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Measurement and Characterization of Granulation Pattern in the IAG Solar Flux Spectrum

BSc Physics Final Project

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Abstract

Hello, this is my work :D

Acknowledgements

Thanks :b

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Chapter 2

Literature Review: Convective movement in the Sun

As previously mentioned, David Gray [3, 4] has significantly advanced the study of granulation patterns in the solar photosphere, with a particular focus on measuring their associated relative velocities with high precision. These developments have enabled more accurate characterizations of other stars by extrapolating the physical principles observed in the Sun. This section explores the different motion characteristics that made the Sun an Interesting star for study.

2.1 General description

The Sun is classified as a yellow dwarf star of spectral type G2V, title achieved for a big amount of hot hydrogen (ionised H in 90 percent) and helium (in 10 percent). What makes this star really unique is his proximity to earth and the facility to study from the planet with precision [5]. Since 1874 when Langley gives a detailed description of granulation on the photosphere [5], the astronomers have been studied different motions and reactions across the layers.

In general we have 2 parts of the Sun: The interior and the outer atmosphere.

The overall structure of the interior is core, radiative and convective zone. Across then the density and temperature fall. Models of its structure give a central temperature of $1.6 \times 10^7 K$ and density to $1.6 \times 10^5 Kg/m^3$, high enough for thermonuclear reactions and remains the central material in plasma like a gigantic atomic reactor. The core generates the 99 percent of the generates which is slowly transerred outwards by radiative diffusion. This part is so opaque cause there are so many collisions, absorptions and reemisions. The effect of this collisions is to increase the wavelength from high-energy gamma rays to visible ligth. The most important layer to this study is the convection zone. In this zone the temperature gradient is great for the material to stay in static equilibrium, and is where the magnetic field is generated [5]. On the other hand, the outer atmosphere consist in photosphere, chromosphere and corona. In this part the density decreases rather rapidly with height above solar surface and the temperature decrease to $4300K$ and then rises through the transition region. Thereafter, the temperautre falls slowly expanding outwards as the solar wind. The most relevant layer is the photosphere, a thin layer of plasma that emits most of the solar radiation and emits a continuos spectrum with superimposed dark absorption lines. Most of this wavelengths are absorbed by the chromosphere, which is transparent. A good expample are the H_α Balmer lines [5].

2.2 The Convection Zone

From the core, He nuclei is built from H nuclei in the proton-proton cycle as say equation (2.1)

$$4^1H \rightarrow^4 He + 2e^+ + 2\nu + 26.7MeV \tag{2.1}$$

Where from the H nuclei is liberated an considerable amount of high frecuency $\gamma-$rays ($26.7MeV$) and the energy of 2 neutrinos (0.5MeV). The strong Coulumb repulsion between positevily charged nuclei increases as the product of their nuclear charges, so only lightest elements will have appreciable reaction probabilities [6]. As the electrons recombine with others particles the photons can be absorbed more easily. With this, decrease the radiative conducity and increases the temperature gradient with the opacity. In the boundary of radiative zone the temperautre is drecreasing rapidly, so it begins a

convective instability and beyond a convective trubulence.. When reaches the low photosphere, some radiation scape from the sun and the material returns to the convective stability [5]. From surface observations the convection appears to be domination by cells: Granules, mesogranules, supergranules and giant cells.
It has been sugested that granulation are driven by the ionization of H and He, and hac¿ve scales comparable with the depths at wihich processes take place [5]. The issue with these granules can perturbe the angular momentum of the sun and the flow patterns in this zone. gfcgfcyfcyc

2.3 Convection Movement

In 1930 Unsold pointed out that the layers below the photosphere should be convective unstable. In 1936 Plasketts sugested that granules looked similar to the pattern of convective cells found in Bernards experiments. This statement are based on fluids heated from below representing hot rising gas elements convecting heat to surface. This last is caused by the Janssen observations in 1885, when take a photography of photospere showing pores and granulation [6]. When the Sun pushes material up through its outer layer, the spectrum exhibits a blueshift. As this material subsequently cools and falls back through the atmosphere, it produces a redshift, but emits less light, making the blueshift dominant.
So, we see the photospheric granules as convective cells. Have been shown to be influenced more by surface tension in the shallow near layers than by the bouyancy forces that drive free convection. Solar convection occurs in a highly compresible, stratified gas [6].
When a liquid layer is heated from below, convection iniciatilly sets in a 2d, horizontal, parallel rolls. The existence of a 3d convection pattern of convection cells that is static is limited to fluids whose viscosity ν is high compared to their thermal conductivity κ (the ratio of this two is the Prandtl number P). Fluids with $P \approx 1$ in Laboratory show little evidence of steady 3D convection, an increase of the gradient temperature leads

to a turbulent flow pattern. But at te photosphere with $P \approx 10^{-9}$ we expect to find turbulent behavior in the granulation if the temperture gradient is sufficient to drive free convection at the observed velocities and horizontal temperature differences [6].

2.4 The Solar Photosphere

Is an extremely thin visible surface layer, is only 100km thick and centered in the region where $T = 5000K$. In high resolution spectrograph shows a granular struture and a filme shows these brigth granules to be in continual motion. These granules represents the top of convective cells that are overshooting the upper convection zone. There are composed by hot, rising and horizontally outflowing plasma rather than cooling material. This is the region where magnetic flux is concentrated [5]. This is because the solar atmosphere is highly inhomogeneous and turbulent but we can take a start point. This is named Harvard-smithsonian reference atmosphere. It cero level is taken as the point where optical depth at a $\lambda = 5000\mathring{A}$ is equal to one.
For a deeper analysis is better to see the static and dynamic photosphere.

2.4.1 Static photosphere: Limb darkening phenomenon

The photosphere intensity falls off towards the limb, cause the temperature decrease of the higher layers as we look nearer the limb. The analysis of this effect provides a direct technique for determining the photosphere temperature structure with depth. This effect drecreases with increasing wavelength, the disk intensity profile becomes more squared at infrared. Since the limb darkening is caused by the temperature gradient we might to expect it to disappear in the infrared or ultraviolet where we observe layers around the T_{min} [6].

2.4.2 Dynamic photosphere. The C-curved profile bisector.

There exists a heigth dependence of the granular velocities. The velocity of an upward moving granule decays much less rapidly than its excess brigthness. The granular material is dark when observed in Fraunhofer lines formed high in the photosphere. So the material is cooler caused by its rapid expansion. Changes in the granulation structure, contrast and velocity field around the spots and network have been infered indirectly from observations of Fraunhofer line profile shapes. The result is characteristically C-Curved profile bisector [6]. The process of the creation in this c-curved profile bisector is listed before:

- The line profile near its mid-depth portion is formed in the most rapidly upflowing bright material. Blueshifted.
- The deepest portion of the line core is formed higher in the decelerated upflow. Less Blueshifted.
- The line wings, where the opacity is least, tend to be formed deepest in the cool. Redshifted.

The bisectors tend to be less c-curved near solar activity maximum that at minimum. Near activity maximum the higher packing density of magnetic flux tubes will tend to disrupt granular convection. [6].

2.4.3 Contributions on angular momentum

The pronounced differential rotation with latitude observed at he photosphere seems to be the result of convective flows driven radially by the bouyancy force and deflected horizontally by the coriolis force due to solar rotation (term of $2\rho\vec{\omega} \times \vec{v}$). Is dificult to datermine wheter the coriollis effects acts on slow global scale axysimmetrical circulations in the meridional plane, on intermediate scale eddies, or on a hierarchy of small eddies [6]. There are two types of contribution on angular momentum.

The first contribution is the meridian circulation. Occurs if axysimmetric meridional circulation are present. Movement of fluids in a vertical plane. In the absence of any other angular momentum transport, a circulation in either sense will tend to spin up the poles and the interior because the fluid carries angular momentum. These regions will be spin up (activating) until the flux of ωr^2 is equal both radius and latitude [6]

The second contribution is the reynolds stresses. These process tends to enforce solid body rotation, then the meridional circulation drive an equatorial aceleration. The reason is that for equal velocity in the meridional plane, the flux of angular momentum per unit mass across the dashed line will be larger toward the equator than away from it. This mechanism depends on the existence of nonaxisymetric convective motions. Because net fluxes of angular momentum in latitudinal or radials directions are produced without requering a net mass flux. They play an important role in the dynamics of turbulent fluids [6].

Neither buoyancy forces, which are strictly radial, nor presure gradients, which must average to zero around the solar circumference, can themsleves influences the suns axysimetric rotation profile [6].

2.5 Solar granulation pattern

When observing images of the solar photosphere, a distinct pattern of bright and dark regions with dynamic behavior becomes apparent, where individual areas continuously emerge and disappear (see figure 2.1). This phenomenon is known as granulation, and each individual region—spanning approximately 700 km in size and lasting between five to ten minutes—is referred to as a granule.

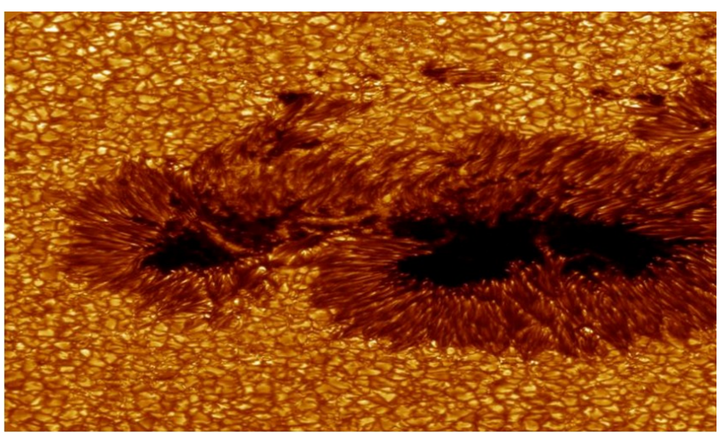

Figure 2.1: A view of the granulation pattern on the Sun's surface. The central regions exhibit blueshifts while the edges display redshifts. Image taken from [1]

Solar granulation arises due to the "eruption" of the convective zone at the base of the photosphere [3]. Spectroscopic observations of the Sun reveal asymmetries in absorption lines caused by the motion of the solar atmosphere within granules. These asymmetries occur because some parts of these convective regions are blueshifted, while others are redshifted. The bright areas of granules correspond to regions where hot gas rises through the solar atmosphere, producing blueshifts in absorption lines. As this gas releases energy in the form of photons at the photosphere, it cools and subsequently descends, creating the darker regions of granules, which exhibit redshifts in absorption lines [7].

This granulation pattern arises from convective motions within the solar photosphere. These motions consist of an upward flow of matter from hotter inner layers to cooler outer regions—and vice versa. This dynamic process induces perturbations in spectral absorption lines, profile asymmetries, and depth-dependent wavelength shifts [4].

In resume is a graphic of doppler shift against line depth, it shows that weaker lines are more blueshifted. Is important because granultion patterns in stars resemble solar patterns, differing only by a scaling factor. Furthermore, these analysis contributes to the understanding and radiation of photospheric hydrodynamic models [8, 3].

2.6 Perturbations in Spectral Absorption Lines

2.6.1 Relativistic Doppler Effect

The Doppler effect is a wave phenomenon caused by the relative motion between a source and an observer, resulting in a measurable shift in the electromagnetic spectrum compared to laboratory or catalog reference values. However, in astronomical contexts—where velocities can be significant—the relativistic formulation of this effect must be applied.

The relativistic Doppler effect accounts for length contraction, as predicted by Einstein's theory of relativity. This introduces an additional correction term to the classical shift, which becomes particularly relevant in high-velocity scenarios or strong gravitational fields.

$$f_{obs} = f_{rep}\frac{\sqrt{1 - v_r/c}}{\sqrt{1 + v_r/c}} \tag{2.2}$$

As indicated in equation (2.2), the observed frequency f_{obs} corresponds to the light detected by an observer, while f_{rep} is the frequency emitted by the source, and v_r denotes its radial velocity [9].

$$z = \frac{\lambda_{obs} - \lambda_{rep}}{\lambda_{rep}} = \sqrt{\frac{1 - v_r/c}{1 + v_r/c}} - 1 \tag{2.3}$$

Since cosmic expansion dominates the universe's large-scale dynamics, the parameter z, known as redshift, was introduced. This term quantifies the relative recession of distant objects and can be expressed through the relativistic Doppler effect, as shown in equation (2.3).

2.6.2 Convective Blueshift and Relative Velocity

However, in our study, we will define this blueshift resulting from specific motions as *convective blueshifts*. This phenomenon occurs when spectral lines in stellar light, including the Sun's, appear shifted toward shorter wavelengths due to convective motions in the star's atmosphere [3]. Taking into account that most astronomical phenomena move with velocities much smaller than light, the equation (2.3) can be approximated to first order.

$$\sqrt{1 \pm v_r/c} \approx 1 \pm \frac{v_r}{2c} \quad \rightarrow \quad z \approx \frac{v_r}{c} \tag{2.4}$$

From the expression (2.4), is advantageous to reform for the equation (2.5) with the approximation of relative velocity.

$$v_r \approx c\frac{\lambda_{obs} - \lambda_{rep}}{\lambda_{rep}} \tag{2.5}$$

With this equation the calculus of relative velocity is straightforward; therefore, the perturbations in spectral absorption lines.

This phenomena is a impediment to determing true radial velocities of stars to accuracies better than a few hundred m/s. Since the strength of the convective distortions and shifts os spectral lines varies across the H-R diagram, we expect the systematic errors in radial velocities [3].

2.7 Asymmetries on Absorption Lines

Absorption spectra from the solar photosphere exhibit asymmetries that may be measured using the bisector method. This technique involves tracing a line connecting the midpoints between the spectral profile's wings at different intensity levels. The phenomenon is particularly prominent in spectral lines of pure elements; for this study, we specifically focus on neutral iron lines (Fe I) due to their low sensitivity to thermal motion, and other virtues, as mention below.

The solar spectrum reveals that our star emits radiation in the visible and infrared ranges following approximately a blackbody curve. This behavior indicates the presence of a continuous opacity source across the observed electromagnetic spectrum. This continuum opacity is primarily due to H^+ ions in the photosphere, which are responsible for hydrogen's contributions to the spectral continuum. According to Kirchhoff's laws, absorption line formation requires lower temperature conditions, which are found precisely in the Sun's outermost atmospheric layers [7]. These regions not only provide the appropriate temperatures for absorption line formation but also exhibit comparatively higher opacity. Among all available spectral lines, those from neutral iron are particularly valuable for solar granulation studies due to two key characteristics: they display significant opacity and relatively low thermal broadening. These properties make Fe I lines excellent tracers of granulation patterns in the solar photosphere [2].

These asymmetries are physically significant because absorption line profiles should theoretically be symmetric under ideal conditions. Their detection directly reveals the influence of photospheric granulation patterns. As demonstrated by Nieminen [2], the asymmetry occurs because each individual profile component contributes a distinct con-

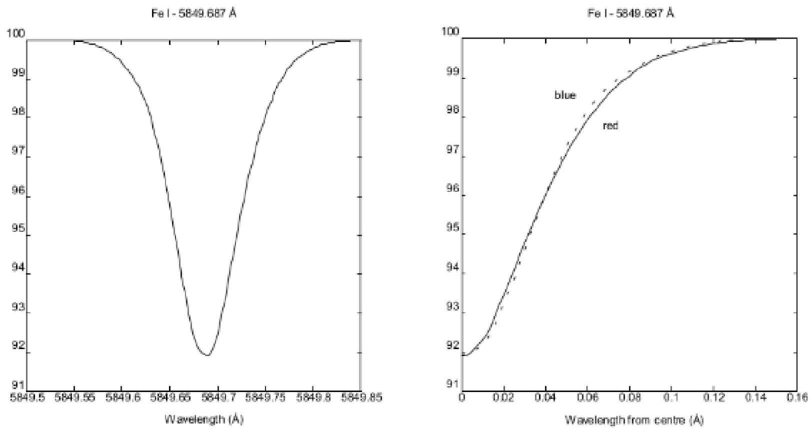

Figure 2.2: Asymmetries on an average absorption line. Can be observed the differences in intensity redshift profile. Image taken from [2]

vective blueshift, reflecting velocity variations between atmospheric layers where convection dominates and the more stable interior regions (see figure 2.2).

Defining the base of what we recognize as the photosphere is not a trivial task, primarily due to the dependence of optical depth on wavelength. This means that the observed radiation must traverse varying densities within the solar medium, where the temperature gradient across this atmospheric layer significantly influences its propagation.

2.8 Chromo-dependence

In the computational project undertaken by the student Manuel Fuentes, the presence of wavelength-dependent variations, known as chromatic dependence, was identified. A complete understanding of this phenomenon remains elusive, necessitating further investigation to analyze it in conjunction with the infrared spectrum.

Indeed, the existing body of research contains limited references to chromatic dependence within the Sun's photosphere. The present proposal aims to explore the underlying factors contributing to this effect; a possible explanation combines rotational line broadening with color-dependent limb darkening [10].

Ellwarth et. al [11] indicates that the wavelength sensitivity of Doppler velocities increases with line depth, highlighting that shorter wavelengths tend to form deeper within the solar atmosphere, where the surface contrast is larger.

Chapter 3

Methodology: Analysis of IAG Solar Flux Spectrum

As the spectral analysis is complicated cause the convective motion, I take an computational approach leading an observational requirement to lead the research.

3.1 Methodology

This research endeavor encompass both analytical and computational components. For the last part, the programming language Python and Jupyter Notebook was used.
The computational aspect focus on identifying the granulation pattern within the solar spectrum by calculating relative velocities using the wavelengths of Fe I.
All analysis data and code used in the process will be uploaded to a GitHub repository, allowing anyone interested to reproduce the results and verify the authenticity of the conclusions presented. Moreover, proper credit will be given to all previous work from other researchers.

3.2 Code optimization

3.2.1 Z-score Standardization

3.2.2 Blend-free Fe I line list

3.3 Spatial resolved solar spectrum

Chapter 4

Results and discussion: Granulation pattern and Characterization of chromodependence

Chapter 5

Conclusions

In terms of conclusions, I have a good graphic :D

Bibliography

[1] S. A. Hamouda, F. F. Alfarjani, and F. Y. Elfituri, "Sunspots production and relation to other phenomena: A review," *International Journal of Science and Research Methodology*, 06 2018.

[2] T. A. Nieminen, "Solar line asymmetries: Modelling the effect of granulation on the solar spectrum," *arXiv*, Aug. 2017. arXiv:1708.06408 [astro-ph].

[3] D. F. Gray, "The third signature of stelar granulation," *The Astrophysical Journal*, vol. 697, p. 1032, May 2009.

[4] D. F. Gray and T. Pugh, "The third signature of granulation in bright-giant and supergiant stars," *The Astronomical Journal*, vol. 143, p. 92, Mar. 2012.

[5] P. Eric, *Solar magnetohydrodynamics*. Kluwer, 1982.

[6] F. Peter, *Solar Astrophysics*. Cambridge research and instrumentation, 1990.

[7] B. Carroll and D. Ostlie, *An Introduction to Modern Astrophysics*. Cambridge University Press, 2017.

[8] D. Dravins, L. Lindegren, and A. Nordlund, "Solar granulation - influence of convection on spectral line asymmetries and wavelength shifts," *Astronomy and Astrophysics*, vol. 96, p. 345–364, Mar. 1981.

[9] B. Ryden, *Introduction to cosmology*. Cambridge University Press, 2016.

[10] D. Hamilton and J. B. Lester, "A technique for the study of stellar convection: The visible solar flux spectrum," *Publications of the Astronomical Society of the Pacific*, vol. 111, p. 1132, Sept. 1999.

[11] M. Ellwarth, B. Ehmann, S. Schäfer, and A. Reiners, "Convective characteristics of fe i lines across the solar disc," *Astronomy and Astrophysics*, vol. 680, p. A62, Dec. 2023.

[12] J. S. Aponte, "Medición de la velocidad convectiva en la fotosfera solar," 2017.

[13] F. Stief, J. Löhner-Böttcher, W. Schmidt, T. Steinmetz, and R. Holzwarth, "Convective blueshifts in the solar atmosphere - ii. high-accuracy observations of the fe i 6173.3 Å line and deviations of full-disk dopplergrams," *Astronomy & Astrophysics*, vol. 622, p. A34, Feb. 2019.