Atlas of the center to limb variation of the solar intensity spectrum

by

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Abstract

The limb darkening function of the Sun in the continuous spectrum is well known and is largely used in the modeling of the solar atmosphere. There has however been a lack of systematic spectrally resolved measurements of the center to limb variation in light intensity. With the Gregory Coudé Telescope at IRSOL in Locarno we have recently carried out an observing campaign with systematic measurements in order to produce a spectral atlas showing the ratio between the light intensity obtained at 9 different heliocentric angles θ and the light intensity measured at the solar disc center. The 9 different heliocentric angles have been chosen so that μ = cos(θ) covers the interval from 0.1 to 0.9 in step of 0.1. The measurements collected till now cover the spectral range from 439 nm to 638 nm.

The obtained data provide observational constraints that can be used to test the validity of multi-dimensional solar atmosphere models,and can be used to better determine the anisotropy of the emergent radiation field on the solar surface. This would allow a better modeling of the the so called Second Solar Spectrum that describes the linear polarization as a function of wavelength measured near the solar limb, which is produced by scattering in the solar atmosphere.

Introduction

The Sun's disk observed at visible wavelengths is limb darkened. The main reason is the temperature decrease with height in the layers from where the radiation is coming, seen at different μ positions, where μ = cos(θ).

The coupling between limb darkening and temperature gradient is not complete, because of non-local thermodynamical equilibrium (non-LTE) effects related to scattering processes, which have no direct relation to temperature. While these effects play a secondary role for continuum radiation they can be important in spectral lines. The opacity, height of formation, and non-LTE effects vary across the profiles of each of the numerous spectral lines providing a rich spectral structure to the limb darkening.

The limb darkening can also be interpreted in terms of the angular distribution of the emergent radiation at the Sun's surface. It is this anisotropy that is the source of the scattering polarization that is referred to as the Second Solar Spectrum (Stenflo & Keller 1997). The anisotropy breaks the symmetry that enables the scattered light to become polarized.

The center-to-limb variation (CLV) of the intensity solar spectrum is richly structured, but in ways that differ profoundly from the usual intensity spectrum (in this context, the First Solar Spectrum) and from the Second Solar Spectrum. Stenflo (2014) suggests referring to the intensity CLV as the Third Solar Spectrum.

Observations

Data are provided at IRSOL facilities:
- telescope: Gregorian, 45 cm aperture and 24 m focal length, field of view of about 200"
- spectrograph: Czerny Turner, focal length 10 m, grating 180 x 360 mm, 316 groves/mm, Blaze angle 63°
- camera: ZIMPOL optimized for intensity measurements
- telescope guiding: Primary Image Guiding system (Küveler et al., 2011)
- limb tracking system: tilting glass plate to keep a constant μ position (μ = 0.1 to μ = 0.4)
- the ZIMPOL software controls: camera, telescope guiding system, spectrograph, limb tracking system. Scripts allow collecting data in an automatic way (Ramelli et al. 2010)

Observations are performed orienting the heliographic North limb parallel to the spectrograph slit using a Dove prism.
The measurement sequence in a particular wavelength is:
- recording flat-field images moving the telescope around a quiet solar area near disk center
- measuring at μ = 0.1- disc center - μ = 0.2 - μ = 0.3- center- μ = 0.4 - μ = 0.5 – center-....

Data reduction

- flat-field correction
- production of an intensity profile averaging over 30 arcseconds along the spatial direction
- normalization of the intensity profile to its continuum
- wavelength determination using the FTS atlas (Kurucz et al. 1984)
- calculation, for each μ position, of the ratio ***R*** of the normalized to their continuum intensity profiles measured at the μ position and at the disk center

Results

Data reduction produces 9 *R* profiles measured at different μ positions, see Figure 2. The CLV in the continuum is well known (Neckel & Labs, 1994), thus the general spectral CLV can be calculated as $C_\lambda(\mu) = R\, C_c$ where: *λ* and *μ* indicates the wavelength and position on the disc dependence of $C_\lambda(\mu) = I_\lambda(\mu) \,/\, I_\lambda(\mu=1.0)$, *R* is the already described ratio, and C_c is the continuum CLV value corresponding to the considered wavelength interval.

Stenflo (2014) has shown there is a non linear relation between *R* and the first solar spectrum for weak to medium-strong lines. This can be used to test solar multi-dimensional models needed for a better quantitative interpretation of the second solar spectrum, governed by non-LTE physics and quantum processes.

Data

Data will be available soon on our site: **www.irsol.ch/data_archive**

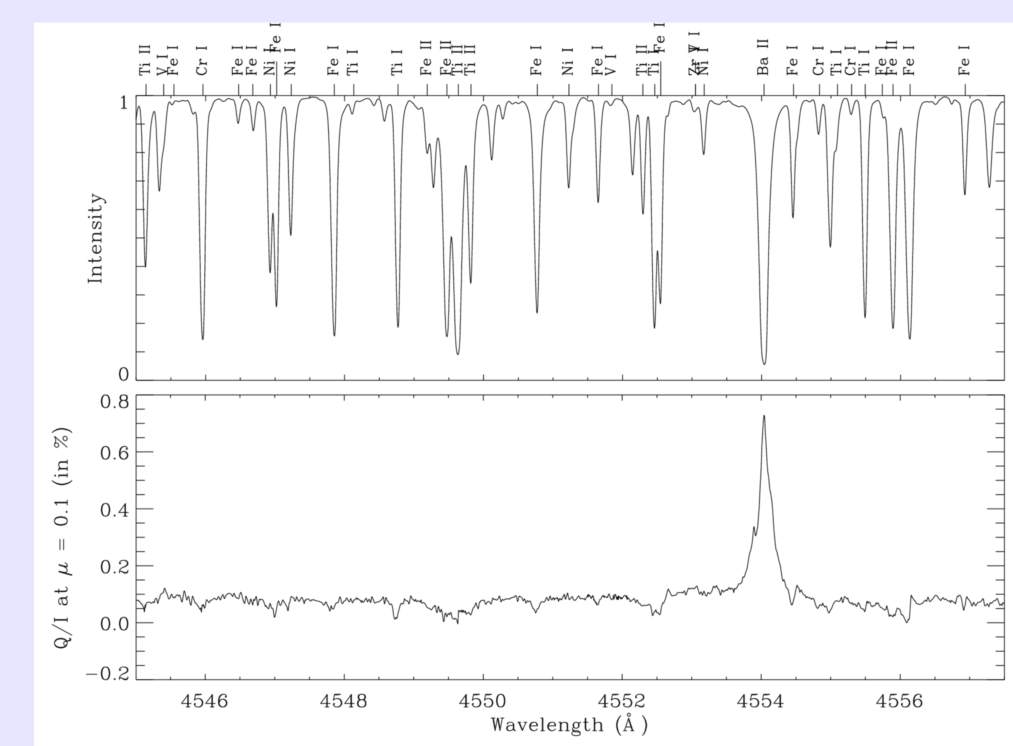

Figure 1
Top panel, the intensity spectrum in the wavelength interval 4545 Å to 4558 Å (First Solar Spectrum); bottom panel, linear polarization measured near the limb at μ = 0.1 (Second Solar Spectrum, see Gandorfer 2002)

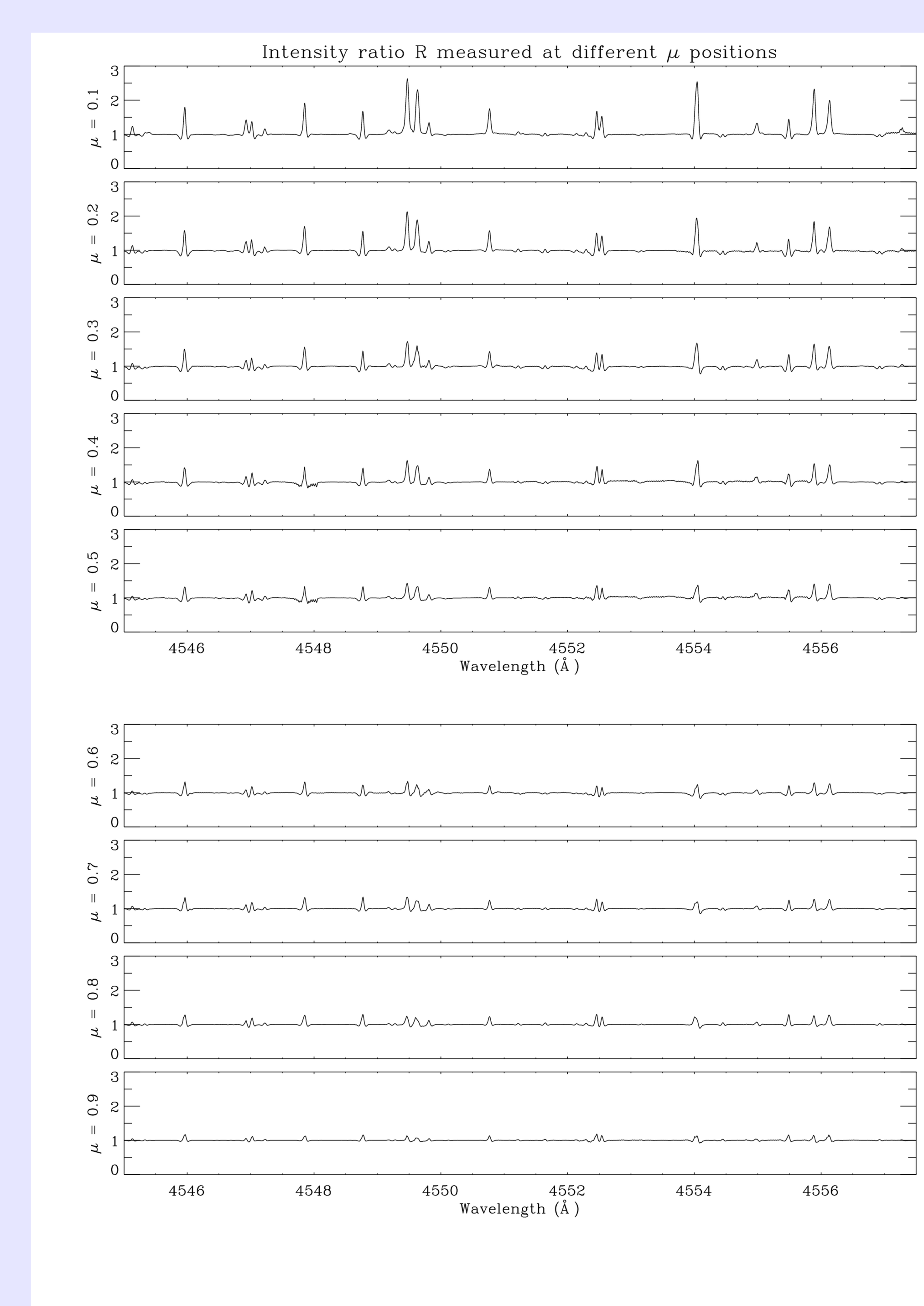

Figure 2
In the same wavelength interval: the ratio *R* between the intensity spectral profile measured at the μ = cos(θ) position indicated on the left, normalized to its continuum, and the intensity spectral profile measured at the disc center, also normalized to its continuum (Third Solar Spectrum, Stenflo 2014)

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