Validating Solar atmosphere models using high spectral resolution, center-to-limb observations of solar Balmer lines

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1. Introduction

Motivation: Solar atmosphere models are used for solar irradiance reconstructions that help predict changes in the Earth's atmosphere and climate, and to model stellar atmospheres to help characterize habitability in exoplanets

Background: Solar irradiance variations occur over different temporal scales (second to millennia), and the amplitude of the variations depends on the spectral range. Variations are driven by solar magnetic activity such as sunspots and or faculae. Center-to-limb observations allow us to sample different depths of the solar atmosphere, by analyzing the difference in absorption at different angles along the solar disk.

Objective: We use high spectrally resolved observations of the quiet Sun, acquired over different positions over the solar disk, to validate quiet Sun solar atmosphere models. We aim to find the model that best matches the observational spectra.

2. Data

Observational Data was gathered by the spectrograph at the Institut für Astrophysik in Göttingen, Germany (IAG) between April 2020 and June 2021. Observations were acquired at 14 positions over the disk, at high spectral resolution (R = 700,000 at 6000Å), in the range 4200Å – 8000Å.

Modelled spectra were obtained using the RH code by Uitenbroek (2001), modified by Kowalski et al. (2017). The five, 1D, static, atmosphere models employed in this study are listed in Table 1. The top 4 models in the table are semi-empirical, while Kurucz uses a forward approach.

5. Conclusions

Through analysis of the core intensity and Full Width at Half Maximum (FWHM) at the hydrogen Balmer lines, we find that mod1001 (Fontenla et al. 2011) matches the IAG observational data best. Mod1001 has slightly larger core intensity and FWHM than the IAG data, more noticeable near the limb in H-β and H-γ. We believe this to be due to an error in the temperature gradient used during synthesis. **After comparing mod1001 and IAG spectra at specific values of μ, we can conclude that mod1001 is the best match along the full center-to-limb variation** (μ = 1.0 – 0.2) at the primary Balmer absorption lines. Certain secondary lines are however less accurate, specifically in H-β and H-γ. As can be seen in Fig 1., and Fig 4., mod1001 has a very slight redshift. We expect this to be due to uncertainties in the datasets used when synthesizing the models

We also recognize that Kurucz model is slightly hindered by its inability to model the solar chromosphere. However, their model shows to be more accurate when modelling spectral lines that form lower in the photosphere.

3. Methodology

Normalizing synthetic spectra was done similarly to IAG, where normalization occurred locally. We carefully inspect the IAG's spectrum to find where the continuum starts on either side of the core, before matching these values to points on the synthetic spectra. A linear function is drawn between these two points, followed by dividing the spectrum by this line in the region of interest. This results in a continuum at unity.

Processing IAG spectrum: Due to noise in the core of the IAG observational data (Ellwarth et al. 2023), we fit a 2nd order polynomial to the bottom of the core. This approach allowed us to determine the core intensity along with their associated uncertainties (Fig. 2).

Finding FWHM height only required doubling the core intensity. For IAG data this was done once without uncertainties and again after adding uncertainties, the difference of these values are our FWHM uncertainties. We then selected the first points on either side of the core with an intensity above and below the calculated height. We interpolated between these points and found points along the lines that match the height. Then we compute the distance between to find FWHM (Fig 3). We then find the closest matching model and directly compare the spectra at specific μ-values (Fig 1,4).

4. Results

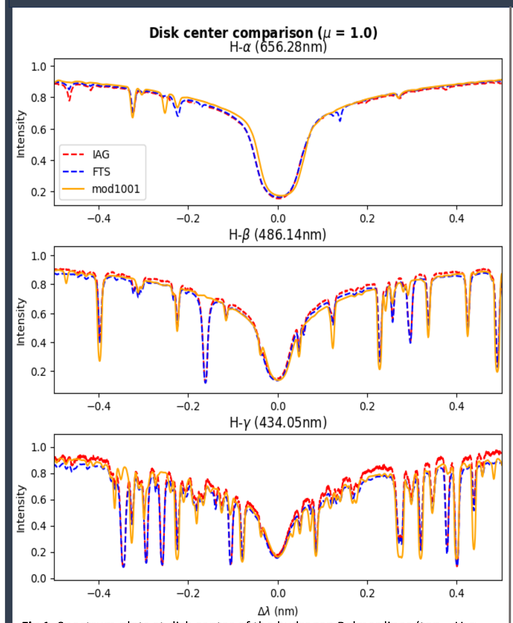

Fig 1. Spectrum plots at disk center of the hydrogen Balmer lines (top = H-α, middle = H-β, bottom = H-γ). Plotted are mod1001 (Fontenla et al. 2011), IAG (Ellwarth et al. 2023), and FTS reference spectrum (Brault & Neckel 1977). There is a small gap in the intensity of the spectra, especially in the H-γ range, this is likely due to a normalization uncertainties as the cores match nicely.

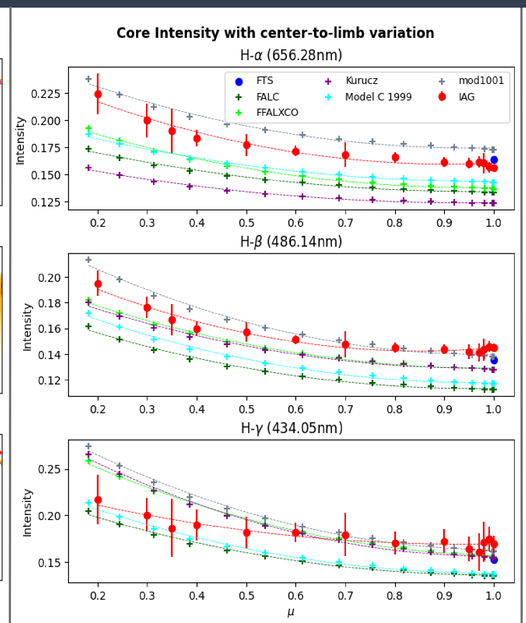

Fig 2. The minimum core intensity of the hydrogen Balmer lines (top = H-α, middle = H-β, bottom = H-γ), with center-to-limb variation. Model 2011 is the closest match, but has slightly higher core intensity compared to the IAG observational data (Ellwarth et al. 2023) near the solar limb.

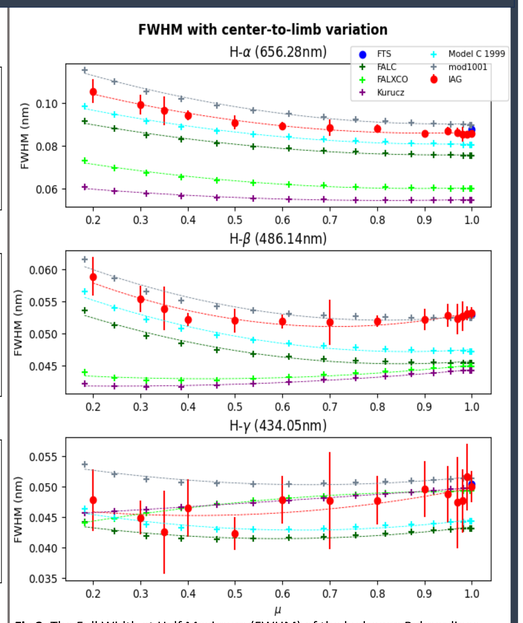

Fig 3. The Full Width at Half Maximum (FWHM) of the hydrogen Balmer lines (top = H-α, middle = H-β, bottom = H-γ), with center-to-limb variation. We notice a slight increase in the FWHM in mod1001 compared to the IAG observational data. The H-γ region had much noise in the IAG spectrum which explains the large uncertainties in the bottom frame.

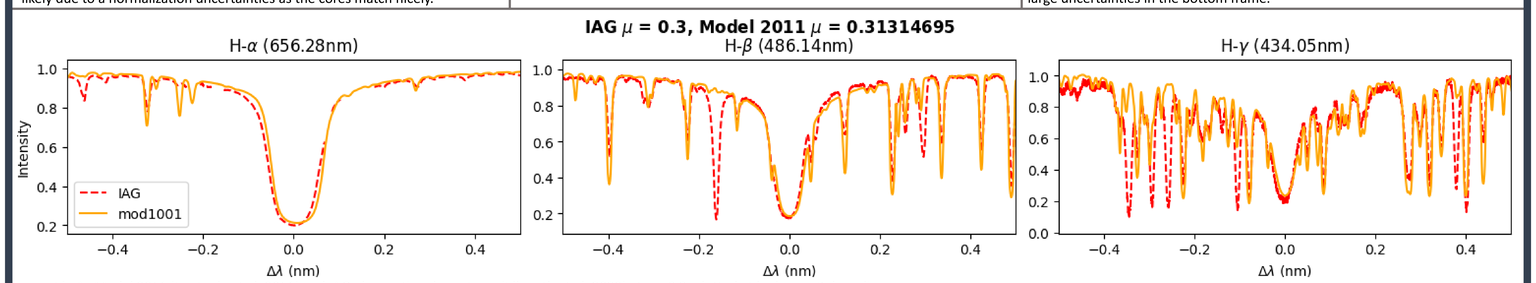

Fig 4. Model 2011 (Fontenla et al. 2011) and IAG observational spectrum (Ellwarth et al. 2023) at μ = 0.3, plotted at hydrogen Balmer lines (left = H-α, middle = H-β, right = H-γ). Small shift in model is likely due to uncertainties in databases used during synthesis.

mod1001	Fontenla et al. (2011)
Model C 1999	Fontenla et al. (1999)
FALC	Fontenla et al. (1993)
FALXCO	Avrett (1995)
Kurucz	Kurucz (2009)

Table 1: Models used in this project and where they came from

6. Next Steps

Further validate using DST and DKIST observational data

Validate Fe absorption lines that form lower in the photosphere

Validate spectra of magnetic features (sunspots, facula, etc.)

7. Acknowledgements

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8. References

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