SOLAR 5-MINUTE OSCILLATIONS AT 2.23 μm

TORBEN LEIFSEN

Institute of Theoretical Astrophysics, University of Oslo,
*P. O. Box 1029, Blindern N-0315, Oslo 3, Norway**

Abstract. Large amplitude solar 5-min intensity oscillations have recently been detected at 2.23 μm using broad band (650 Å FWHM) photometry (Leifsen and Maltby, 1990). Large intensity amplitudes in a broad range in the near infrared was unexpected, and several questions concerning the source of the high amplitudes were raised. In an attempt to study the nature of these oscillations, time series of spectra have been obtained with the Fourier Transform Spectrometer (FTS) of the McMath telescope at National Solar Observatory at Kitt Peak. We present preliminary results from a 10 day long run in May 1991 in support for the suggestion that the results may be useful in both helio- and asteroseismological investigations.

Key words: infrared: stars – stars: oscillations – Sun: oscillations

1. Introduction

The interpretation of the observed solar 5-min oscillations as the evanescent tails of standing acoustic eigenmodes trapped in a sub-photospheric cavity (Ulrich, 1970; Leibacher and Stein, 1971) is presently widely accepted. Deubner (1975) confirmed this interpretation when the predicted ridges in the $k-\omega$ diagram was found from velocity measurements. The techniques have later been refined (e.g., Harvey and Duvall, 1984), and lately Nishikawa and Hirayama (1986) detected the predicted ridges in the $k-\omega$ diagram in broad band intensity measurements. Ground based observations of global luminosity oscillations have proven to be very difficult (Andersen and Domingo, 1986; Jimenez *et al.*, 1988), and most ground based observations of global solar oscillations are velocity measurements (e.g., Libbrecht *et al.*, 1990). High quality measurements of oscillations in the solar irradiance have been obtained from space based instruments (Woodard and Hudson, 1983).

Large amplitude infrared 2.23 μm solar intensity oscillations were detected in photometer observations obtained at Oslo Solar Observatory in 1987 and 1988. Five wavelength regions ranging from 0.67 μm to 2.23 μm and 7 circular entrance apertures ranging from 0.5 to 4.3 arcmin were observed simultaneously at all wavelengths with the same detector. The 2.23 μm region showed remarkably higher amplitudes than the other wavelength regions. The observed power was concentrated to the 2.5–3.5 mHz region, suggesting that we observe the well known 5-min oscillations. A comparison of the integrated power in the 2.5–3.5 mHz range as a function of spatial resolution shows that the power drops of toward lower resolution.

Full disk observations from June 1988 show the familiar 5-min oscillations near 3 mHz but also a strong feature near 4 mHz. This feature varies considerably from day to day, and it coincides in frequency with the fundamental p-mode resonance of the chromosphere (Deming *et al.*, 1986). However, using a second order Fourier Transform and an autocorrelation analysis it was possible to identify a 135 μHz

* Observations obtained as a Visiting Astronomer, National Solar Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

D. M. Rabin et al. (eds.), Infrared Solar Physics, 271–276.

spacing between peaks in the 4 mHz feature. This suggests a high frequency tail of the 5-min oscillations.

2. Observations and Data Reduction

Two main questions arise from the photometer observations; one relates to the high power observed at 2.23 μm and the other concerns the nature of the power spectrum. We have choosen to address these questions by using the McMath telescope with its Fourier Transform Spectrometer at the National Solar Observatory on Kitt Peak. Two observing modes were used: A 50 arcsec circular area at the solar disk center was observed using the McMath East Auxilliary Telescope. Spatially integrated light was observed using the McMath main heliostat and two flat mirrors. Active guiding was used in the imaged mode. Two time series were obtained in May 1991; one in the imaged mode at the solar disk center over a 4 day long period and one with integrated light lasting 6 days.

These observations consist of time series of spectra separated in time by 1 minute and with a spectral resolution of 0.014 Å in the spectral range 2.0–2.5 μm. Each spectrum contains 825 Kilobytes of data. Twelve hours of observations result in 580 Megabytes of data. In order to handle these long time series each spectrum was divided in shorter spectral intervals (typically 630 Å for a time series of four days duration) and stored on several optical disks. Each series of intensity measurements in time at a given wavelength element was then treated as a separate time series. Each time series was normalized by dividing by a 20 min running mean, thus removing all long period variations, and cosine bells were added at the ends and before and after interruptions in the time series. Then power spectrum analysis was applied to each time series.

One of the main aims of the project and the main reason for using the Fourier Transform Spectrometer is to identify the sources of high intensity amplitudes in the 2.0–2.5 μm region of the solar spectrum and distinguish between solar oscillations and possible oscillations originating from the terrestrial atmosphere. Line identifications were taken from *An atlas of the Solar Spectrum from 1850 to 9000* cm^{-1} (Livingston and Wallace, 1991) and the Hall (1973) atlas for solar lines, and from the HITRAN molecular database (Rothmann *et al.*, 1992) for terrestrial lines.

In order to study the variation of the power spectra as a function of wavelength, each powerspectrum was plotted in a 3-dimensional shaded-surface image (Figs. 1 and 2). The x-z plane represents power spectra at given wavelength elements. In this way we can study the variation of the power spectra by comparing the results obtained for solar atomic and molecular lines, the continuum and for lines formed in the Earths atmosphere.

3. Results

A study of the four days of disk center observations revealed the following: It was immediately apparent that a large number of spectral lines in the observed wavelength region show large intensity oscillations. A majority of these lines show a frequency distribution in the power spectrum that resembles the well known solar p-

mode oscillations. A few lines show a distinctly different frequency distribution, with some power in the 2–4 mHz region but with the power increasing strongly towards lower frequencies. These lines were indentified as water vapor lines originating in the terrestrial atmosphere. All the other lines showing high power were identified as solar lines.

There are several hundred solar spectral lines in the observed wavelength region, including the 2-0 and 3-1 bands of CO and several atomic lines. Figure 1 shows a power spectrum of an extract of the solar spectrum containing several lines from the CO 3-1 band. The ridges parallel to the y-axis correspond in wavenumber to CO lines. The familiar distribution around 3 mHz from solar p-modes are clearly seen. Figure 2 shows similar ridges in power spectra from a region in the solar spectrum containing several atomic lines.

All terrestrial molecular lines (expect water vapor), i.e., mainly CH_4, show no intensity oscillations above noise. This excludes the possibility of bands of terrestrial lines as the source of the observed high amplitude oscillations. The wavelength region shown in Figure 2 includes several CH_4 lines. None of these show intensity oscillations.

Even though water-vapor lines in the region show intensity oscillations, they are far to few and have a distinctly different power distribution to account for the observed intensity oscillations. A comparison of time series integrated over wavenumber both including and excluding the water-vapor lines show that the water vapor lines have little or no influence on the observed power spectra. The main reason for this is that relatively few water vapor lines contribute to the power and they tend to be concentrated to the edges of the 2.23 μm window.

Both molecular and atomic solar lines also show velocity oscillations with the familiar p-mode power distribution. We are currently analysing the velocity data and the phase between the velocity and line intensity oscillations. There is no doubt that the observed intensity and velocity oscillations in the solar lines are of solar origin.

There are indications of power in the 2.0–3.5 mHz region in the continuum region of the spectrum. However, the signal is comparable with noise, and no firm conclusions can be drawn yet as the noise level approaches the signal level in the photometer observations. At this point further observations are needed.

A six day long time series in spatially integrated light mode gives no firm conclusions, mainly because of telescope tracking problems during observations, introducing low-frequency power (around 1 mHz) with a severe leakage into the 3 mHz region.

4. Conclusion

The new observations obtained, with different equipment at an other site show intensity oscillations of solar origin in the 2.23 μm region. This conclusion is strengthened by the fact that terrestrial spectral lines (except water vapor) show no sign of oscillations above noise. The possible influence of water vapor absorption in the Earth's atmosphere is of minor importance due to the fact that the wavelength region in question contains only a few lines. The disk center observations show both

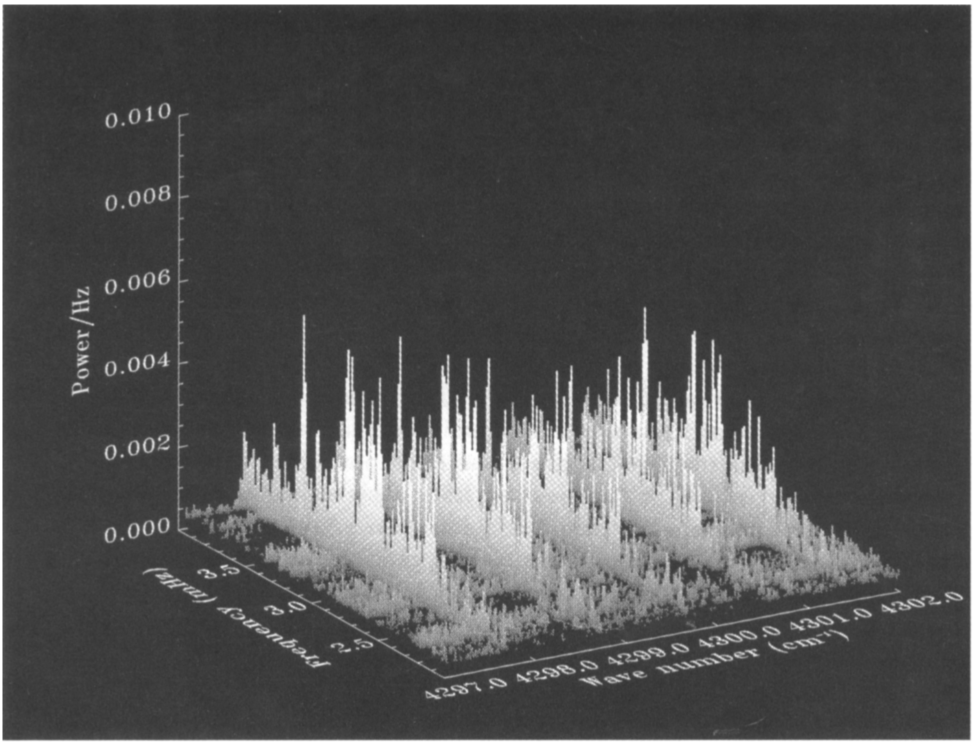

Fig. 1. Power as a function of wavelength (x-axis) and oscillation frequency (y-axis) in a time series lasting four days observed at the solar disk center. A 50 arcsec entrance aperture was used. The ridges with maximum around 3 mHz are solar intensity oscillations in the solar R36-R40 lines of the CO 3-1 band.

https://doi.org/10.1017/S0074180900124520 Published online by Cambridge University Press

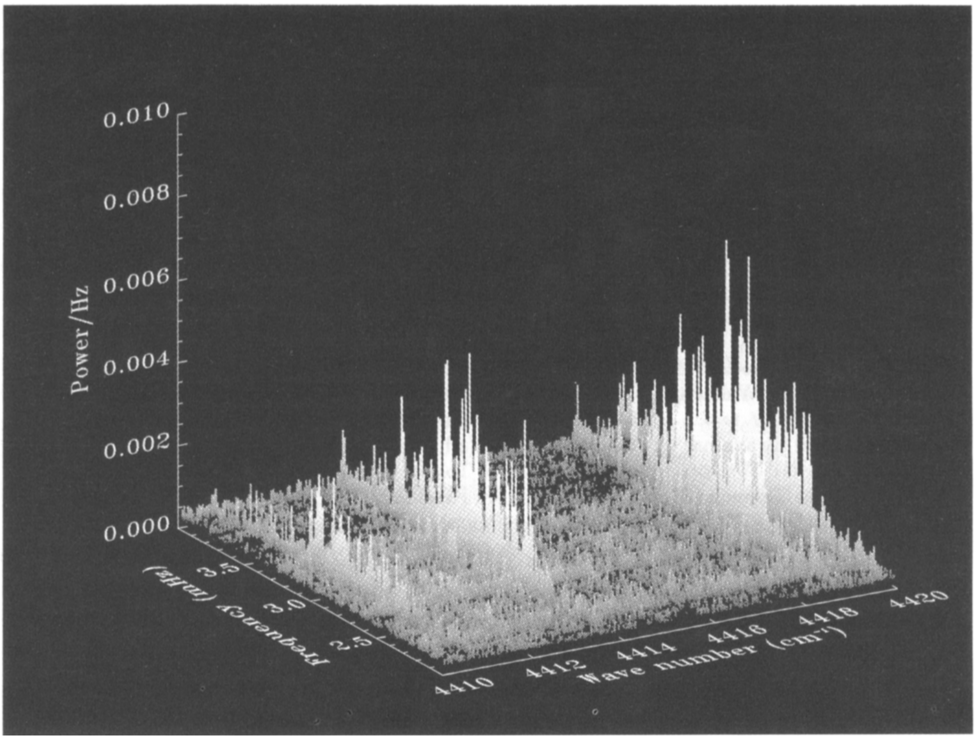

Fig. 2. Power as a function of wavelength (x-axis) and oscillation frequency (y-axis) in a four day long time series at the solar disk center with a 50 arcsec entrance aperture. The ridges are solar intensity oscillations in solar Si (4410.7 cm^{-1}), CaI (4413.1 cm^{-1}), CaI (4413.6 cm^{-1}) CaI (4418.4 cm^{-1}), CaI (4418.7 cm^{-1}) and Fe (4419.7 cm^{-1}) lines. Note that terrestrial CH_4 lines in this spectral region show no intensity oscillations.

intensity and velocity oscillations in solar lines from the CO 2-0 and 3-1 bands as well as in atomic lines in the wavelength region. We are currently working on velocity–intensity phase studies. In the case of continuum oscillations and the spatially integrated light observations an improved observing procedure including a better normalization of the FTS spectra, an improved signal/noise ratio and better telescope tracking is needed in order to obtain a signal level comparable to that of the photometer observations. This will be attempted on the McMath/FTS in a run scheduled for June 1992. In addition simultaneous photometer observations in five wavelength bands are planned with the same telescope.

Acknowledgements

I wish to thank the Telescope Allocation Committee at the National Solar Observatory for allocating observing time to the project, Paul Hartmann, Claude Plymate and Jeremy Wagner for enthusiastic observing support, Dr. Jim Brault and Greg Ladd for valuable help, and Professor Per Maltby for helpful discussions and suggestions.

References

Andersen, B. N. and Domingo, V.: 1986, in J. Christensen-Dalsgaard and S. Frandsen (eds.), 'Advances in Helio- and Asteroseismology', *IAU Symp.* **123**, 67.

Deming, D., Glenar, D., Käufl, H. U., Hill, A. A., and Espenak, F.: 1986, *Nature* **282**, 591.

Deubner, F. L.: 1975, *Astron. Astrophys.* **44**, 371.

Hall, D. N. B.: 1973, *An Atlas of Infrared Spectra of the Solar Photosphere and of Sunspot Umbrae*, Kitt Peak National Observatory, Tucson, Arizona.

Harvey, J. W. and Duvall, T. L.: 1984, *Jet Propulsion Lab. Publ.* **84-84**, 165.

Jiménez, A., Pallé, P. L., Roca Cortés, T., Andersen, B. N., Domingo, V., Alvarez, M. and Ledezma, E.: 1988, *Seismology of the Sun and Sun-like Stars*, ESA SP-286, p. 163.

Leibacher, J. W. and Stein, R. F.: 1971, *Astrophys. J. (Letters)* **7**, 191.

Leifsen, T. and Maltby, P: 1990, *Solar Phys.* **125**, 241.

Libbrecht, K. G., Woodard, M. F., and Kaufmann, J. M.: 1990, *Astrophys. J. Suppl.* **74**, 1129.

Livingston, W., and Wallace, L.: 1991, *An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000* cm^{-1} *(1.1 to 5.4 μm)*, National Solar Observatory Technical Report no. 91-001.

Nishikawa, J. and Hirayama, T.: 1986, in Y. Osaki (ed.), *Hydrodynamic and Magnetohydrodynamic Problems in the Sun and Stars*, University of Tokyo, p. 215.

Rothmann, L. S., Gamache, R. R., Tipping, R. H., Rinsland, C. P., Smith, M. A. H., Chris Benner, C., Malathy Devi, V., Flaud, J.-M., Camy-Peyret, C., Perrin, A., Goldman, A., Massie, S. T., Brown, L. R., and Toth, R. A.: 1992, *J. Quant. Spect. and Rad. Transf.*, to appear in special edition.

Ulrich, R. K.: 1970, *Astrophys. J.* **162**, 993

Woodard, M. and Hudson, H. S.: 1983, *Nature* **305**, 589.