A Search for Radial Velocity Oscillations in Procyon

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ABSTRACT. I describe here a new technique for precision radial velocity measurements, using an iodine absorption cell in front of the slit of a high resolution spectrograph. A CCD in a continuous readout mode records a timeseries of stellar spectra with a duty cycle of unity. In January 1987, observations were obtained on two clear nights with bad seeing. No oscillations were detected in the data, but the technique shows promise for significantly better results under better conditions.

Introduction. Acoustic oscillations in the sun have been observed, without spatial resolution, both as radial velocity oscillations and intensity oscillations in integrated sunlight, the latter from spacecraft measurements. A power spectrum of the solar radial velocity signal shows a series of sharp peaks uniformly spaced in frequency with a separation of 70 μHz. The oscillation power is a maximum at around 3 mHz (5-minute period) with an amplitude per mode of roughly 10 cm/sec, and the ratio of intensity to velocity oscillations is

$$\frac{(\Delta F/F)^2}{v^2(\mathrm{cm}^2/\mathrm{sec}^2)} \approx 1.5 \times 10^{-14}.$$

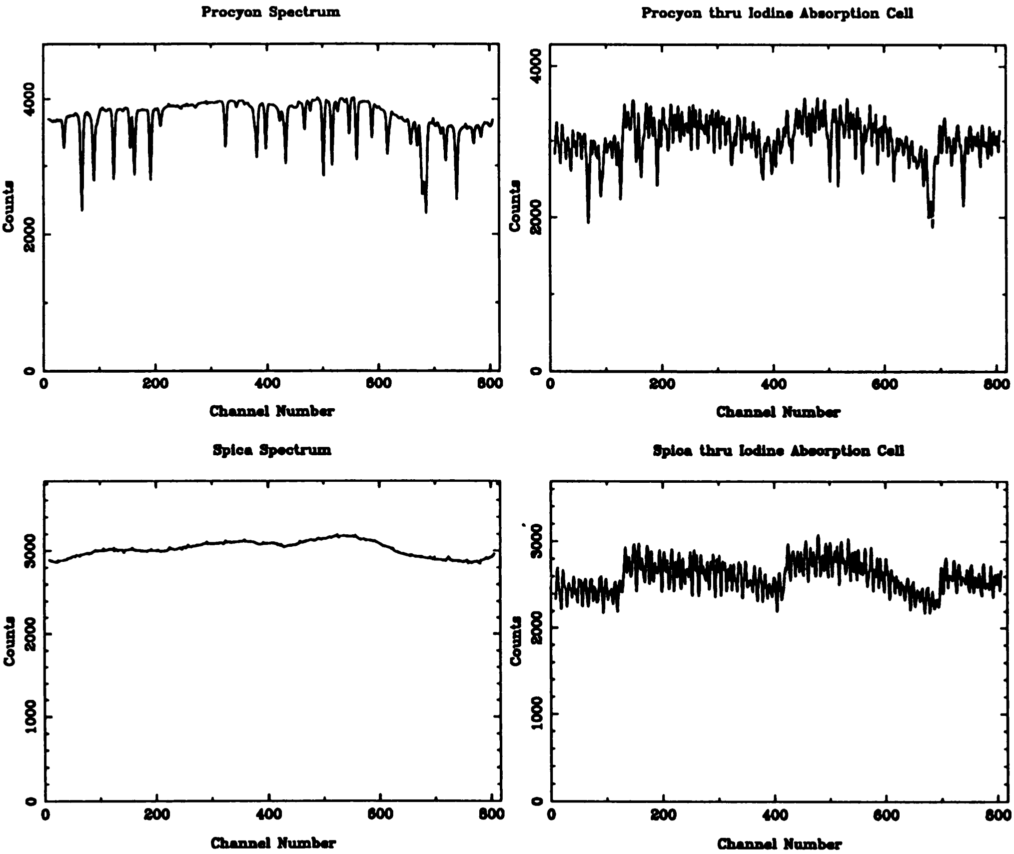
Solar oscillation frequencies are currently being used to learn about the internal structure of the sun, while the mode amplitudes provide information about the convective excitation process. It is likely that observations on other stars will be as informative as on the sun, if oscillations can be detected for some number of stars.

Since the oscillation amplitudes are very small, detection is a formidable challenge, and it is not yet certain if solar-type oscillations have been observed on stars other than Ap oscillators. Perhaps the best detection is that by Gelly, Grec, and Fossat (1986, see also Fossat, these procedings) on Procyon, using a sodium resonance filter. They measured oscillations with periods near 10 minutes, velocity amplitudes of 70 cm/sec per mode, and a mode spacing of 40 μHz. A resonance filter offers the advantage of high stability, but the disadvantage of very limited spectral coverage, namely the Na D lines. If oscillations on fainter stars are to be measured, then it is likely that radial velocity observations using many lines will be necessary.

Observations. I have been investigating a new technique for precision radial velocity measurements, using an iodine absorption cell in front of the slit of a high resolution spectrograph. Several dozen sharp iodine lines around 5350 Å, added to the stellar spectrum, serve as a stable wavelength reference spectrum, and there is no inherent restriction on the number of stellar lines that

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 83–86.

can be used. In order to obtain an adequate duty cycle for a bright star such as Procyon, the CCD detector was read out slowly and continuously, giving a timeseries of spectra with a duty cycle of unity.



Procyon Spectrum

Procyon thru Iodine Absorption Cell

Spica Spectrum

Spica thru Iodine Absorption Cell

Figure 1. Sample stellar spectra, taken with the 5-meter Hale telescope coude spectrograph. A TI 800 x 800 CCD was used, covering a region of the spectrum 50 Å wide near 5350 Å.

Figure 1 shows a sample of the data. At the beginning of each evening's observations a reference Procyon spectrum was taken, followed by a spectrum of Spica which served as a flat-field, and a spectrum of Spica through the iodine cell. The rest of the night was used collecting a timeseries of spectra of Procyon through the iodine cell. Due to bad weather only two useable nights of observations were obtained, with 3 arcsecond seeing. In order to keep the highest spectral resolution, a fairly narrow 0.25 arcsec slit was used, and measurement showed that the bad seeing caused a factor of 10 in light to be lost at the slit.

In a one-minute integration a velocity accuracy of approximately 15 m/sec was achieved with this data. After subtracting the known shifts due to earth rotation, slow drifts in the measured

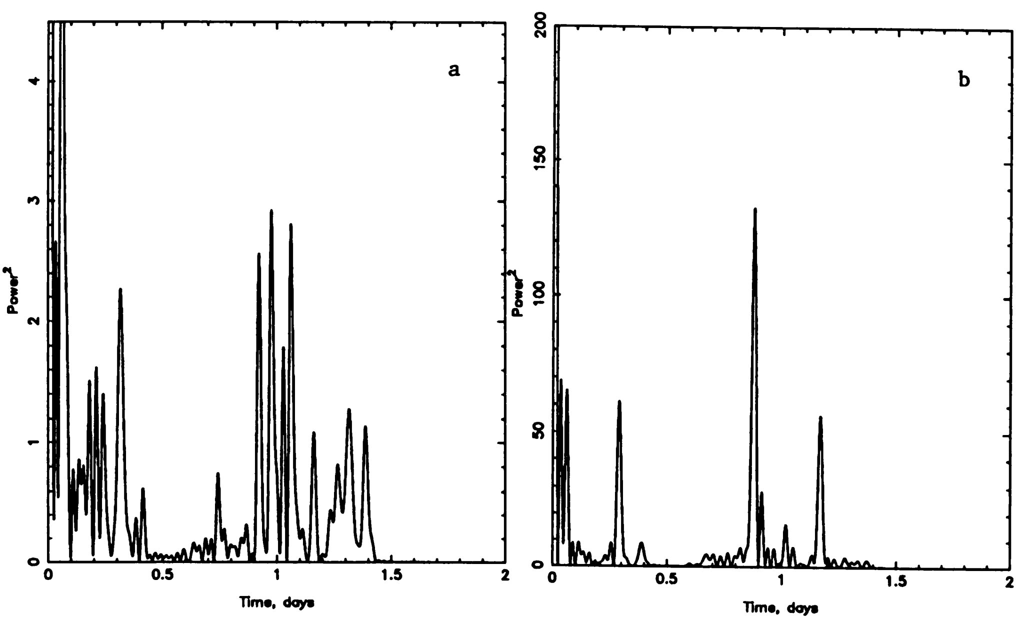


Figure 2. (a) Power spectrum of the velocity power spectrum, where the power outside the region 1.17 to 1.65 mHz was set to zero. The process follows the analysis described by Gelly, Grec, and Fossat, and produces an autocorrelation function. (b) The same analysis applied to the same data, but with an oscillation of 3 m/sec/mode added to the raw data, with a mode spacing of 40 μHz.

velocity were observed at the level of nearly 100 m/sec, which were found to be correlated with fluctuations in the density of iodine in the cell (and thus presumably with the iodine temperature, since the cell heater was not in a servo loop). The stability of the system was adequate for measuring acoustic oscillations, and with better temperature regulation the long-term stability could be greatly improved.

Using the known count/photon ratio of the CCD, and the measured Procyon spectrum in Figure 1, the measured velocity noise was found to be comparable to that expected from simple photon counting noise. However it must be noted that one photon was counted only for every 800 which struck the primary mirror. This poor efficiency was the result of an overall spectrograph efficiency of approximately 2 percent, the factor of 10 loss at the slit mentioned above, and losses from absorption in the iodine cell. Thus the realization of the photon noise limit was due in part to the poor photon counting efficiency.

The timeseries of radial velocity measurments was Fourier transformed, producing a power spectrum which was not distinguishable from random noise. To search for an oscillation spectrum with modes that are uniformly spaced in frequency, the analysis described by Gelly, Grec, and Fossat (1986) was performed. Basically the power spectrum was itself Fourier tranformed over the frequency range 1.17-1.65 mHz, forming an autocorrelation of the data. If a solar-type spectrum were present in the data, then a set of uniformly spaced peaks should appear in the autocorrelation function, along with nulls for the daytime gaps. The results are shown in Figure 2, both for the data and for the data with an artifical oscillation signal added to the measured velocity timeseries. From this we see that no oscillations are present in these data, and that an upper limit of 1 m/sec/mode is indicated. These data are consistent with the French detection of 70 cm/sec/mode.

The Future. Although the present data are not good enough to detect acoustic oscillations in Procyon, I believe the measurement technique described is worthy of further attention. First of all, with better seeing and a good image slicer or scrambler, most of the slit losses could be avoided, giving a factor of 3 increase in the velocity S/N. Although the spectrograph efficiency seems poor, it is unlikely to be greatly improved in the future, since even the very carefully designed Hamilton spectrograph boasts an efficiency of 4 percent (see Vogt, these proceedings). The biggest gain will come by replacing the 50 Å wavelength coverage here by several thousand Angstroms, giving an additional improvement of a factor of 5-10. With these improvements it is likely that oscillations could be measured on many stars.

Although existing echelle spectrographs could provide the extended wavelength coverage desired, it is worth noting that the duty cycle on a bright star is quite low with current machines (say, 5 seconds to expose, followed by 45 seconds to read out), and so unless fast-readout CCDs are pressed into service it will be difficult to achieve these gains.

Reference

Gelly, B., Grec, G., and Fossat, E. 1986, *Astron. Astrophys.* **164**, 383.

S. Vogt: I think that the thing which is limiting you at the moment is your relatively low dispersion. Assuming typical wavelength accuracies of 0.01 pixels, your limit should be ~ 40 m/sec. It's primarily a question of dispersion, not S/N.

K. Libbrecht: Nothing fundamental limits you to 0.01 pixel. For instance, most of my work on solar oscillations is done with 0.25 Å resolution, and we measure down to 1 mm/sec.

G. Walker: Once one tries to measure displacements of less than 10 m/sec there are seeing effects, microseismic effects, and drifts, all which can become important. I agree that high dispersion is called for, combined with a vacuum spectrograph.

K. Libbrecht: The iodine reference spectrum reduces most of these problems, especially seeing across the slit. We may see small systematic errors with higher S/N, but for now all our high frequency errors are explained by simple photon noise. That's the problem we need to really worry about when looking for these short-period oscillations.

D. Baade: Is the precision of you measurements conceivably limited by Spica being a double-lined spectroscopic binary and also a nonradial oscillator?

K. Libbrecht: I don't think that's a problem.

E. Fossat: I would like to remind you, or should I say sell you, of the project of Pierre Connes, of an absolute accelerometer taking advantage of the whole stellar spectrum. Unfortunately, Connes himself has not given a price for this project. I don't know who can pay for it.