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P-mode power variation with solar atmosphere as observed in the NaD1 and K spectral line

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In this work we investigate p-mode power variation with solar atmosphere. To this aim we use THÉMIS observations of NaD1 (λ5896Å) and K(λ7699Å) spectral lines. While formation heights of K spectral line is essentially located in the photospheric layer, the formation heights of the NaD1 line span a much wider region: from photosphere up to chromosphere. Hence we had the chance to infer p-mode power variation up to the chromospheric layer. By analyzing power spectra obtained by temporal series at different points of the NaD1 and K spectral lines, we confirm and quantify the increase in p-mode power towards higher atmospheric layers. Further, the large span in formation heights of the NaD1 line induces a larger enhance in p-mode power with solar atmosphere compared to the K spectral line.

1 Introduction

Solar oscillations are standing waves confined within a cavity. But only acoustic oscillations with frequencies below the Lamb acoustic cut-off frequency (ν_{ac}) are trapped in the resonant cavities beneath the photosphere, while the motion behaves exponentially in the atmosphere. This exponential behavior provides the upper reflection of p modes. Solar atmospheric theory shows (Balmforth et al. (2003)) that the acoustic cutoff frequency for the solar atmosphere is $\sim$5300μHz. For $\nu \geq \nu_{ac}$ p modes are no longer trapped in the Sun's interior and propagate through the chromosphere as traveling waves. The waves that are observed come primarily from the position in the atmosphere, where the waves are evanescent. Therefore as we move higher up in the Sun's atmosphere, due to the decreased density, the pressure waves have a larger amplitude.

Solar oscillations can be observed by Doppler shifts of spectral lines. Since variations of the opacity with wavelength correspond to a change of the depth at which the emerging radiation is formed, any oscillation measured using a particular solar line will originate at different heights of the solar atmosphere. This allows us to detect the increase in p-mode power with atmosphere, by comparing oscillation amplitude obtained in spectral lines formed at different atmospheric layers. In fact, the farthest points from the line center of a spectral line are generated in the lower layers of a stellar atmosphere, while, the closest points to the line center of the spectral line in the higher layers. In the mid 1980s Isaak (Isaak et al. (1989)) used both potassium (K) and sodium (Na) resonance scattering spectrometers to simultaneously record Doppler velocity measurements from the Sun. The two instruments, operated at the same site (Observatorio del Teide, Tenerife) from August 12th to September 16th 1985, yielded 27 days of useful data. As sodium is more abundant in the Sun's atmosphere, unit optical depth (i.e. the height at which 1/e photons can escape without further interaction), is achieved higher up in the atmosphere than for the less abundant potassium. They found that amplitudes of the signal observed using NaD1 was larger than K. This investigation aims to characterize p-mode power variation with atmosphere when observing the solar surface with NaD1 and K spectral lines. The results of this survey could have strong implications for ground based networks like BiSON(**Bi**rmingham **S**olar **O**scillation **N**etwork and GONG(**G**lobal **O**scillation **N**etwork **G**roup). In fact we will show that it is possible to improve the signal to noise ratio by using solar oscillations measurements at different heights of the solar atmosphere.

2 The Data sets

2.1 The observations

THÉMIS telescope allowed to make simultaneous measurements of several spectral lines: NaD1 (λ5896Å), Fe(λ6173Å), K(λ7699Å), Ni (λ7777Å). Two of them are used to perform Sun-integrated Doppler shift velocity measurements for helioseismological purposes: 1) GOLF experiment on board of the SOHO (**SO**lar and **H**eliospheric **O**bservatory) satellite launched in December 1995 (Domingo et al. (1995), Gabriel et al. (1995)). It measures the Doppler shift of the neutral sodium doublet (NaD1 λ5896Å, NaD2 λ5890Å); 2)

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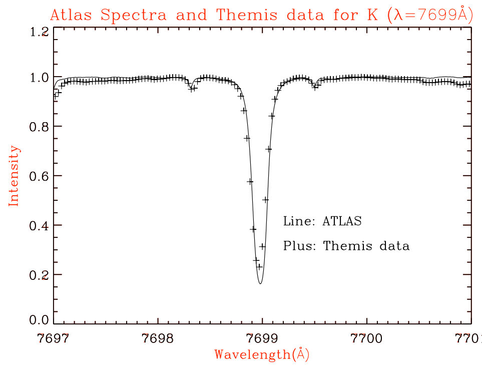

Fig. 1 A comparison of the observed (plus sign) spectral line K(λ7699Å) with the ATLAS spectra (continuous line).

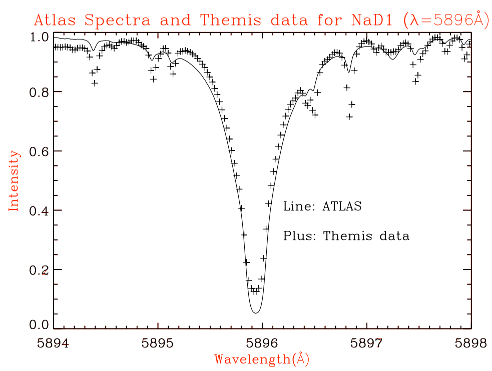

Fig. 2 A comparison of the observed (plus sign) spectral line NaD1(λ5896Å) with the ATLAS spectra (continuous line).

BiSON, made of six stations distributed around the world, performs Doppler shift measurements of the K (λ7699 Å) line (Chaplin, et al. (1996)). The observations have been taken on the 30th of August 2005 in the quiet and active Sun. They consist of time series of about 50 minutes of high resolution with a cadence time of 50 seconds. The spatial resolution is 0.44 arcsec per pixel. In this survey we use the data in quiet Sun and we will use, for our purposes, only the two helioseismological NaD1 and K spectral lines.

2.2 The SQUV data reduction

We used SQUV (**S**tokes **Qu**ick **V**iewer) for the retrieval of the Stokes parameters from raw THÉMIS data. Fig. 1-2 show K and NaD1 absorption line profiles compared with the spectra gathered from the instruments placed aboard the space platform, **AT**mospheric **L**aboratory for **A**pplications and **S**cience (ATLAS). K and NaD1 spectral lines are pretty much different; in fact the NaD1 line is disturbed by the presence of a blended Fe line (λ5895.007 Å) and with two unknown lines at $\sim$ 5896.3 Å. Furthermore we can spot few similarities between the two spectral lines:

- the level of the continuum in both profiles is a bit different from the one provided by the ATLAS spectra;

- the bottom of the two lines is a bit higher up compared to the one provided by ATLAS spectra;

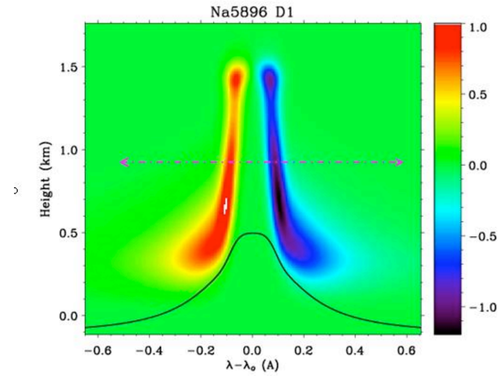

Fig. 3 Response Functions (RFs) for the observed spectral lines. On x axis we have the shift in wavelength, while on y axis we have the height in kilometers.The height in Km is in 10^3. Red colors, therefore, identify intensity enhancements, while blue color refer to decrease in intensity.The purple line represents the begin of the chromospheric region.

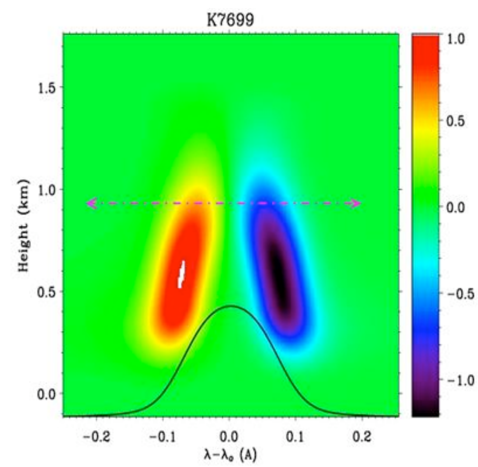

Fig. 4 Response Functions (RFs) for the observed spectral lines. On x axis we have the shift in wavelength, while on y axis we have the height in kilometers.The height in Km is in 10^3. Red colors, therefore, identify intensity enhancements, while blue color refer to decrease in intensity.The purple line represents the begin of the chromospheric region.

- the position of the minimum in both cases is shifted towards blue value.

We adjusted these differences by performing the calibration of the signal.

2.3 The formation heights of the spectral lines

Response functions (RFs) to velocity perturbations are a powerful tool for the analysis of the information content and diagnostic potential of spectral lines. These functions measure the reaction of the line profile when the atmosphere is perturbed locally at a given height (Jiménez-Reyes et al. (2007); Socas-Navarro et al. (1998)). Fig. 3-4 show the RFs for NaD1 and K spectral lines. The shape of the two RFS are pretty much different. They span completely different regions of the solar atmosphere. Keeping in mind that the

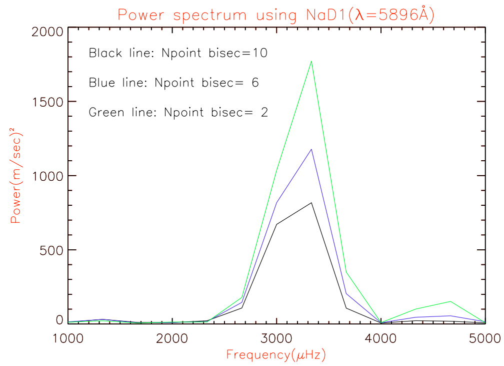

Fig. 5 Power spectrum as obtained at different points of the NaD1 spectral lines. Different colors identify time series obtained by different points along the NaD1 line. Black curve is the FFT obtained by the farthest point from the line center of the absorption line. Green curve is the FFT obtained by the closest point from the line center of the absorption line.

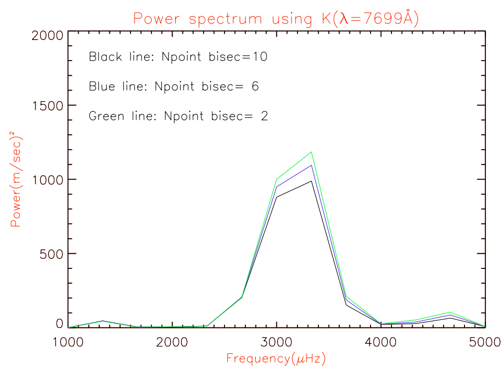

Fig. 6 Power spectrum as obtained at different points of the K spectral lines. Different colors identify time series obtained by different points along the NaD1 line. Black curve is the FFT obtained by the farthest point from the line center of the absorption line. Green curve is the FFT obtained by the closest point from the line center of the absorption line.

chromosphere begins at about 800-900 Km above the solar surface, we can state that K RFs is almost concentrated in the photosphere, while NaD1 RFs has a further component in the chromosphere. Therefore the NaD1 spectral line gives us the chance to span a much wider region of the solar atmosphere.

3 Oscillations in Sun's atmosphere

3.1 The velocity power as observed with NaD1 and K spetral line

We build velocity time series corresponding to each point of the spectral line, by applying the bisector method. Then we performed the Fast Fourier Transform and we obtained the p-mode power spectrum at different heights in the solar atmosphere of solar oscillations. Fig.3 shows the power spectrum obtained by the observations made on K and NaD1 line. The length of observations was 50 minutes, hence we

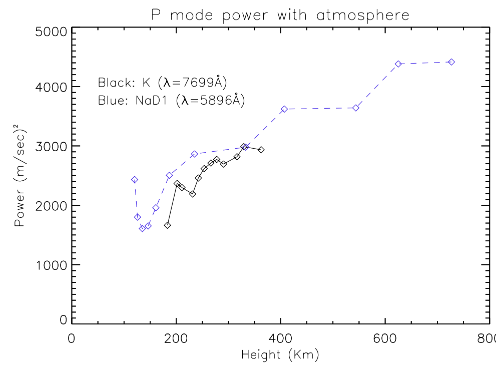

Fig. 7 P-mode power variation with solar atmosphere for the NaD1 and K spectral lines.Black line represents the p-mode power variation as observed with K spectral line, while blue line is p-mode power variation determined with NaD1 spectral line.

got a resolution of 0.3 mHz. With this resolution we are not able to resolve the modes in the frequency range of the five minute oscillations, but we observe an enhance in the power in that interval, where the oscillations are supposed to be. As we expected the power increases with the altitude, but we can clearly see a greater enhance in the power from the NaD1 line compared to the one observed with the K line. While in fact for the potassium line the increase we have is about of 15%, for the NaD1 line is around twice of the intial power. Further, the greater enhance in p-mode power is observed in the region of 3-4mHz, while at low frequency this effect is rather weak.

3.2 P mode power with height

To the aim to get an estimate of the height at which the profile is formed for each of the points along the absorption line profile, we decided to take as height the point at which the RFs reaches 50% of its integrated value. Fig. 7 shows the p-mode power as function of the height by using the NaD1 and K lines. As we expected the two lines are pretty much different as result of the regions in the atmosphere they explore: ideally, we can travel through areas from ~150 km above the photosphere up to 800 km with the NaD1 line. Because of this, the enhance in power, corresponding to the NaD1 spectral line, is much stronger compared to the enhance in power with the K spectral line. From photosphere to chromosphere the gain in p-mode power is double, when we observe the Sun with NaD1 spectral line.

4 Conclusions

We investigated p-mode power variation with solar atmosphere. To this aim we used THÉMIS observations of NaD1 and K spectral lines. Theoretically we expect to observe an enhance in p-mode power as we observe higher up in the solar atmosphere. NaD1 and K spectral line are formed in two different regions of the solar atmosphere: K spectral line has a photospheric origin (Fig.4), while NaD1 spectral line has its origin in two different solar atmospheric layers: one component has a photospheric origin and the second one a chromospheric origin at around 800Km (Fig.3).

Theoretically we expect to observe an enhance in p-mode power with atmosphere. We observed this enhance and we quantified the increase in p-mode power: the velocity oscillation amplitude double its value, when the observations are performed at different points on the NaD1 line in a frequency range of 2-4mHz. At low frequencies, the variation of the relative signal strengths with NaD1 line in the atmosphere is rather weak. Therefore, observing at different heights in the solar atmosphere could help us in reducing the intrinsic solar noise into the Doppler velocity signal.

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