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Monitoring solar activity with PEPSI

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Abstract. Synoptic Sun-as-a-star observations are carried out with the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI), which receives light from the Solar Disk-Integration (SDI) telescope. Daily spectra are produced with a high signal-to-noise ratio, providing access to unprecedented quasi-continuous, long-term, disk-integrated spectra of the Sun with high spectral and temporal resolution. We developed tools to monitor and study solar activity on different time-scales ranging from daily changes, over periods related to solar rotation, to annual and decadal trends. Strong chromospheric absorption lines, such as the Ca II H & K λ3934 & 3968 Å lines, are powerful diagnostic tools for solar activity studies, since they trace the variations of the solar magnetic field. Other lines, such as Hα λ6563 Å line and the near-infrared (NIR) Ca II λ8542 Å line, provide additional information on the physical properties in this highly complex and dynamic atmospheric layer. Currently, we work on a data pipeline for extraction, calibration, and analysis of the PEPSI/SDI data. We compare the SDI data with daily spectra from the Integrated Sunlight Spectrometer (ISS), which is part of the Synoptic Long-Term Investigation of the Sun (SOLIS) facility operated by the U.S. National Solar Observatory (NSO). This facilitates cross-calibration and validation of the SDI data.

Keywords. Sun: chromosphere, Sun: activity, instrumentation: spectrographs, techniques: spectroscopic, methods: data analysis

1. Introduction

For decades scientists monitor one important aspect of our Sun, *i.e.*, the Sun's activity and magnetic cycle, by measuring the magnetic field strength or by building time-series of various indices serving as indications of the solar activity and magnetism (Keil *et al.* 1998; Livingston *et al.* 2007; Bertello *et al.* 2010). There is a well established 11-year activity cycle: part of the 22-year Hale cycle, *i.e.*, the Sun's magnetic cycle. Its existence was first recognized from observations of sunspot appearance, number, and migration. Active regions mark location on the solar surface with strong magnetic fields. These fields are rooted in the solar interior, where they are shaped and guided by dynamo processes. The magnetic fields facilitate the energy transport through solar atmosphere, provide energy and serve as a trigger for powerful solar flares and eruptions. Thus, solar magnetism is the force shaping many aspects of the solar system environment, *i.e.*, the heliosphere.

Solar activity monitoring provides the much-needed background for theoretical models explaining the solar and stellar dynamo and as input for planning and operating space missions. Many diagnostic tools were developed to support this effort, *e.g.*, magnetic field extrapolations based on synoptic full-disk vector magnetograms, precise measurements and predictions of the solar radio, X-ray, and particle fluxes, and classification of the active regions, sunspots, and eruptive or energetic events (Ermolli *et al.* 2014). Using spectroscopic proxies to study the variations of the global solar magnetic field is an integral part of this effort to characterize the solar cycle. In this work, we introduce preliminary results of calibration and evaluation procedures, which later will ensure the precise derivation of the activity indices based on PEPSI/SDI Sun-as-a-star observations.

The Ca II H & K lines are powerful tools to examine the solar atmosphere's stratification, using their formation height and magnetic sensitivity. Magnetic heating introduced in plage and network regions cause emissions in the cores of these strong chromospheric absorption lines. An important feature is the sensitivity of the line-core intensity to variations of the magnetic fields. This aspect was used by Pevtsov *et al.* (2016) to reconstruct long-term magnetic variations. Other chromospheric lines such as the He I NIR triplet, the Ca II NIR line, and the Hα line show a similar behavior but less pronounced. Hα is a good tracer of the development and evolution of, for example, filaments and prominences.

2. Observations and standard data reduction

PEPSI is a state-of-the-art, thermally stabilized, fiber-fed, high-resolution spectrograph for the 11.8-meter (light-gathering ability) Large Binocular Telescope (LBT) at Mt. Graham, Arizona. Typically the LBT with its large light-gathering power feeds starlight to PEPSI. However, the spectrograph can also receive sunlight from the SDI telescope. The observed spectra contain a multitude of photospheric and chromospheric spectral lines in the wavelength range of 380–910 nm. The spectral resolution is $\mathcal{R} = 250\,000$, and an average exposure time 0.3 s. The signal-to-noise ratio varies between 2 000:1 and 8 000:1 depending on the wavelength. The standard data reduction steps of the spectra includes dark and flat-field corrections, scattered light subtraction, wavelength and flux calibration, etc. A detailed description of the PEPSI data reduction pipeline is given in Strassmeier *et al.* (2018). In 2018, PEPSI/SDI started the routine daily observations. However, the data for a comparative study discussed in this paper were obtained during two separate campaigns in 2015 and 2016.

3. Software development and data reduction specific to SDI

Line profiles in the desired wavelength region are retrieved from PEPSI FITS files using the IDL software repository SolarSoft (Freeland & Handy 2012). The Optical Solar Physics research group at AIP actively develops an IDL software library 'sTools' (Kuckein *et al.* 2017) for high-resolution imaging and spectropolarimetry. Initially intended for the data reduction of the post-focus instruments at the 1.5-meter GREGOR solar telescope (Schmidt *et al.* 2012), the scope of sTools was expanded to include other instruments such as PEPSI/SDI.

In order to calculate reliable activity indices, we need a precise wavelength and intensity calibration. Thus, we developed a method for fine tuning the continuum calibration of the PEPSI/SDI spectra. In the first step, we align and add the all spectra taken over the course of a single day. On average PEPSI/SDI takes approximately 200 single-exposure spectra per day. Comparing this daily average profile to the NSO Fourier Transform Spectral (FTS, Kurucz *et al.* 1984) flux atlas, we determine accurate continuum levels. We are using the ratio between PEPSI/SDI daily average profile and FTS atlas to correct the continuum if necessary. This task include the following steps: (1) we compute the ratio of the SDI and FTS spectra, which is then decomposed into its Fourier components; (2) the ratio is restored for a chosen (smaller) number of Fourier coefficients, which strongly depend on line profile shape; (3) the restored ratio is applied to the SDI spectrum, thus, providing the proper continuum correction. For validation, single and average spectra are compared to spectra from the same day but obtained with SOLIS/ISS (Keller *et al.*

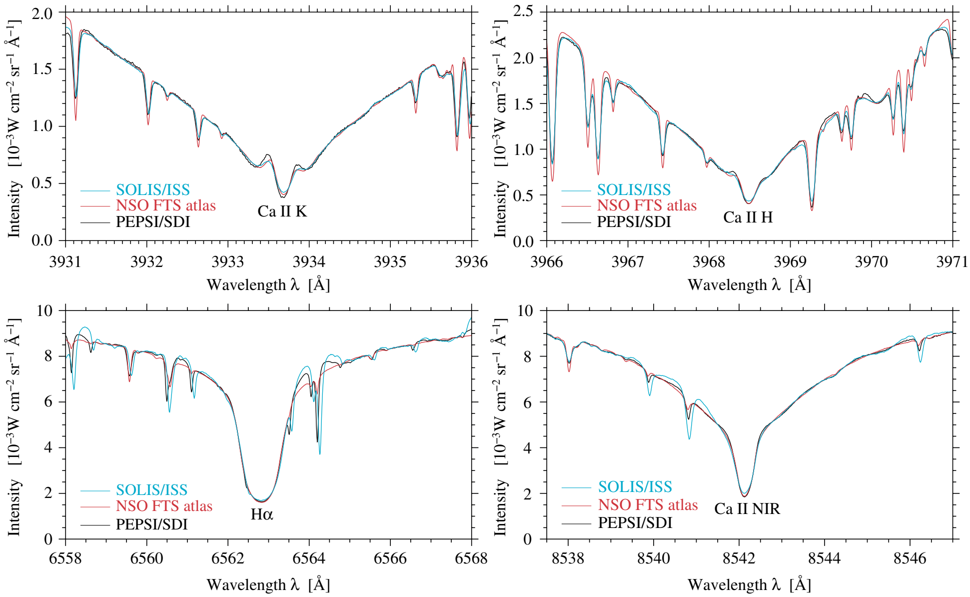

Figure 1. Sun-as-a-star spectra of the Ca II H & K lines (*top*) and the Hα & Ca II NIR lines, commonly referred to as the infrared triplet (*bottom*). The PEPSI/SDI (*black*) and SOLIS/ISS (*blue*) spectra on 2016 November 17 are compared to the NSO FTS spectral atlas (*red*).

2003). The results are presented in Fig. 1. In general, we see a relatively good agreement between PEPSI/SDI and SOLIS/ISS spectra in wings of selected spectral lines. Some differences are present in the cores of strong lines. These processed PEPSI/SDI spectral profiles are ready for further analysis, including comparing Sun-as-a-star spectra with spatially resolved solar images linking spectral features to various solar phenomena.

References

Bertello, L., Ulrich, R. K., & Boyden, J. E. 2010, *Sol. Phys.*, 264, 31

Ermolli, I., Shibasaki, K., Tlatov, A., & van Driel-Gesztelyi, L. 2014, *Space Sci. Rev.*, 186, 105

Freeland, S. L. & Handy, B. N. 2012, SolarSoft: Programming and Data Analysis Environment for Solar Physics, Astrophysics Source Code Library

Keil, S. L., Henry, T. W., & Fleck, B. 1998, in *ASP Conf. Ser.*, Vol. 140, Synoptic Solar Physics, eds. K. S. Balasubramaniam, J. Harvey, & D. Rabin, 301

Keller, C. U., Harvey, J. W., & Giampapa, M. S. 2003, in *Proc. SPIE*, Vol. 4853, Innovative Telescopes and Instrumentation for Solar Astrophysics, eds. S. L. Keil & S. V. Avakyan, 194–204

Kuckein, C., Denker, C., Verma, M., *et al.* 2017, in *IAU Symp.*, Vol. 327, Fine Structure and Dynamics of the Solar Atmosphere, eds. S. Vargas Domínguez, A. G. Kosovichev, L. Harra, & P. Antolin, 20–24

Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm (Sunspot, New Mexico: National Solar Observatory)

Livingston, W., Wallace, L., White, O. R., & Giampapa, M. S. 2007, *Astrophys. J.*, 657, 1137

Pevtsov, A. A., Virtanen, I., Mursula, K., Tlatov, A., & Bertello, L. 2016, *Astron. Astrophys.*, 585, A40

Schmidt, W., von der Lühe, O., Volkmer, R., *et al.* 2012, *Astron. Nachr.*, 333, 796

Strassmeier, K. G., Ilyin, I., & Steffen, M. 2018, *Astron. Astrophys.*, 612, A44

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