Understanding variability of Solar Balmer lines

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Introduction

Precise, adequately high-cadence, long-term records of spectral variability at different temporal scales lead to better understanding of a wide variety of phenomena including stellar atmospheres and dynamos, evolution of the magnetic fields on a stellar photosphere, convective motions, and rotational periods. These, in turn, are fundamental for the detectability of exoplanets, the characterization of their atmospheres and habitability, as well as characterization of stellar magnetospheres and winds. The Sun, viewed as a star via spectral irradiance measurements, offers a means of exploring such measurements while also having the imaging capability to help discern the causes of observed spectral variations. In this study, we investigate the variability of solar Balmer lines (H-α, β, γ and δ) observed by space-borne radiometers, combining these precise, long-term observations with abundant, high-resolution data from the ground-based NSO/ISS spectrograph. We relate the detected variability to magnetic features on the solar disk. We find that on solar-rotation timescales (~month), the Balmer line activity indices (defined as line-core to line-wing ratios) closely follow variations in the total solar irradiance (which is predominantly photospheric), thus frequently (specifically, during passages of big sunspot groups) deviates from behavior of the line-activity indices that track chromospheric activity levels. At longer timescales (years), the correlation with chromospheric indices increases, with periods of low- or even anti- correlation found at intermediate timescales. Comparisons with Balmer-line variability patterns obtained from a semi-empirical model indicate the periods of low/anti correlations should be attributed to the increase of the relative abundance of network, which affects the Ca-index while leaving almost un-altered the Hα-index.

1.Measurements

Instrument	Observable	Resolving Power	Temporal scale
OMI+TROPOMI	H-β, γ, δ indices	~850	Solar rotation
SCIAMACHY+GOME-2	H-α index	~2000	Solar rotation
ISS	H-α index	~300000	Decadal
PSPT	Feature masks	N/A	Solar rotation to Decadal
SORCE/TIM	Total Solar Irradiance	N/A	Daily to Decadal
San Fernando Observatory	CaIIK Plage Index	N/A	Solar rotation to Decadal
USAF-SOON	Dark Photometric Index	N/A	Solar rotation to Decadal

Balmer indices were derived by the analysis of measurements acquired with space-based radiometric observations (OMI, TROPOMI, Sciamachy, GOME-2) as well as ground-based spectrographic observations (NSO/ISS).

Radiometric observations are not affected by atmospheric observational conditions. Because we found them to be affected by long-term degradation, we employed them for analyses only on short temporal scales. All radiometric data were detrended by subtracting average intensity computed over a 61-days temporal window in order to remove long-term instrumental trends.

NSO/ISS observations are affected by daily variations resulting from varying atmospheric conditions, so we employed them for analyses over the longer temporal scales.

Other *Activity Indices* were employed for comparison: the Total Solar Irradiance (TSI) measured by the SORCE/TIM radiometer; the CaII-plage-index produced by the San Fernando Observatory (SFO-CaII, Chapman et al. 1997), and the Dark Photometric Index (Coddington et al. 2016).

Full-disk images acquired with the Precision Solar Photometric Telescope (PSPT) were employed for quiet and active region identification by using the SRPM algorithm (Fontenla&Harder, 2005).

3.Results: Decadal temporal scale

The Hα core-to-wing ratio was estimated from ISS observations and compared with the index computed from the model and with the SFO-CaII index. Results, summarized in Fig. 3, are: 1) (Left) In both measurement and model, the Hα index varies in phase with the activity cycle. 2) (Center) The Hα and CaII indices often decorrelate, especially on short temporal scales. The correlation increases and is always positive on the longer temporal scales (T≥ 2.5 years). 3) (Right) The correlation increases with solar activity.

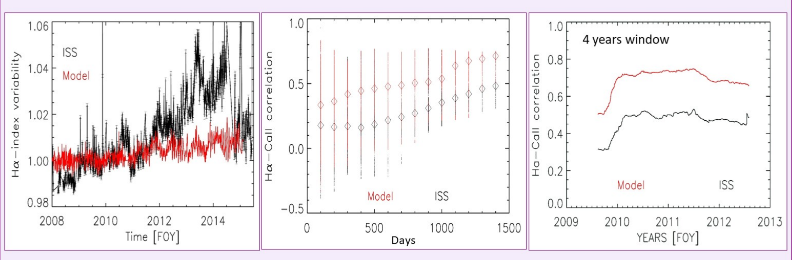

Fig.3 Left: Long-term variation of the Ha-index derived from ISS measurements and the model (left) . Center: Correlation coefficients between the CaII-index and the Hα-index as a function of the temporal window.; diamonds represent the median values of the distributions. Right: Temporal variation of the correlation coefficients between the CaII-index and the Ha-index computed over a temporal window of 4 years

The ISS measurements produce a variability that is higher with respect to results reported from previous measurements (i.e. Meunier & Delfosse 2009), which most likely results from instrumental induced trends that are still under investigation.

2.Model

Irradiance variability was reconstructed using a semi-empirical approach, schematically depicted in *Fig. 1*. **Step 1**: Magnetic features were identified on full-disk observations acquired in the red and CaII-K spectral ranges with the Precision Solar Photometric Telescope (PSPT). **Step 2**: Balmer lines are synthetized under Non-Local Thermodynamic Equilibrium using the RH code (Uitenbroek 2001), and the set of atmospheric models by Fontenla et al. 1999. The set includes two atmospheric models for the quiet Sun, two for the network and one for sunspots; for penumbra we employed the atmospheric model by Fontenla et al. 2011. **Step 3**: Irradiance variability is reconstructed by combining synthetic spectra with the daily variation of the area coverage of features identified on the PSPT images.

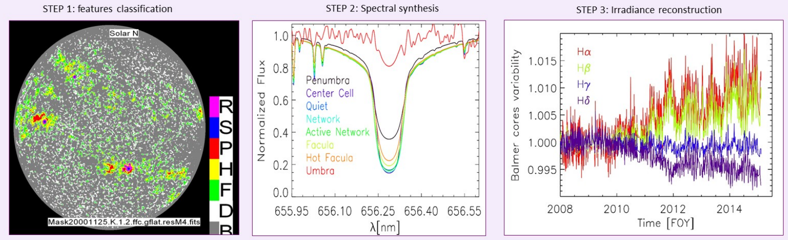

Fig.1 Workflow of the semi-empirical Irradiance reconstruction.

4. Results: Solar rotation temporal scale

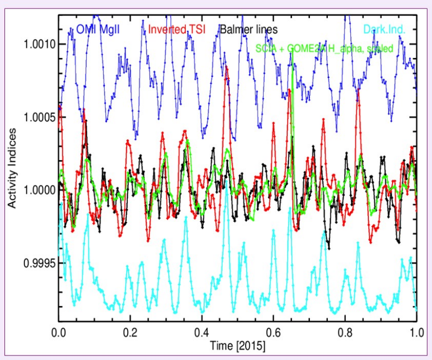

Fig.4 Comparison of Variability of the Balmer and Hα index estimated from radiometric measurements with different activity indices. Activity indices have been scaled and shifted for visualization purposes.

A *Balmer-index* was defined as the sum of the core-to-wing ratio of the H-β,γ,δ as measured by OMI and TROPOMI.

A *Hα-index* was defined as the ratio of the average line intensity (sampled at 5 spectral positions) and the nearby continuum intensity, as derived from the SCIAMACHY+GOME2 composite.

Fig.3 shows an example of the variability of the two indices measured during 2015, at the peak of activity of Cycle 24. Both Balmer indices closely follow the variability of the inverted-TSI, and often deviate from the variability measured in chromospheric indices (e.g. at times 0.25 and 0.53 in Fig. 3)

Results obtained from the model (Fig. 4) confirm that the Balmer indices closely follow the trend of the inverted TSI.

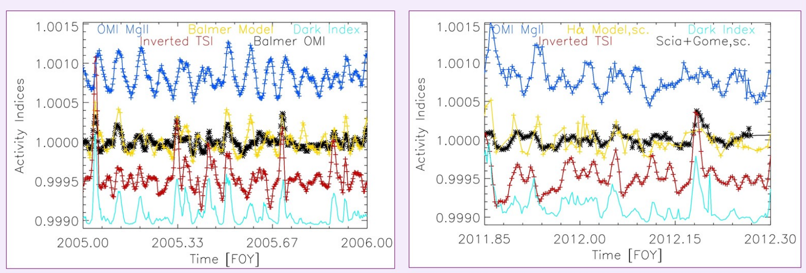

Fig.5 Comparison of Variability of the Balmer (left) and Hα-indices (right) derived from the model and from radiometric measurements. The Hα indices have been rescaled by a factor of 3. Other activity indices are shown for comparison. Activity indices have been scaled and shifted for visualization purposes.

5.Conclusions

- **On Solar rotation time scale, both model and measurements indicate that the Balmer indices closely follow the inverted TSI and thus often deviate from the behavior of chromospheric indices.**
- **On the longer temporal scales, both model and measurements indicate that the correlation between the Ha-index and the CaII-index increases, and both the indices vary in phase with the activity cycle.**
- **Fig. 1 shows that the Balmer line profiles of network models are similar to those of quiet-sun models, thus indicating that the Balmer indices are almost insensitive to the network. This result most likely explains the low/anti correlation with the chromospheric indices (which are sensitive to the network) found at levels of low activity.**

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