ASTEROSEISMOLOGY FROM EQUIVALENT WIDTHS: A TEST OF THE SUN

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1. Introduction

Kjeldsen et al. (1995) reported a probable detection of solar-like, low-amplitude p-mode oscillations in η Bootes using equivalent width measurements from low-resolution spectra of hydrogen Balmer lines. However, this detection has not been confirmed so far. Indeed, there is no confirmed detection of p-mode oscillations in a solar-like star using the equivalent width technique or any other approach (Bedding 1998).

An important test of the equivalent width method consists in applying it to integrated solar light. This has been done by Kjeldsen et al. (1995), but they did not detect an obvious excess in the power spectrum at 3 mHz at their noise level of 5.1 ppm. While techniques such as accurate Doppler measurements have been tested using solar light, there has been no successful test of the equivalent width technique using Balmer lines on the Sun.

We recently obtained six continuous days of solar integrated light measurements with a low-resolution spectrograph, but have failed so far to see clear evidence for p modes. Hence, we recorded resolved solar observations where we integrated only over a small part of the solar disk to enhance the apparent amplitude of the oscillations. This allows us to test the equivalent width technique, understand how it works, estimate the expected amplitude for integrated sunlight measurements, and compare it to theoretical amplitude predictions for the Sun.

2. Observations and Data Reduction

The time series was obtained with the 1.5-m McMath-Pierce main telescope and the stellar spectrograph. The telescope was out of focus so that the effective area observed on the Sun covered about 1 arcmin. One camera of the Zurich Imaging Stokes Polarimeter ZIMPOL I (e.g. Keller 1992, Povel 1995) with its fast read-out of 38 ms per frame and 12-bit sampling was used to obtain spectra at a very high signal-to-noise ratio. We observed for 4.3 hours with a sampling rate of 1/15 Hz and a dispersion of 0.27 Å/pixel. An effective signal-to-noise ratio of 2.6×10^4 per pixel was achieved by adding 128 frames in 15 s and averaging along the spectral lines.

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We subtracted the dark current and spectrograph stray-light, but no flatfield correction was applied due to the lack of a suitable lamp. However, if the flatfield is constant in time, its influence on the final power spectra should be negligible.

The Doppler velocity was determined by cross-correlating the individual spectra with the average spectrum and subtracting spectrograph drifts as measured with a fiducial mark in the optical system.

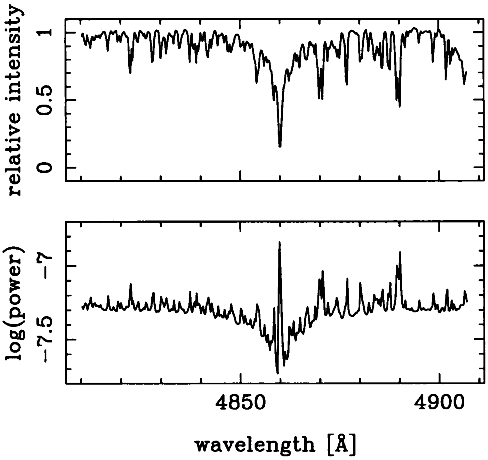

Figure 1. Power in the 2 to 4 mHz band as a function of wavelength around the Hβ line.

The following steps were applied to the time series of each spectral pixel: normalize and remove long-term trends to obtain the fractional variation independent of the intensity; decorrelate against apparent Doppler shift signal to remove the influence of intensity variations due to Doppler velocities and spectrograph drifts; and calculate the power spectrum with two-point filtering (e.g. Duvall et al. 1993) and apodization to minimize the leakage of large-amplitude low-frequency variations into the 5-minute band. Finally, the power spectra were integrated between 2 and 4 mHz to estimate the power in the 5-minute band as a function of wavelength (see Figure 1).

The Hβ equivalent width was determined by measuring the intensity in Gaussian windows centered on Hβ and two continuum locations. The equivalent width is then given by $1-I_{\mathrm{H}\beta}/I_{\mathrm{continuum}}$, and the fractional variation is determined by normalizing with a fifth-order polynomial to remove long-term variations.

Power spectra of the Doppler velocity, the intensity in the continuum windows, the Hβ window, and the Hβ equivalent width were calculated using two-point filtering and apodization.

3. Results

The 5 minute oscillations are reduced in Hβ to about 70% of the continuum signal as shown in Figure 1. A similar effect has been seen in Hγ and Hδ by Ronan et al. (1991). Therefore, at least for the sun, the equivalent width technique relies on the suppression of the oscillation signal in the Balmer lines as compared to the continuum. The measured signal corresponds to the difference in amplitude between the Hβ line and the continuum, which is only about a third of the absolute amplitude in the continuum. However, the fractional variation in the equivalent width is similar in amplitude to the fractional variation in the continuum.

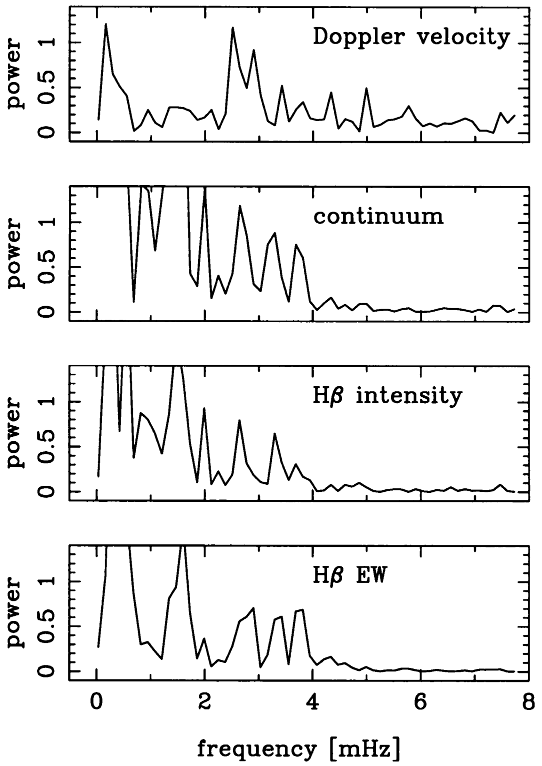

Figure 2. Power spectra of four quantities of resolved solar light (arbitrary units).

Figure 2 shows the power spectra for Doppler velocity, and the fractional variations of the continuum intensity, the Hβ intensity, and the Hβ equivalent width. The intensity measurements show considerable low-frequency power due to atmospheric transparency variations. The Hβ equivalent width shows a clear power excess around 3 mHz.

TABLE 1. Equivalent sine-wave amplitudes of solar integrated-light observations estimated from resolved solar observations.

quantity	resolved	integrated light	reference
velocity amplitude	60 m/s	0.23 m/s	Kjeldsen & Bedding (1995)
continuum amplitude	1.2×10^{-3}	4.6 ppm	estimated here
Hβ equivalent width	1.0×10^{-3}	3.8 ppm	estimated here

For asteroseismology, the amplitudes determined with these resolved observations are not of interest. What is of interest are the amplitudes we would expect for integrated light. They can indeed be estimated by assuming that the scaling factor between the velocity amplitude around 5 mHz for resolved and integrated light can also be applied to other quantities (see Table 1). This extrapolation of the oscillation signal seen in the spatially resolved data suggests an amplitude of about 3.8 ppm for integrated light measurements of the Hβ equivalent width. As usual, we quote the amplitude of a sine wave that matches the observed power spectrum.

4. Discussion

Spatially resolved observations of the Hβ equivalent width at solar disk center reveal that the oscillation signal is suppressed in the wings of Hβ as compared to the continuum. This leads to a clear signal around periods of 5 minutes in the Hβ equivalent width. The amplitude of the absolute (in contrast to the fractional) variations is about three times smaller in the equivalent width as compared to the continuum. The amplitudes of the fractional variations are of similar magnitudes. However, since the absolute amplitude is important for the signal-to-noise ratio, continuum measurements from space should be more sensitive than equivalent width observations.

Our estimate for the integrated-light continuum amplitude is in good agreement with theoretical predictions and other observations, both giving amplitudes of 4.7 ppm (Kjeldsen & Bedding 1995). Our estimate of 3.8 ppm for the amplitude of the fractional variation of the Hβ equivalent width is substantially smaller than the theoretically predicted amplitude of 6 ppm (Bedding et al. 1996). However, the accuracy of our extrapolation is limited and cannot rule out the predicted, higher amplitude.

The Hβ equivalent width power spectrum in Figure 2 shows considerable power at frequencies below 2 mHz, which is not expected since the equivalent width should be independent of atmospheric transmission variations. These variations at low temporal frequencies are not correlated with intensity fluctuations or the position of the spectrum on the detector. They might be due to wavelength dependencies of scintillation and transparency variations, tiny water vapor blends, chromospheric activity, or the evolution of solar features.

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