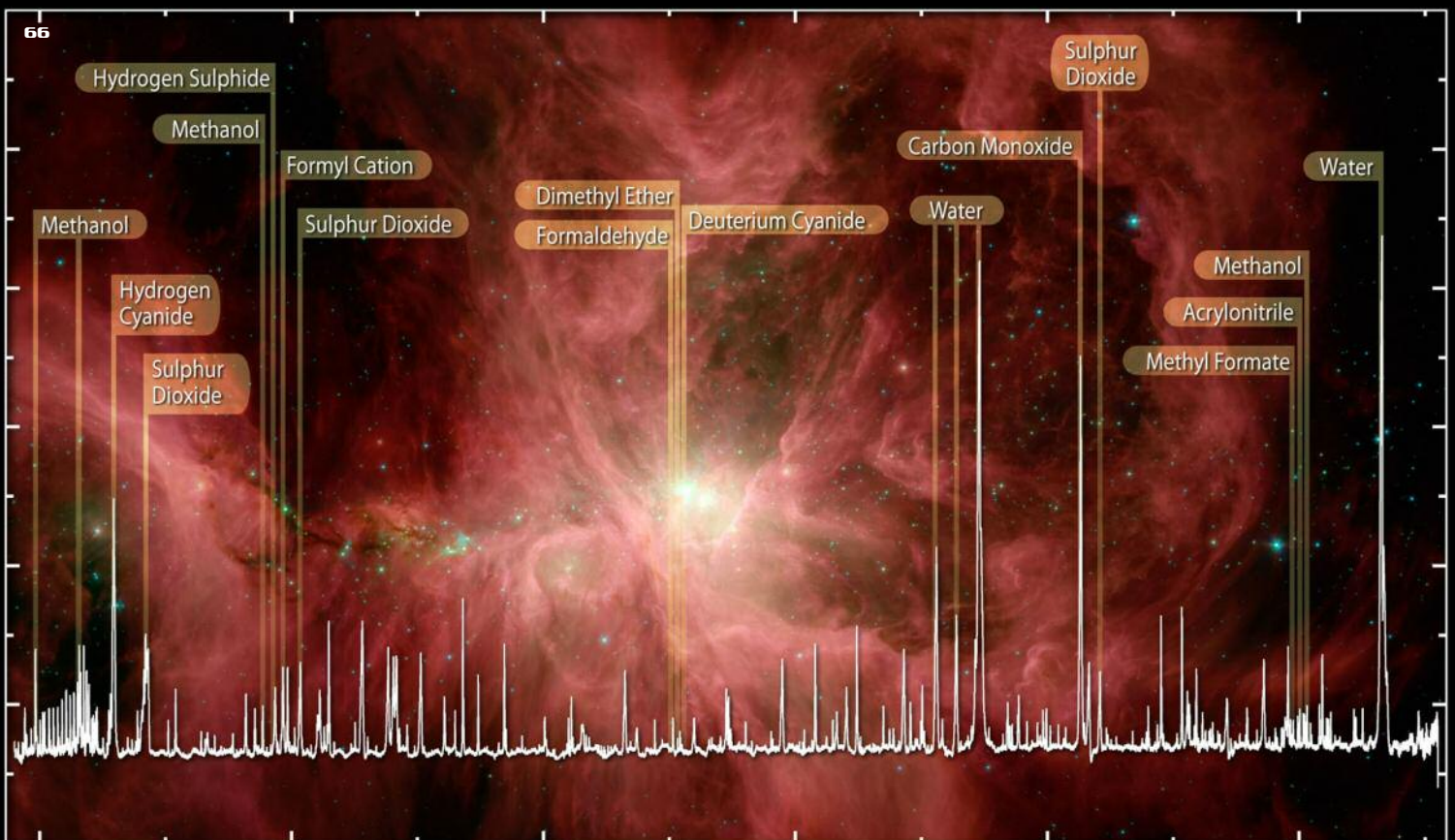


Experiments with amateur spectroscopy



Infrared spectral lines in the Orion nebula recorded by the HIFI instrument on the Herschel space observatory last March. [ESA, HEXOS, HIFI consortium]

You certainly can't get to the cutting edge represented by the picture on the previous page, but even spectroscopy at an amateur level can lead to scientifically valid results. This article shows how.

The pages of *l'Astrofilo* have already seen a good article by Chiara Riedo on astronomical applications of a home made spectrograph. Here we will try to show that an amateur astronomer can obtain useful scientific results with a spectrograph designed and built at home, without having to spend a fortune on a professional instrument. A spectrograph is an optical instrument capable of forming a coloured spectrum

by separating light according to its wavelength. A wide range of light sources can be studied, such as an incandescent solid, a candle flame, the glare of the Sun, a star, a nebula or a comet (to name but a few).

Each colour in the spectrum corresponds to a well defined wavelength. The light from a normal incandescent light bulb gives a "continuous" spectrum in which the colours merge together smoothly, while for other bodies (including many astronomical sources) the continuous spectrum is interrupted by dark lines, more or less pronounced, as if at those wavelengths the light were absent or strongly attenuated. In other cases, instead of dark lines, bright lines appear. The modest power of the telescopes of most amateurs has always been the main barrier to the spread of interest in spectroscopy, accept of course for solar spectroscopy.

Today, however, with the availability of very sensitive detectors based on CCD and CMOS technology, an interesting project in stellar spectroscopy can be carried out even with small telescopes of around 10 centimetres diameter.

The construction of a perfectly functional spectrograph is within the reach of a "serious" amateur: the cost is modest and



External view of the spectrograph built by Vittorio Lovato for the 500mm f/8 Ritchey-Chrétien telescope at the Libbiano Astronomy Centre.

the construction challenges are considerably less than those involved in building a telescope (especially from the mechanical point of view). The main difficulty, if anything, is getting hold of a good plan to follow.

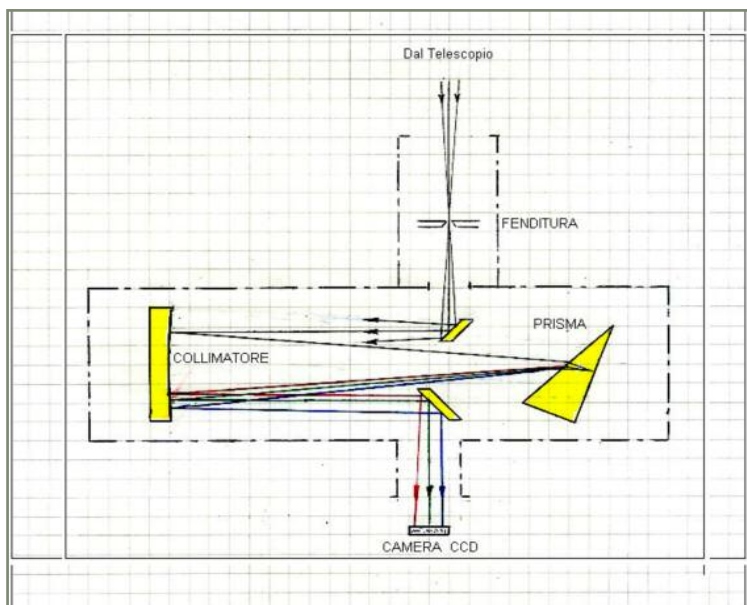
The project and the building of the spectroscope

Our spectroscope, that uses a retro-reflecting Littrow quartz prism as the dispersing element, was intended to be used with the 500mm (f/8) Ritchey-Chrétien telescope at the Libbiano Astronomy Centre (near Pisa, Italy) that is managed by the Alta Valdera Amateur Astronomy Association.

Quartz is used because it is transparent to UV radiation, unlike glass. To avoid the attenuating effects of glass at these wa-

rays that arrive at the prism are "collimated", that is, parallel. The prism refracts and reflects back the light beam, now separated into its various wavelengths, each of which, still made up of parallel rays, illuminates the other half of the collimator. This, in turn, focuses the rays onto the sensor, and it is here that the spectrum is formed.

The spectrum is made up of a continuous succession of images of the slit in the various colours. With this picture in mind it is relatively intuitive that the narrower the slit the greater ability to discriminate



Schematic diagram of the catadioptric, auto-collimating configuration.

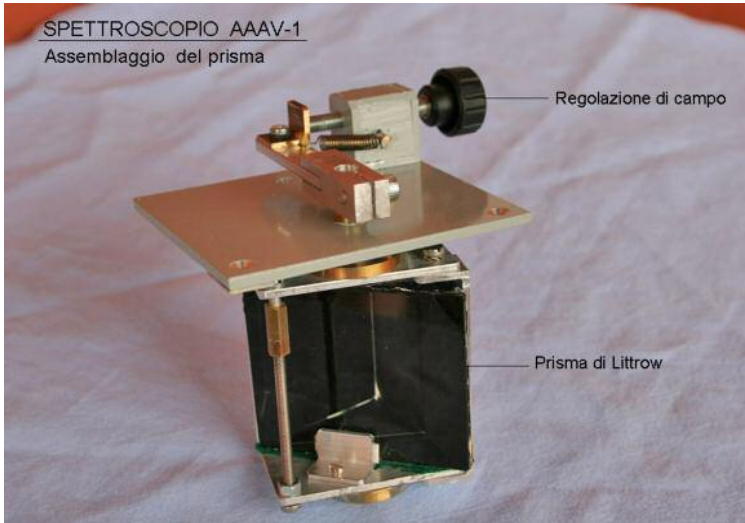
between adjacent wavelengths (the resolving power).

The resolving power of the instrument depends on the size of the diffraction disk of the stellar image. For the telescope in use this is theoretically very small (about 10 μm) but in practice atmospheric turbulence makes it much larger, even by a factor

of 10. The size of the pixels of the sensor also effect the resolving power if they are larger than the slit aperture. The prism used in the spectroscope has a refraction angle of 31.5 degrees and a base of 32mm; the entrance face measures 50x60mm and makes an angle of 42 degrees with the optical axis. The fact that the light beam makes a return trip through the prism means that both the dispersion and the resolving power are doubled. This kind of prism can distinguish two spectral lines separated by 0.6 \AA in the UV-blue and by 4 \AA in the red. The mean reciprocal dispersion is about 200 $\text{\AA}/\text{mm}$ at the focal plane (2 $\text{\AA}/\text{pixel}$

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The Littrow prism in its mounting with the field adjustment knob.

with 10 μm pixels), bearing in mind that the dispersion of a prism is greater in the blue than in the red.

The prism is mounted on a rotating support resting on a needle pivot attached to the base of the spectroscope housing. A device, visible in the above photo, allows the angle of incidence of the prism to be varied externally, allowing the full length of the spectrum to pass over the sensor.

The collimator is a 60mm diameter spherical mirror with a focal length of 200mm (photo below). The focal ratio ($f/3.3$) is



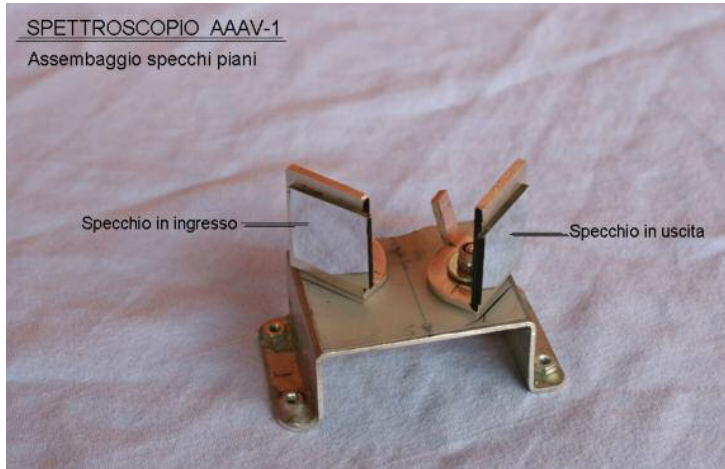
The spherical collimator mirror mounted on its slider, essential for micro-focusing.

faster than the telescope ($f/8$), a rule that all autocollimating spectrographs must obey to obtain maximum efficiency. Lastly, there are two flat rectangular (but elliptical ones would work fine) deviation mirrors (top of next page), one at the entrance and one at the exit of the optical path.

As far as the slit is concerned, although not strictly necessary in the case of stars, it is useful to counter the loss of resolution when the seeing is bad. For the Sun, planets or any other extended object, on the other hand, the slit is indispensable. Our spectrograph has a slit of variable width, bought on the optical surplus market in the USA at a relatively low cost, and is of excellent quality. Its very small size means that it was possible to place it in the 2" mount that connects to the telescope, and it can be varied from the outside (bottom of next page). This is a very robust and compact assembly. Opposite the slit is a 4mm micro prism about half as high as the slit, that allows the light of a reference light source (fluorescent lamp) to enter the slit parallel to the radiation from the source. In this way

it is both possible to compare the spectrum of the object with that of a known source and to note the locations of spectral lines of known wavelength. This is essential for the analysis of the recorded spectra.

All of the above is mounted in a housing made from 1.5mm aluminium plate bent into a U-shape along its length. On the open side the container is strengthened with a small aluminium frame which also serves as support for the 3mm plywood inspec-



The two plane mirrors placed at the entrance and exit of the spectrograph, used to deflect light beams by 90 degrees.

Preparation for a typical night of observations with the spectrograph

We should point out that when using the 500mm Ritchey-Chrétien

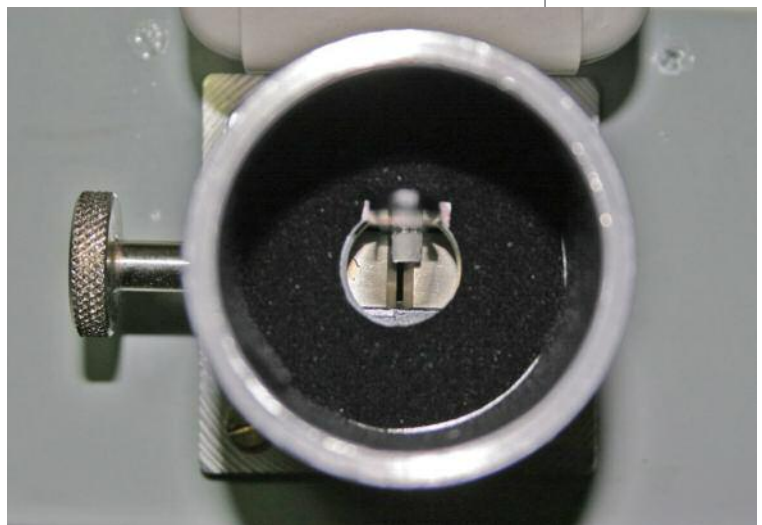
tion panel. The two ends are closed with 3mm plywood. The weight of the whole instrument is 1.2 kg.

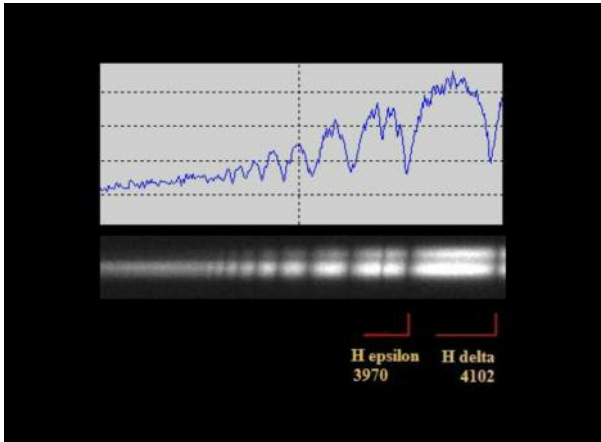
As we said, the spectrograph was designed for a 500mm diameter f/8 telescope but it can be used on telescopes with a similar optical design even if the aperture is different. It can also be used on refractors as long as they are not faster than f/6.6. For other telescopes either a larger collimator can be used or one accepts a loss of efficiency. The CCD camera normally used is a Starlight Express with 1.25" (31.8mm) mount but other CCD cameras (and CMOS sensors) can be used.

One of the possible modifications of the spectrograph would be to replace the Littrow prism with an equilateral triangle prism (with 60 degree refraction angle). In this case it is necessary to add a flat reflector mirror after the prism. The rest stays the same. The resulting instrument would have double the resolving power and dispersion of the version with the Littrow prism. All of the optical components used in the construction are available in the USA at the SurplusShed at very reasonable prices (www.SurplusShed.com).

The slit, with its external fine adjustment knob. In front of the slit is the micro-prism which allows light from a reference source to enter the instrument.

at Libbiano the use of the slit is essential even for stellar spectra. This is for two reasons. The first is that with a focal length of 4 metres, even with atmospheric turbulence at a minimum, the stellar source cannot be point-like. The use of a slit is the only way to maintain the high resolution of the spectrum. The second is that with a very narrow slit, even significant guiding errors do not result in "confused" spectral lines. However, a narrow slit does imply longer integration times. For the spectrograph to work the slit must be placed simultaneously at the focus of the telescope and the collimator (the second criterion is achieved in the





A segment of the spectrum of Denebola (spectral class A3) with the lines of H-delta and H-epsilon indicated. The many other hydrogen lines visible in the spectrum were used to make a kind of "standard ruler", against which to compare other sources.

For subsequent data processing it is very important that the CCD is oriented in such a way that the spectral lines are parallel to the vertical edges of the frame.

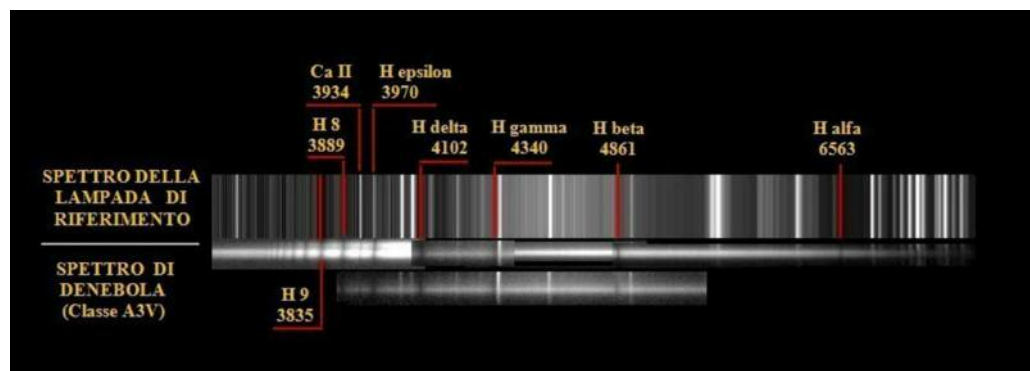
To line-up the slit with the focus of the R-C we obviously have to attach the spectrograph to the telescope, and be sure that the telescope is in turn well aligned with the guide scope. In this way we can centre a "target" star in the guide scope and be sure that it falls on the spectrograph slit (now completely open at this stage).

construction of the spectrograph, although tiny adjustments can be made). The focusing of the slit on the CCD sensor is something that is done only once. After having mounted the CCD on the spectrograph, the reference source incorporated in the instrument is illuminated (a fluorescent lamp producing emission lines of known frequency that we can turn on and off as needed). Care must be taken to set the adjustment knob so as to centre the brightest part of

Once sure that the CCD "sees" the stellar spectrum we close the slit as much as possible, finding the best compromise between integration time and resolution, taking care to keep the spectrum on the sensor. The spectrum is in focus when, using the electric focuser (software Robofocus), its image is at its narrowest. This point is found iteratively by alternately adjusting the focus and taking images.

If we use a bright star with strong hydro-

The spectrum of the reference lamp (top, with the Balmer series of hydrogen labeled) alongside the spectrum of Denebola (bottom).



the lamp spectrum (the yellow/green region that also has strong lines) on the sensor.

Taking images of the spectrum with the slit only just open (using the Maxim DL software) one adjusts the spectrograph's focusing knob until the emission lines from the lamp are as narrow as possible. This ensures that the image of the slit is in focus on the sensor.

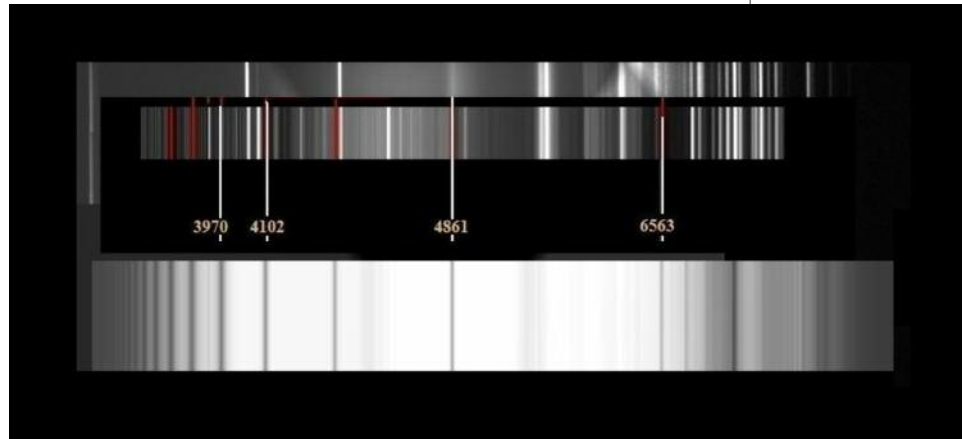
gen lines for this operation, we can work with very narrow slits (15-20 μm) and the resulting focus is more precise. After this phase is completed the spectrograph is ready for a night's work.

In order to avoid problems due to guiding errors it is important that the spectrograph be mounted on the telescope so that the slit is parallel to the motion in right ascension. Thanks to the accurate

polar alignment of our telescope the star doesn't drift in declination (at least for reasonable integration times), and any small errors in right ascension just cause movement along the slit, so the spectrum is always visible.

spectra integration times vary between a few seconds with a slit of 15-20 μm for the brightest stars, to 90 seconds with a 50 μm slit for the 9th magnitude nova V2491 Cygni. Exposure times are longer for faint extended objects for which the

The spectrum of Sirius (bottom) and the reference lamp (top) compared to our "standard ruler" (middle). The standard ruler is simply the spectrum of the reference lamp with the Balmer lines added in the correct locations. As can be seen, the indicated Balmer lines line-up perfectly with the lines in the spectrum of Sirius.



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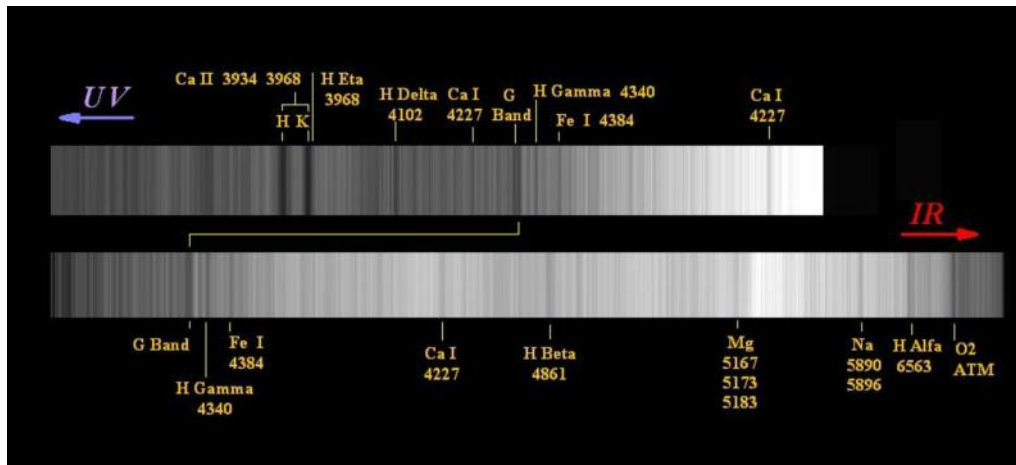
Imaging and composition of the spectra

Once the instrument is prepared the recording of the spectrum is fairly straightforward. At this point it's necessary to find the right compromise between integration time and slit width for the magnitude of the target.

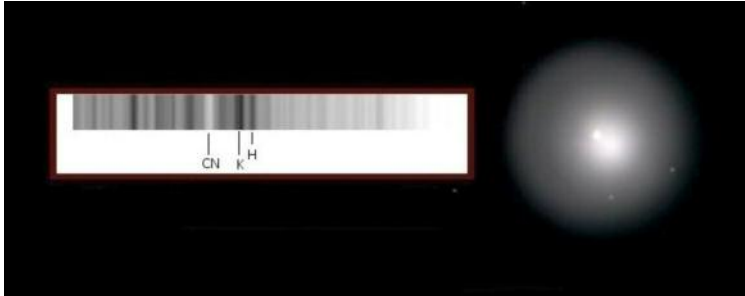
The narrower the slit the more the spectral lines appear sharp and narrow. Experience to date shows that for stellar

use of the slit is essential. Guiding problems have only presented themselves in attempting to observe a comet, due to the proper motion, which in the case of Lulin, was very fast.

To keep the cometary nucleus in the slit during the integration we fitted the 180mm APO guide scope with a 40mm illuminated reticle eyepiece. This allows visual guiding corrections to be made even with faint objects like Lulin. After having centred a bright star in the slit



Spectrum of the Moon (reflected Sun light) obtained on 27th October 2007.



The spectrum of comet 17/P Holmes showing cyanogen (CN) emission lines. On the right is an image of the comet.

that we do in Photoshop.

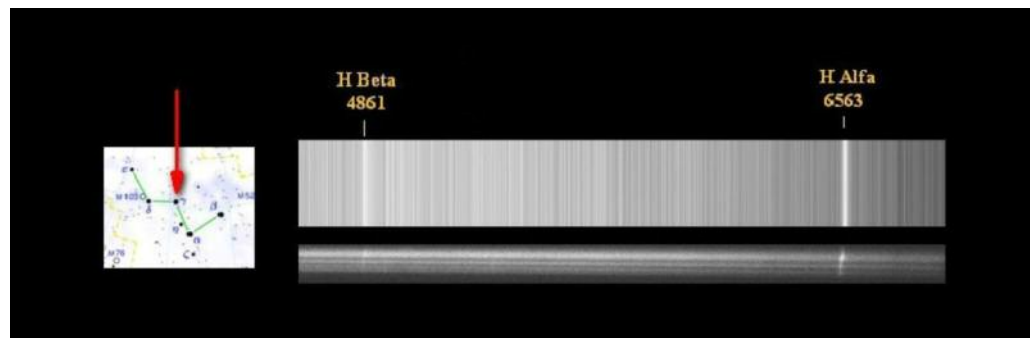
To make the most of the spectrograph, however, we need to be able to determine the wavelength of unknown lines, such as those in a comet spectrum, for example.

we centred the illuminated reticle in the guide scope eyepiece on this star. We then pointed the telescope at comet Lulin so as to centre it on the reticle. We therefore found the nucleus perfectly positioned on the spectrograph slit, opened to 120 μm .

The prism spectrograph described here is (by choice) a moderate dispersion instrument, that with a 4 metre focal length telescope produces a spectrum longer than the sensor. To cover the

At this point we must bear in mind that the prism produces a spectrum with a non-linear distribution of wavelengths. Going from red to violet the same number of Ångströms occupies an ever larger segment of the spectrum. Therefore, we built a kind of "standard ruler" by taking the spectrum of Denebola at the same time as that of the reference lamp. We then marked on the reference spectrum the positions of various hydrogen lines easily visible in the spectrum of Dene-

Spectrum of γ Cas with its characteristic emission lines.



whole spectrum, from the violet to the red, 4 images must be taken, of which the first and last are recognisable because they show extinction towards the shortest (ultraviolet) and longest (infrared) wavelengths.

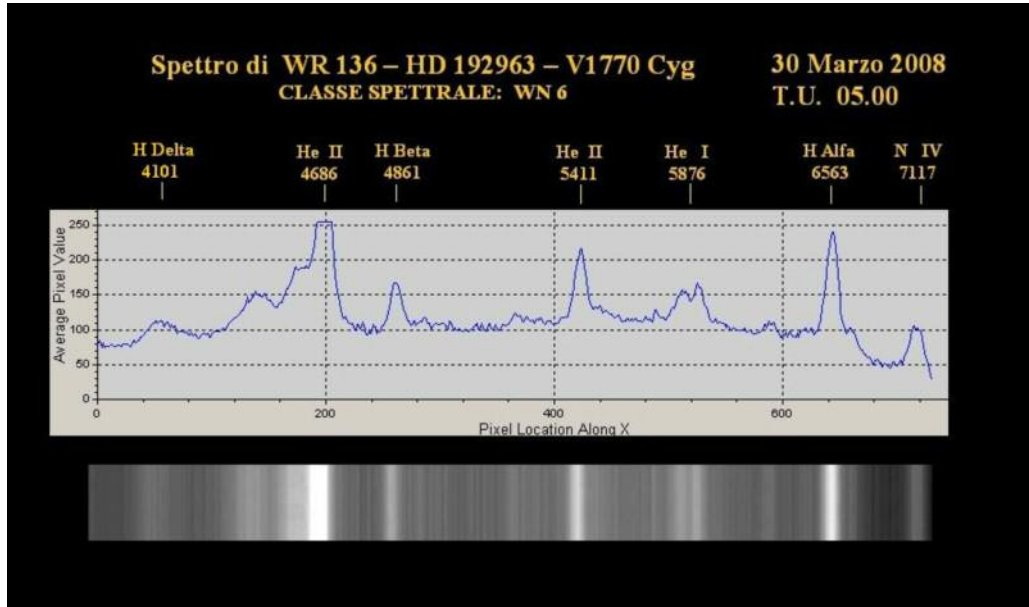
To construct the whole spectrum we must therefore "assemble" the 4 partial images, and it is here that the built-in reference source comes in very useful. The CCD imaging is controlled via Maxim DL, that automatically saves the images in FITS format. Once the frames to be analysed are selected, we transform them into JPEG format, which is easiest for the subsequent reduction

bola (see page 71). This ruler could then be used by removing the spectrum of Denebola and putting that of another source in its place. To test to see if the method worked we used the spectrum of Sirius, and found, with satisfaction, that the hydrogen lines on the ruler lined up perfectly with those in the stellar spectrum (top of page 72).

Some of the spectra obtained

The first test of the spectrograph was on 27th October 2007. The presence of the Moon allowed us to find the correct focus for the spectrograph on the

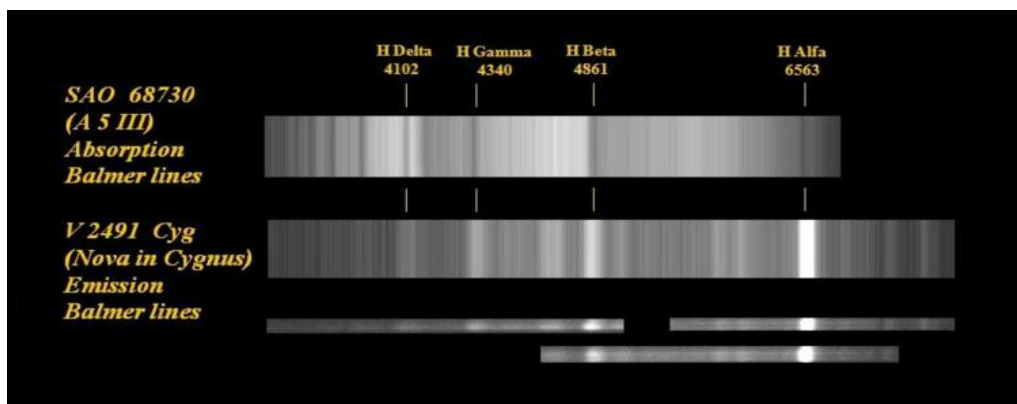
Spectrum of the Wolf-Rayet star WR 136 taken on 29th March 2008. The emission lines characteristic of this type of star can be clearly seen.



500mm telescope. The lunar spectrum (bottom of page 72) is the result of the assembly of 7 partial integrations, executed with Maxim DL and reduced with Photoshop.

Some characteristic solar lines and some atmospheric lines are marked. The same evening the spectrograph was pointed at comet 17/P Holmes, that had been visible by the naked eye for only a few days thanks to an outburst in its nucleus. Comets reflect sunlight and so their spectra show the main solar absorption lines, like the K and H lines of carbon, clearly visible in Holmes. More interesting, instead, are the emission lines, connected with activity in the cometary nucleus. The CN (cyanide) line is very clear in the

graph we took another spectrum of the comet the night after. Using Maxim DL we superposed the spectra from the two nights and found that they overlapped perfectly. This assured us that the final spectrum obtained was truly that produced by the spectrograph and that it hadn't been altered by subsequent image analysis. The same night we took the spectrum of a peculiar object, Gamma Cassiopeiae, a giant blue variable classified as a



Holmes spectrum as can be seen in the figure at the top of the previous page. To check the reliability of the spectro-

"shell star". Due to its rapid rotation this star throws off rings of gas at irregular intervals that causes its brightness to

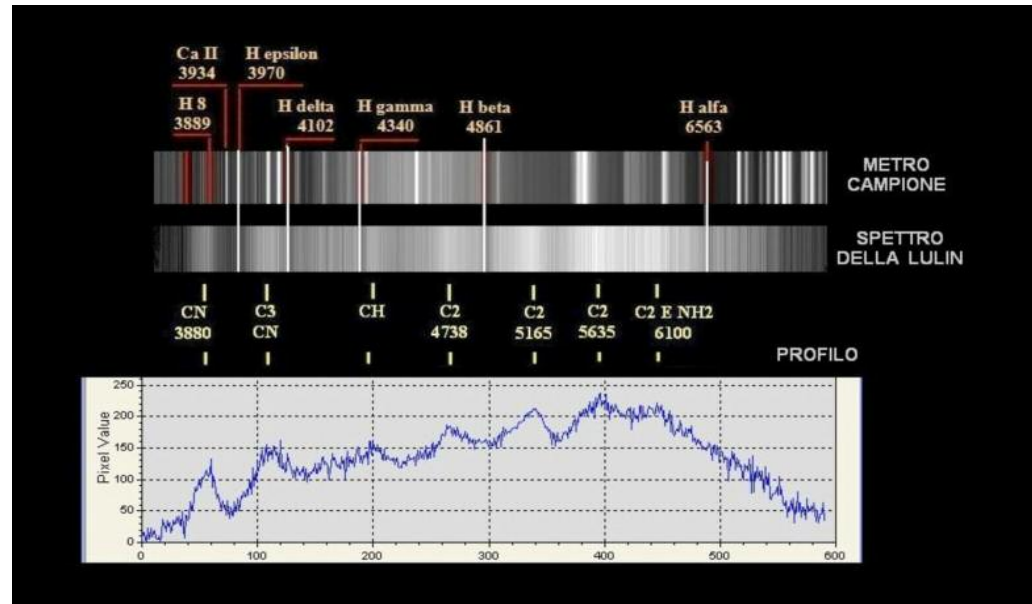
Spectrum of the nova V2491 Cyg. The lines of the Balmer series in emission coincide exactly with the same lines in absorption in the nearby star SAO 68730, spectral class A5 III.

Final reduction of the spectrum of comet Lulin, taken on 26th February 2009. The spectrum and its profile, made with Maxim DL, identify the various molecules present in the comet (CN, C₃, CH, C₂ e NH₂) at the relative frequencies.

vary between magnitude 3.0 and 2.15. The expulsion of gas explains the emission lines characteristic of this type of star (spectral class B0.5 IV e). Particularly evident in the spectrum on page 73

perfectly with that in emission of the nova (page 74, bottom).

Perhaps the most satisfying spectrum is that we obtained in February 2009 of comet C/2007 N3 Lulin. In this case we



(bottom) are the H- α and H- β lines of hydrogen.

One of the most interesting observations was made on 29th March 2008 of the magnitude 7.5 Wolf-Rayet star WR136. This lies in the nebula NGC 6888 in Cygnus. Wolf-Rayet stars are blue, as hot as O-stars, but show strong emission lines (from hot, dense gas jets emitted from the star and carried outward by a very powerful stellar wind) clearly visible in the spectrum on page 74 (top).

On 15th April 2008 we recorded another interesting phenomenon: the nova V2491, that had appeared a few days earlier in Cygnus. The nova explosion violently compresses the stellar atmosphere generating strong hydrogen emission lines.

By taking the spectrum of the nearby star SAO 68730 (spectral class A5 III) and placing it alongside that of the nova it can clearly be seen how the Balmer series in absorption of the star coincides

used our "standard ruler" and a freely available program (Visual Spec) to correctly identify the principal molecules from which the comet is made (see above).

Vittorio Lovato, honorary president of the astronomical society of Voghera and associate member of the Astronomical Association of Alta Valdera (both in Italy), is mainly involved with the design and construction of instruments for amateur astronomers. Recently he has been especially involved with the construction of spectrographs.

Alberto Villa is president of the Astronomical Association of Alta Valdera (Italy) where he is head of the spectroscopy, eclipses and extra-solar planet sections. He observes at the "G. Galilei" Observatory in Libbiano (Pisa).