/100) the generic formula becomes:

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

In the specific case of our example, where Δλ = 0.1296, it become:

(0.1296 x 10^13)/444935733 = **2913 Gauss**

The statistical error

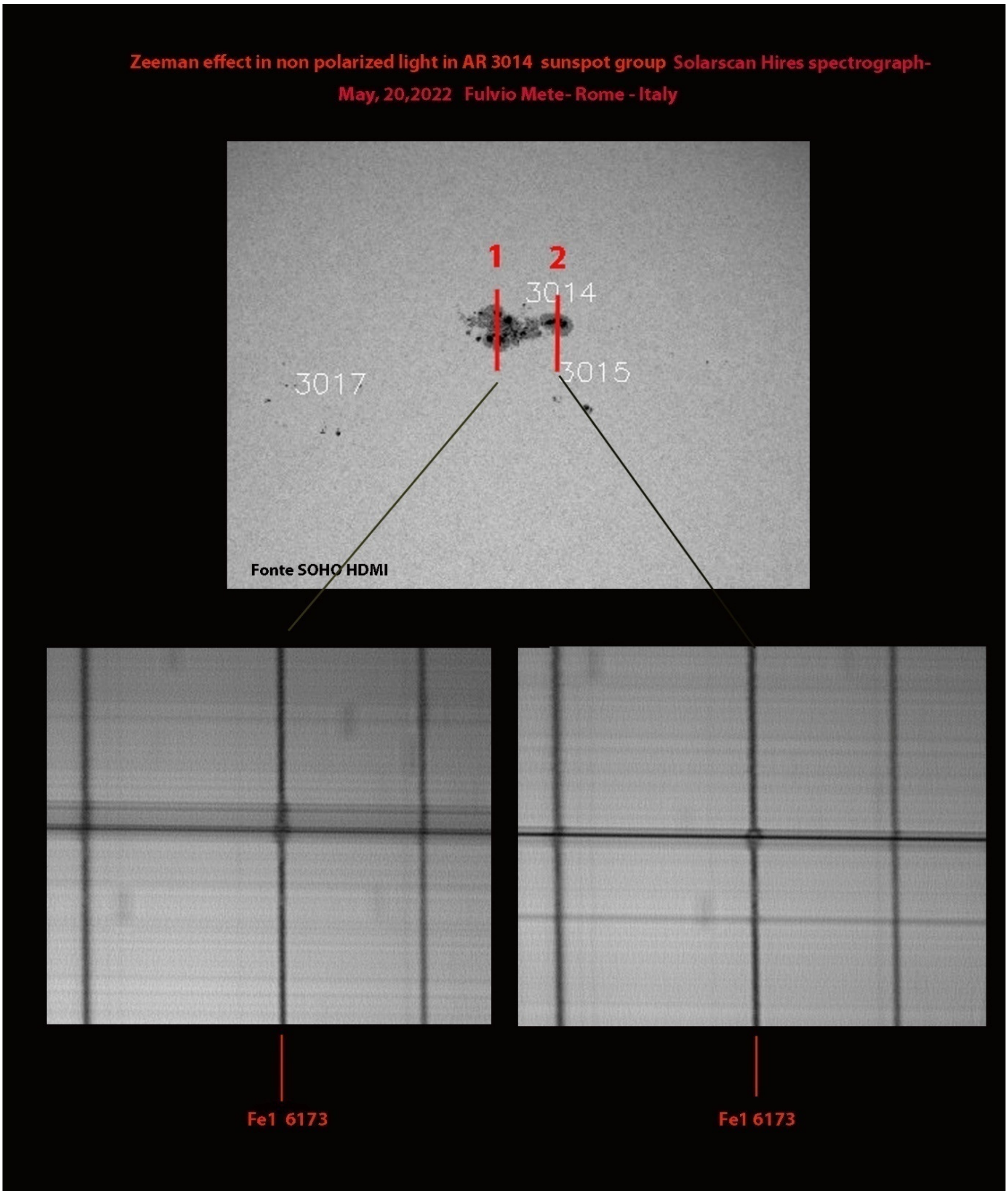
(0.002 x 10 ^13) /444935733 = **45 Gauss**

So finally the magnetic field of the spot in our example is calculated as:

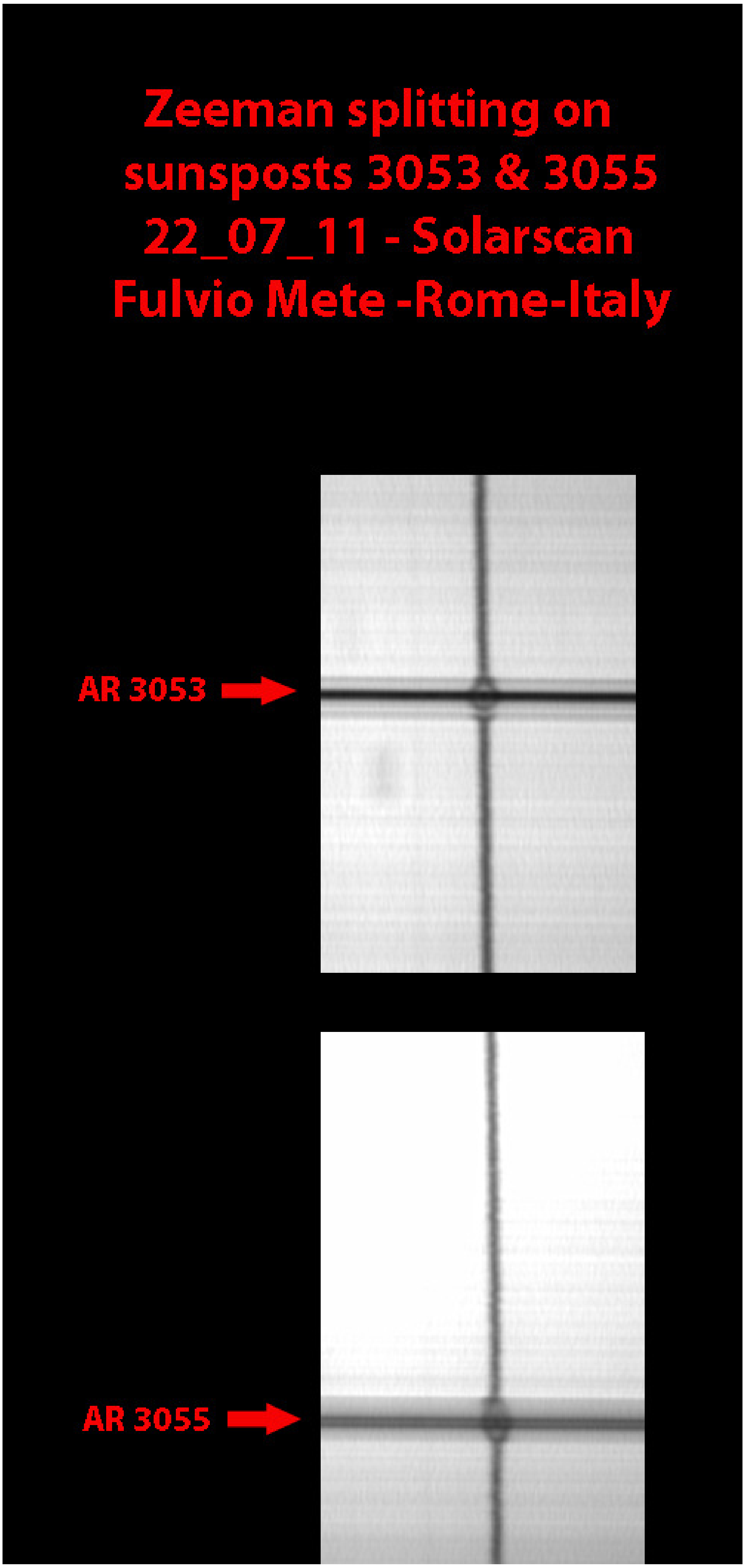
2913 +- 45 Gauss *

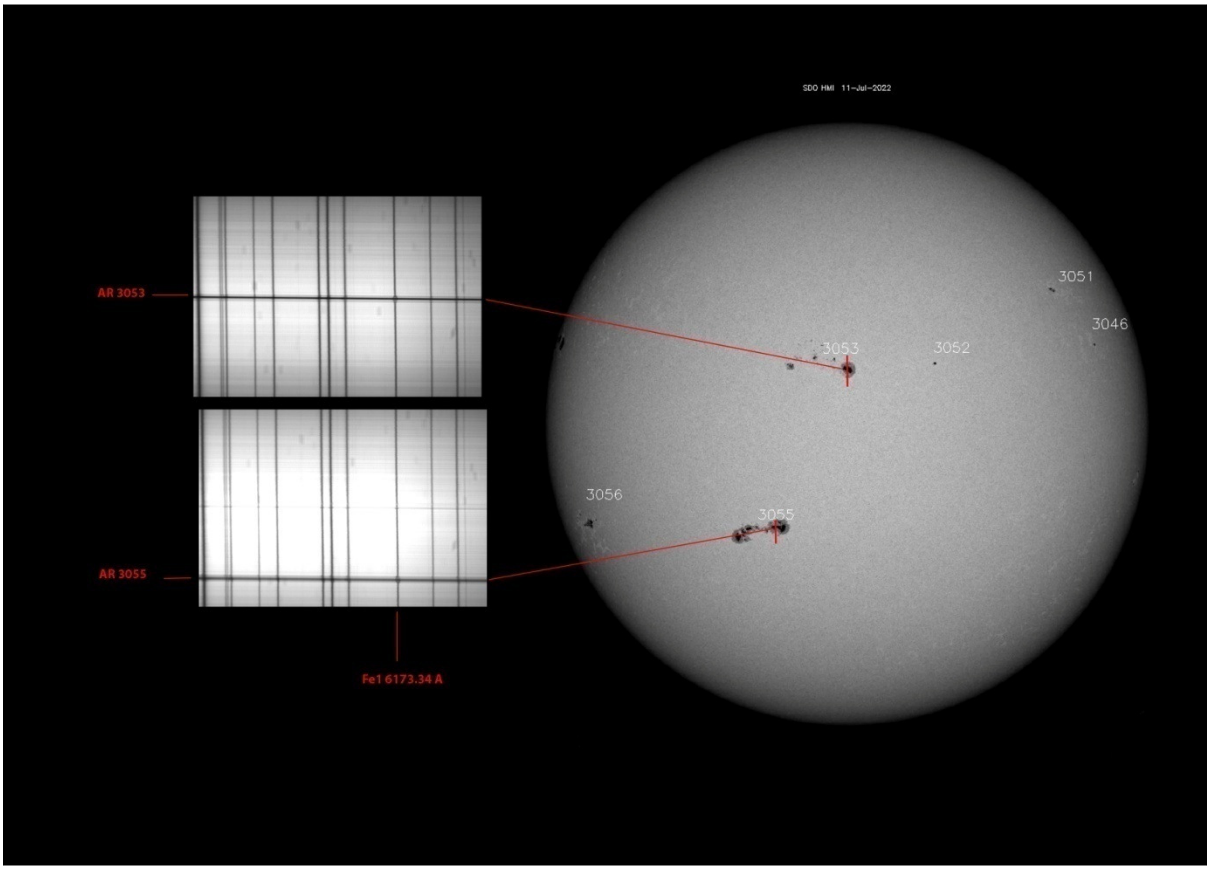
Some recent examples

The following images show the Zeeman splitting of AR 3014 on May 20 2022 and that of AR 3053 and 3055 on July 11 2022.



Zeeman effect in non polarized light in AR 3014 sunspot group Solarscan Hires spectrograph-
May, 20,2022 Fulvio Mete- Rome - Italy
1
2
3014
3015
3017
Fonte SOHO HDMI
Fe1 6173
Fe1 6173


Zeeman splitting on
sunsposts 3053 & 3055
22_07_11 - Solarscan
Fulvio Mete -Rome-Italy
AR 3053
AR 3055



The Solarscan, as currently configured, allows the spots above approximately 1500 Gauss to be measured with distinct splitting and not just showing the simple thickening of the lines. It is nevertheless a powerful means of investigation and allows observations once the domain of solar Towers such as that of the Rome Observatory, which carried out this task of measuring the magnetic fields of sunspots in the 1960s and 70s in tandem with Mount Wilson.

For details on the operational methods of measurement work, also see the article by the author on the website lightfrominfinity.org at the link:

http://www.lightfrominfinity.org/Osservazioni%20Zeeman%20del%202017/Le%20observations%20Zeeman%20del%202017.pdf

Conclusions

We have reached the end of this new edition on solar observations with digital spectroheliography, and once again we have seen the unexpected and surprising possibilities of instruments built with unsophisticated means, but with a great desire to succeed and enthusiasm.

In a word, on a small balcony or terrace of your home, we can imagine having installed a 20 or 30 metre solar tower thanks to which the Sun, our star, is observed and examined minutely in all its most hidden aspects with common video cameras within reach of all pockets and thanks to some sophisticated freeware programs. It is a further demonstration of how the progress of information technology has profoundly affected our existence, making the unimaginable possible in not just a few decades, but even a few years ago.

I would like to conclude with a greeting to all the amateur astronomers from all the countries who have started and continue to fuel the passion for spectroheliography, thanks to those who have made sophisticated image construction programs available free of charge, and best wishes to everyone those who here in Italy or elsewhere want to put their skills at the service of this branch of Astronomy.

Rome, May, 22 2024

Acknowledgments

A special thanks to Ken Harrison for his careful and precise work in translating this book into English

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