Publ. Astron. Obs. Belgrade No. 74 (2002), 1 - 2 *Invited lecture*

SOLAR OPTICAL SPECTROSCOPY IN THE ONDŘEJOV OBSERVATORY

P. KOTRČ

Astronomical Institute, v.v.i., Academy of
Sciences, Fričova 298, Ondřejov, Czech Republic
E–mail pkotrc@asu.cas.cz

Abstract. Solar astrophysics based on observations and spectroscopic methods was implemented in the Astronomical Institute of the Academy of Sciences in Ondřejov in the middle of 1950's. First, the solar patrol service started to use spectrohelioscope for detection of flares and for measurement of the Hα line width during flares. Then, the Multichannel Flare Spectrograph with an unique construction was put into operation in 1958 and was used for detection of photographic spectra in several diagnostically important lines simultaneously for more than 2 solar cycles. A prototype of large horizontal spectrograph (Czerny-Turner type) was build in 1960' and was mainly used for measurements of solar magnetic and velocity fields. Since 1980's two new horizontal solar telescopes with spectrographs were developed and delivered by Carl Zeiss Company are used in the Ondřejov Observatory. Physical properties and parameters of solar flare and prominence plasma based on spectral observations and computer modelling began to be studied intensively. Recently, the two spectrographs were modernized as concerns their optics, controlling electronics and detectors. Spectra of solar active phenomena obtained with a high spectral and temporal resolution are used together with data from space experiments to understand better some specific tasks of solar physics. The contribution briefly describes both historical an contemporary instrumental spectroscopic facilities as well as some important results obtained using the solar optical spectral observations at Ondřejov.

1. A BRIEF HISTORY

Astronomical Institute of the Academy of Sciences in Ondřejov near Prague follows a very long tradition. Astronomy has been taught as one of the main subjects at Charles University from its very beginning in 1348. Among the distinguished scientists of the older periods, Thadeaus Hagecius (Tadeáš Hájek), Tycho Brahe, Johannes Kepler, Christian Doppler and even Albert Einstein worked on astronomical subjects in Prague. The Ondřejov Observatory itself (Location: 50 N, 15 E, altitude 528-546 m above sea level, 35 km SE to Prague center, 5 km E to D1 Highway Exit 20) was founded as a private observatory by brothers Josef and Jan Frič in 1898 and it become to be world-known since the beginning by designing and using perfect astronomical-geodetic instruments which were listed among the most precise instruments in the world. In 1928 Josef Frič dedicated the Observatory to the Czechoslovak Republic.

Figure 1. Old part of the Ondřejov Observatory is located on a hill. A view from the air.

A real major development of the Ondřejov Observatory began in 1952 after it become a part of Astronomical Institute of the just created Czechoslovak Academy of Sciences. Besides of traditional astronomical disciplines as astrometry, study of ionosphere and interplanetary matter, stellar astronomy and astrophysics, a new branch - solar research has been implemented. Systematic observations of the Sun in optical and radio bands as well as statistical studies on solar activity phenomena were performed aiming and determining the solar effects on the Earth. Later on spectroscopic studies started in order to determine the physical substance of processes in the Sun. Observatory disposed also a medium-size double solar telescope (photosphere and chromosphere) and a solar coronagraph for prominence observations. In the end of 1969 solar research from artificial satellites, especially solar X-ray photometry started.

For a more detailed site explanation see Figure 1, where besides the historical astronomical domes the solar facilities (painted white) can be found. To the right is the pavilion of the first horizontal solar spectrograph (now museum of V. Šafařík) behind it the spectro-helioscopes were located (see the round white-painted shelter covering the coelostat). The large house in the background is the Solar Department building from 1954, now with a solar patrol dome on the roof. At the building southern end is the coelostat tower for feeding the Multichannel Flare Spectrograph (see the large front wall without windows on the second floor). The solar prominence coronagraph was located in one of the small observing houses with the sliding roof in the central bottom part of the slide.

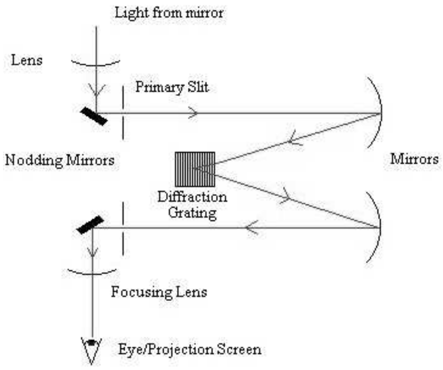

Figure 2. Optical schema of the spectroheliocope.

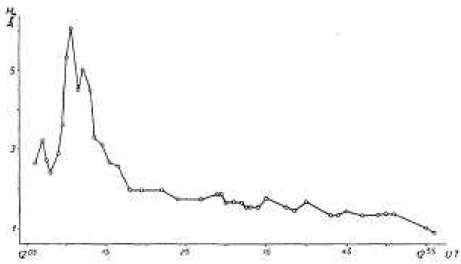

Figure 3. Measurements of the effective Hα line width in a flare with the spectrohelioscope.

The oldest solar optical spectroscopic observations at the Ondřejov observatory were performed in 1939 when Dr. B. Šternberk dismounted a Hale-type spectrohelioscop in Stará Ďala in Slovakia (now Hurbanovo). In difficult conditions of the beginning of the WWII he was able to pack the device, transport it to Ondřejov located the remnant of the former Czechoslovakia and start to explore it in a provisory pavilion at the old observatory hill. The spectrohelioscop had two prisms, a Mt Wilson-type grating with 600 groves/mm and a line-shifter, for the optical schema see Figure 2. It was fed by Φ8/f600 cm refractor. Since the year of 1948, after a decade of rather sporadic utilization, systematic spectrohelioscopic observations of solar chromosphere in the Hα line, especially flares and prominences began. The device was used until 1963, then replaced by a new Hale-type spectrohelioscope already placed at a nearby builded more comfortable pavilion. Solar light for this spectrohelioscope was provided by a Jensch horizontal coelostat. Observations of the two simple spectroscopic devices were used for an eye-piece optical patrol of solar activity. As the width of Hα line in solar flares was systematically measured (see Fig. 3), lots of these data were used for classifications and statistical studies of flares and were published in scientific journals, mostly in the Bulletin of Astronomical Institute of Czechoslovakia. In 1970 observations with the spectrohelioscope were ceased and replaced by a medium-size solar patrol telescope equipped with a Šolc-type narrow band Hα filter.

2. MULTICHANNEL FLARE SPECTROGRAPH

The first solar optical spectrograph at the Ondřejov Observatory is dated 1958 when a Multichannel Flare Spectrograph (MFS) was installed, see Valníček et al. (1959). The feeding coelostat consisted of two flat mirrors (ϕ 360mm and 280mm). The telescope was a horizontal one with the main objective mirror of ϕ 230mm/f 1350mm. The light concentration of its grating (sized 90 x 100mm^2, 600 groves/mm) was directed into the second right order with resulting linear dispersion of 1Å/mm.

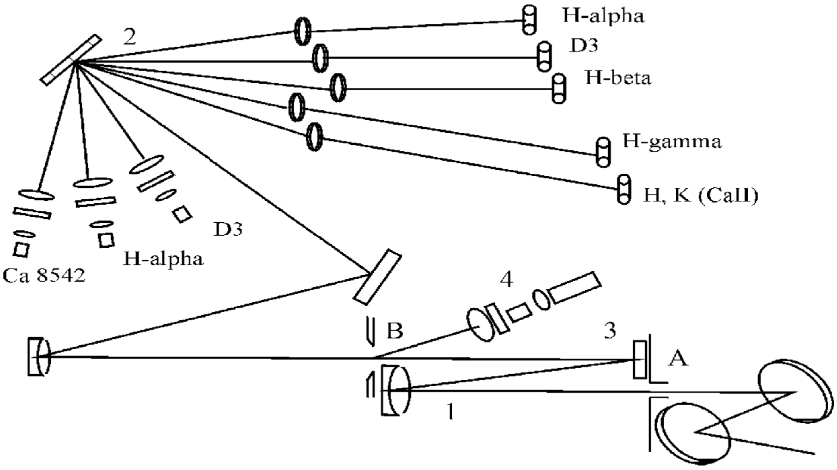

Figure 4. Optical schema of the Multichannel Flare Spectrograph. In addition to former photographic cameras and detectors (right up), 3 CCD video-cameras were lately used (left) and slit-jaw camera system was installed (marked as 4).

It was used for a simultaneous detection of spectra of solar flares and prominences on photographic plates sized 13 x 18 cm in spectral bands 120 Å wide around diagnostically important lines in the 2nd right-hand order: Hα (from 6503 to 6623 Å), D3 (5829 - 5949 Å, D-lines of Sodium & D3 of Helium), Hβ (4797 - 4917 Å), Hγ (4277 - 4397 Å & FeI, FeII, TiI multiplets), CaII H & K (3870 - 3990 Å, Hϵ, Hζ, H & K of CaII and lots of lines of Fe, Ti, Al, Si, He...) and in the third left-hand order with dispersion of 0.67 Å/mm the higher members of the Balmer series up to the Balmer limit (3640 - 3814 Å from H$_{10}$ to H$_{\infty}$ including multiplets of FeI, Ti II and Ca II). The device was modernized several times (in 1970's from electronic tubes to integrated circuits, in 1980's photographic plates were changed to 35 mm film strips, in 1990's first analog and then digital CCD video cameras were installed), see Kotrč (1993) and Kotrč (1997). Optical schema of the MFS can be seen in Figure 4. In the period of videocameras, images of the spectra in three lines and slit-jaw were taken simultaneously with cadency of 25 per second, see Figure 5.

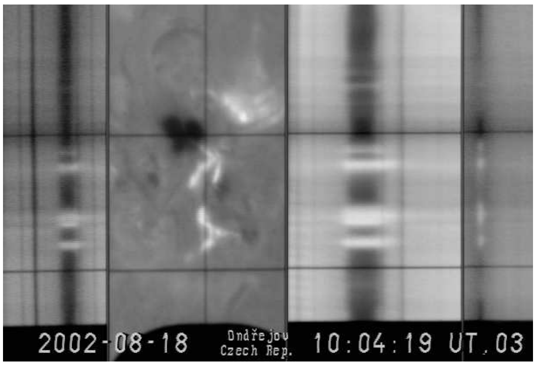

Figure 5. A MFS video-image consisting of Hβ spectrum, Hα slit-jaw image and Hα spectrum and CaII 8542 Å spectrum of flare kernels (from left to right).

Even the dynamical range of the digitized composed signal from the video cameras was 8 bits only, the main advantage of this kind of observation was the high temporal resolution, i.e. 25 frames per sec. We used this occasion for study of rapid processes in solar flares and eruptive prominences. However, as the MFS was located on the second floor of the rather busy solar department building (see Figure 1) and its stability was influenced by frequent vibrations of the sensitive optical system and by medium local seeing. Therefore it was continuously discussed to perform solar spectral observations using other Ondřejov facilities. As concerns the MFS, in 2004 it was reduced to a simple spectrograph for testing filters, cameras and new optical systems.

3. MFS SPECTRA - RESULTS

Photographic spectra observed in the first period of MFS (with photographic detectors) were analyzed and interesting results concerning physical parameters in flares and prominences were obtained. E.g. Blaha, Kopecký & Švestka (1962) performed analysis of 244 flare spectra from the point of view of the line asymmetry and shapes of various chemical species as helium and metals. Švestka and Fritzová-Švestková (1967) studied high Balmer series lines (H_{11} - H_{14}) and derived electron densities and other parameters in flares. Ruždjak (1981) analyzed the MFS spectra of flare loops to derive kinetic temperature, microturbulence and hydrogen density of the plasma falling in the loops. Heinzel et al. (1994) compared optical flare spectra from the MFS, radio data and hard X-rays and found an interesting explanation of the blue asymmetry in optical spectral lines. The interpretation was based on so called return current effect which influences the electron beam as well as the heating of atmosphere. The resulting downward plasma flows, together with non-LTE opacity effects, lead to a blue asymmetry in Balmer lines.

Karlický et al., (2001) used the MFS spectra to study large Doppler velocities in unique, almost regular elliptical features observed in the Hα spectra of the May 15, 2000 eruptive prominence. These features were interpreted in the frame of axially symmetric models of the eruptive prominence. The axially symmetric detwisting process of the magnetic flux rope of the eruptive prominence was recognized, see Figure 6. An easier interpretation of various symmetric structures in eruptive prominence spectra can be achieved with kinematic models of Havlíčková & Kotrč (2005).

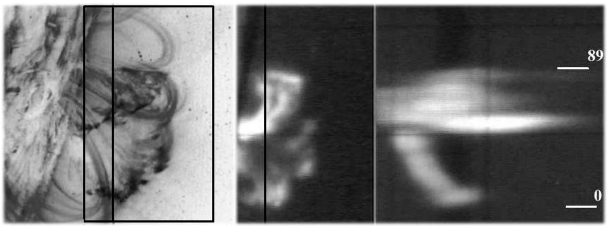

Figure 6. Eruptive prominence as studied in Hα slit-jaw image (center) and spectrum (right) taken at the MFS and combined with the EIT image (left).

The ratio of the Hα/Hβ line profiles was analyzed (Kashapova et al., 2008) as a diagnostic indicator of non-thermal particle effects in solar flares, see Figure 7. Differences between the Hα/Hβ profile ratio in the line center and at the distance of 0.5Å from the line center were studied in various phases of flares as concerns presence of responses to non-thermal effects. Variations of this parameter were compared with the HXR flux evolution for the 26 June 1999 and the 18 August 2002 solar flares. The sign of the parameter changed from negative to positive value only for these flare kernels where coincidence with the HXR sources indicated presence of accelerated particles. However, no such a change was found for the other kernels. The revealed effect was compared with information obtained from correlation between the temporal fluctuations of the Hα and Hβ line and the HXR flux. The obtained results seems to be important from point of view of their possible diagnostic applications.

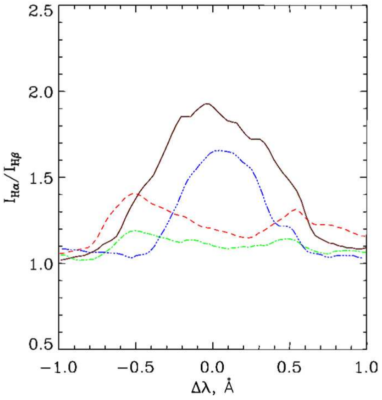

Figure 7. A ratio of Hα/Hβ profiles at various places of flare kernels. The "sidelobes" detected at some profiles (dashed lines) are considered as evidence of accelerated particles beam interaction with dense layers of solar atmosphere.

The studied rapid changes in the flare spectra are connected with superthermal particles, mainly the electrons accelerated in energetic processes. When magnetic field is reconnected in a solar flare, superthermal particles are decelerated in dense layers of the chromosphere and the surrounding plasma is heated. This results in an intensive radiation in chromospheric and transition region lines. As these processes are accompanied by plasma movements, Doppler shifts and various asymmetries of lines formed in this atmospheric layers are directly detected in the spectra. Therefore, either direct or undirect evidence of accelerated particles were considered and related solar flare optical spectra have been studied from these points of view. Having sufficient spectral, temporal and spatial resolution, some of these rapid processes in flares are also detectable in optical spectra. An undirect manifestation of the superthermal electrons and their role in solar flare has been detected by Heinzel et al. (1994).

The MFS observations from all its history, especially those of flares and eruptive prominences were used for study lots of another interesting topics as e.g. asymmetry of spectral line profiles and the related plasma flows in flares, damping and Stark effect studied from width and shape of higher Balmer series lines and the electron density deduced from it. Dynamics of plasma flows and rotational movements in eruptive prominences and chromospheric surges, as well as instrumental profiles and calibration procedures, etc. were intensively studied as can be seen from the list of literature hereafter. Even nowadays, both the photographic and the video archive of the MFS observations lasting until June 2004 are still a valuable source of information obtained from solar activity spectra, see the http://www.asu.cas.cz/˜ sos/ web page.

4. CZERNY-TURNER SPECTROGRAPHS

In the 1960s a prototype of solar horizontal telescope with Czerny-Turner spectrograph was developed to measure solar magnetic fields both using the photoelectric magnetograph and the photographic methods of the Zeeman effect, (see Bumba et al, 1976). It was designed by V. Bumba as a system able to rotate along its optical axis, finished in 1969, fed by 55/55 cm coelostat, M1=45cm/35m, spectrograph of the Czerny-Turner type, grating 600 groves/mm, size 150x140 mm^2, two camera mirrors of f/980 cm for photographic and photoelectric detection of solar magnetic field based on Zeeman effect and velocity fields. Due to installation of photoelectric magnetograph (with fixed output slits) no more rotation was able.

Figure 8. New (northern) part of the Ondřejov Observatory as seen from the air.

A small series of five HSFA telescopes was designed by the Carl Zeiss Jena company according to the experience with the Ondřejov rotating horizontal spectrograph. (HSFA is an abbreviation from the German expression Horizontal Sonnen Forschungs Anlage, i.e. Horizontal Device for Solar Investigations) device. They were delivered to Czechoslovakia in 1980's. Two of the series (i.e. the HSFA1 which was used more or less as magnetograph, while the HSFA2 was dedicated to classical solar spectroscopy with high spectral resolution) were located in the new part of the Ondřejov observatory, close to the 2m stellar telescope dome (see Figure 8) at about 700 m north of the solar department building. The pavilions of the HSFA1 and HSFA2 are at the left upper part of the slide. Some parameters of the HSFA2, including the instrumental profile, have been measured by Sobotka and Kotrč, (1987). The device was used for optical spectroscopy but also for near-infrared spectroscopy of quiescent prominences (Heinzel et al. 1986). For a general view of the HSFA2 facility see Fig. 9.

Figure 9. The HSFA2 horizontal solar telescope and spectrograph.

5. MODERNIZATION

After two decades of using the two large horizontal solar telescopes with spectrographs, both the HSFA1 and the HSFA2 underwent important reconstruction. A concept for the reconstruction of the electronic control systems of the two large horizontal solar telescopes with spectrographs has been described by (Klvaňa et al. 2001). The original designation of the two instruments was mostly preserved. The HSFA1 measurement of magnetic and velocity fields has been stopped, while HSFA2 was rebuilt to a multichannel spectrograph equipped with CCD cameras. The reconstruction of the electronic control systems was the most important task. The up-to-date electronic equipment was planned to do a remote control of numerous functions of the instrument. It offers a large amount of automated procedures and it is resistive to disturbances caused by atmospheric electricity. It has to be pointed out that in the same period when the two HSFA devices were built, used and then reconstructed and modernized, the theoretical capability in the Ondřejov Solar Department grew substantially as well. It enabled to interpret solar spectra on a qualitatively higher level for theoretical modelling and a better understanding of physical processes in the Sun.

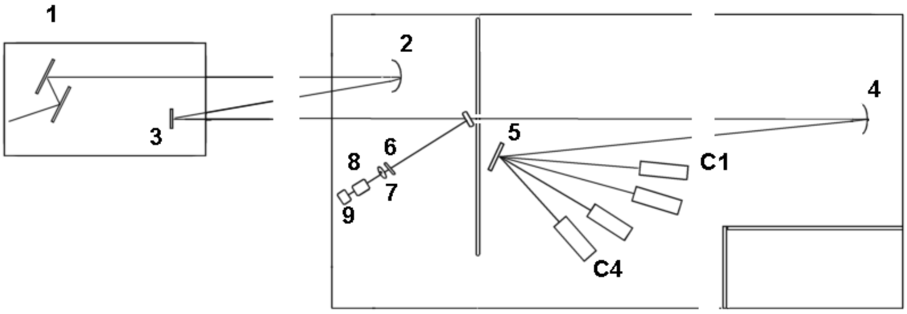

Figure 10. Optical schema of the HSFA2. 1 - two ϕ 60 cm coelostat mirrors, 2 - main objective ϕ 500 mm / f 34850 mm, 3 - flat mirror ϕ 320 mm, 4 - collimator ϕ 250 mm / f 10000 m, 5 - diffraction grating, C1 ... C4 - cameras for individual spectral regions. Slit-jaw system: 6 - broad band filter, 7 - objective, 8 - narrow band Hα filter Day Star, 9 - CCD camera.

The spectrograph was rebuild from the Czerny-Turner configuration to the multicamera version, see Fig. 10. The goal of the rebuilding was to enable simultaneous spectral observations in several diagnostically important lines with the best possible spectral and temporal resolutions. We had to respect the limited width of the pavilion building. Therefore we carried out optimization of the imaging optics for CCD cameras with small detector chips for various options of the current and for a different diffraction grating, see Kotrč & Kschioneck, 2003. We suggested optical schemas with a folded pattern of beams, (the main camera mirror ϕ 200 mm, f 2500 mm) and put it in practice.

The lines were selected according to their diagnostic importance as well as to the location in the spectrograph: Hα (6563 Å), D3 (5875 Å), Hβ (4861 Å), CaII K resp. CaII H (3934 resp. 3968 Å) and the CaII IR 8542 Å. Thus, instead of the one large photographic detector in the former spectrograph we now have 6 CCD cameras. Five of them are placed at these lines and the sixth is in the new slit-jaw system with the monochromatic Hα filter, see Fig. 10. Next to it an auxiliary telescope with a video camera providing information about position of the solar image in the slit plane is located.

The former grating from Bausch & Lomb with C=632.1 mm^{-1}, width W=206 mm, height H=154 mm, angle of incidence φ=51^{o}, and with maximum intensity concentrated into the 4th order was replaced by the Richardson grating, C=1200 mm^{-1}, width W=206 mm, height H=154 mm, blaze angle φ =17.5^o, and with maximum light concentrated into the 1st order. Therefore, after the grating replacement the spectral resolving power decreased from 521 000 to 247 000. Thus, the spectral resolution $\Delta\lambda$ for the Hα line is 26 mÅ while for CaII H or CaII K the spectral resolution is 16 mÅ. These values in combination with new small size detectors mean that the possibilities are quite satisfactory. However, a further improvement of the camera objectives, especially at the shortest wavelengths is planned to fit the theoretical and practical spectral resolution limits.

The fast CCD cameras VDS Vosskühler CCD-1300LN have pixel size 6.7μm × 6.7μm, chip size s=pH× pV=1280(H) × 1024(V) pixels. To increase amount of light and the temporal resolution, version of binning pV=1280(H) × 512(V) pixels is used. Cameras are combined with Matrix Vision grabbers. They are 12 bits and their controlling PCs are connected with the telescope/spectrograph controlling server.

6. HSFA2 SPECTRA - RESULTS

The HSFA2 is still operated in a test regime to study its new parameters, to check all its weak points and find optimal solution for the further improvement. Nevertheless, the device has actively participated in international coordinated campaigns as that for HINODE, TRACE, SOHO and Ground-based observations of quiescent prominences and filaments. HSFA2 provided calibrated Hα intensities in the prominence on 2007 April 25. Data were used for estimation of the Hα opacity and its correlations with intensities in EUV bandpass as observed by TRACE 195 Å, XRT and EIS (Heinzel et al. 2008).

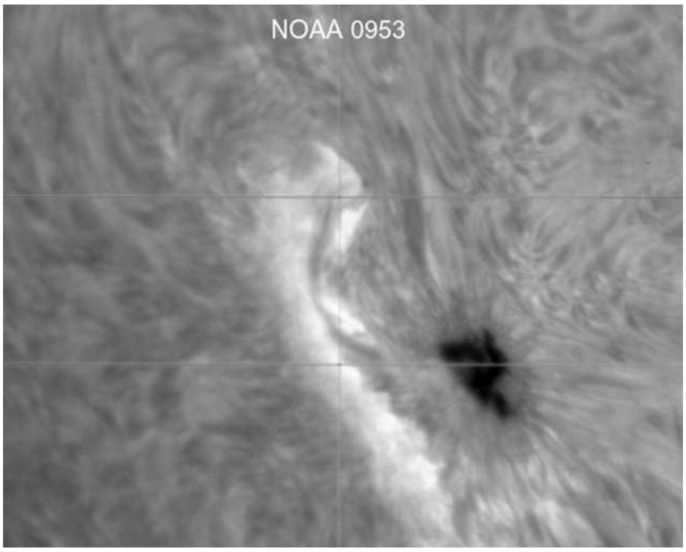

Figure 11. Hα slit-jaw image of active region from the reflexing slit. Vertical line is the slit, while two horizontal hairs mark the geometrical scale.

Main missions of the HSFA2 are as follows: The device is dedicated to solar active phenomena observations (flares, prominences, filaments, spicules, dark mottles etc.).

The main advantages are flexibility and availability of the instrument. The only limitations are weather and season of the year. We stimulate and appreciate cooperation with other ground based telescopes (optical and radio). We also support space born devices. The main aims are spectral diagnostics and modelling of phenomena. Education and practical training of students is considered as an important task for that device. Data are generally available at www.asu.cas.cz/˜ sos/ in the latest.data in two modes view/full. The full data can be reached with permission due to still testing program calibration SW is partly developed and available on the website mentioned above. Solar community is encouraged to use observations and make suggestions and proposals for using the spectrograph.

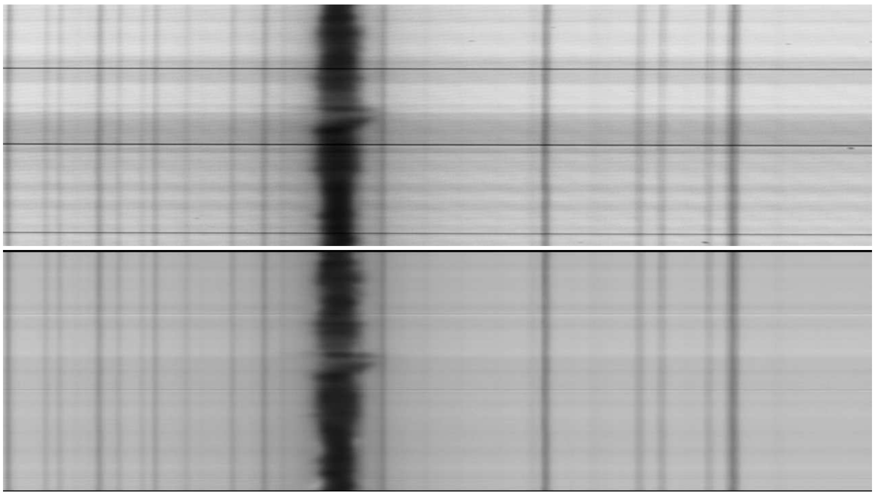

Figure 12. Hα spectrum of active region before (up) and after (bottom) the flat-fielding.

An active participation of students of the Belgrade University during their summer practise in 2007 and 2008 helped to solve several particular problems. They created a procedure for iterative determination of optical thickness τ_0 in the Hα line in both calibrated and non calibrated data as a tool for fast estimation of the prominence parameters (Milić et al., 2009). Other useful tools as a procedure for numerical determination of proper exposure time for CCD cameras and a procedure for selecting good pictures (without shifts of hairs). This one is briefly described in Racković et al. (2009). Other contribution is a procedure for recognizing overexposed and underexposed pixels. We hope these contacts may result in an even more fruitful cooperation in the future.

Acknowledgements

This work was supported by the institutional project AV0Z10030501 of the AS CR. The author appreciates support of the University in Belgrade during his stay at the XVth National Conference of Astronomers of Serbia.

References

Ambrož P., Kotrč P.,: 2002, in A. Kučera (ed.), Joint Organization for Solar Observations, Annual Report 2001/2002, p. 50

Blaha M., Kopecký M. & Švestka Z.: 1962, *Bulletin of the Astronomical Institute of Czechoslovakia*, **13**, 85

Bumba V., Klvaňa M., Macák P.: 1976, *Bulletin of the Astronomical Institutes of Czechoslovakia* **27**, 257.

Havlíčková E., & Kotrč P.: 2005, *Cent. Eur. Astrophys. Bull.*, **30**, 43.

Heinzel P., Kotrč P., Sobotka M., Zloch F., Scherbakova Z. A.: 1986, *Contributions of the Astronomical Observatory Skalnaté Pleso* **15**, 171

Heinzel P., Karlický M., Kotrč P., Švestka Z.: 1994, *Solar Physics*, **152**, 393.

Heinzel P., Kotrč P., Mouradian Z., Buyukliev G. T.: 1995: *Solar Physics*, **160**, 19.

Heinzel P., Schmieder B., Vial J.-C., Kotrč P.: 2000, *Astronomy and Astrophysics*, **370**, 281

Heinzel P.; Schmieder, B.; Fárnik, F.; Schwartz, P.; Labrosse, N.; Kotrč, P.; Anzer, U.; Molodij, G.; Berlicki, A.; DeLuca, E. E.; Golub, L.; Watanabe, T.; Berger, T.: 2008, *The Astrophysical Journal*, **686**, 1383

Karlický M., Kotrč P., Kupryakov Yu.A.: 2001, *Solar Physics*, **199**, 145

Karlický M., Kotrč P., Kupryakov Yu. A.: 2003, *Solar Physics*, **211**, 231

Kashapova L. K., Kotrč P., Kupryakov Yu. A.: 2008, *Annales Geophysicae*, **26**, 2975

Klvaňa M., Kotrč P., Knížek M., Sobotka M., Heinzel P.: 2001, *Astronomische Nachrichten* **322**, 371

Kotrč P., 1997: *Hvar Observatory Bulletin* **21**, 97

Kotrč P., Heinzel P., Karlický M., Knížek M., Jiřička K.: 1995, *M. Saniga (ed.), Joint Organization for Solar Observations, Annual Report* **1994**, 196

Kotrč P., Heinzel P., Knížek M., 1993, in A. von Alvensleben (ed.), Joint Organization for Solar Observations, Annual Report 1992, p. 114

Kotrč P., Schmieder B., Karlický M., Heinzel P.: 1997, *Solar Physics*, **172**, 199

Kotrč P., Karlický M., Šimberová S., Knižek M., Varady M.: 1998, *Solar Physics*, **182**, 393

Kotrč P.: 2002, *Astronomishe Nachrichten*, **324**, 324

Kotrč P.: 2003, *Hvar Obs. Bull.*, **27**, 179

Kotrč P., Kschioneck K., 2003, *A. Wilson (ed.), Solar Variability as an Input to the Earth's Environment*, ESA SP-535 , p. 717

Milić I., Dejanić S., and Kotrč, P.: 2009, *Publ. Astron. Obs. Belgrade*, this issue.

Plunkett S. P., Vourlidas A., Šimberová S., Karlický M., Kotrč P., Heinzel P., Kupryakov Yu.A., Guo W.P., Wu S.T.: 2000, *Solar Physics*, **194**, 371

Prosecký T., Kotrč P. and Berlicki A: 2005, *Cent. Eur. Astrophys. Bull.*, **30**, 31

Racković K., Nikolić S., and Kotrč, P.: 2009, *Publ. Astron. Obs. Belgrade*, this issue.

Ruždjak V.: 1981, *Bulletin of the Astronomical Institute of Czechoslovakia*, **32**, 144

Schmieder B., Heinzel P., Wiik J. E., Lemen J., Anwar B., Kotrč P., Hiei E.: 1995: *Solar Physics*, **156**, 337.

Sobotka M., Kotrč P., 1987, *Bulletin of the Astronomical Institutes of Czechoslovakia* **38**, 272

Švestka Z. & Fritzová - Švestková L.: 1967, *Solar Physics*, **2**, 87

Valníček B., Letfus V., Blaha M., Švestka Z., Seidl Z., 1959, *Bulletin of the Astronomical Institutes of Czechoslovakia* **10**, 149