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Observing solar-like oscillations: recent results

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Abstract. We review recent progress in observations of ground-based oscillations. Excellent observations now exist for a few stars (α Cen A and B, μ Ara), while there is some controversy over others (Procyon, η Boo). We have reached the stage where single-site observations are of limited value and where careful planning is needed to ensure the future of asteroseismology.

Key words. stars: individual (α Cen A, α Cen B, Procyon, η Boo, μ Ara, β Vir, HR 2530, ϵ Oph, η Ser, ξ Hya) — stars: oscillations — Sun: helioseismology

1. Introduction

Observations of solar-like oscillations are accumulating rapidly. It is amazing to recall that only a few years ago, and despite intense efforts by several groups, we were still waiting for the first confirmed detection. Oscillations have now been measured for many main-sequence and subgiant stars using spectrographs such as CORALIE, ELODIE, HARPS, UCLES and UVES. In this review we concentrate on some of the most recent results – for reviews of earlier work, see Bouchy & Carrier (2003) and Bedding & Kjeldsen (2003).

2. Velocity versus Intensity

Which method is to be preferred for measuring oscillations? It is helpful to examine the wealth of superb oscillation data available for the Sun. Figure 1 shows amplitude spectra from 20-d time series taken with two different instruments on board the SOHO spacecraft: GOLF (which measures velocity) and VIRGO (which measures intensity). In both cases the Sun is observed as a star, with the light being integrated over the full disk. Both these amplitude spectra show the regular series of peaks that is characteristic of an oscillating sphere, but we also see a sloping background from granulation that is much higher in intensity than in velocity. This background represents a fundamental noise limit and makes velocity observations of stars potentially much more sensitive than photometry.

Another well-known advantage of velocity measurements, although not discernible in Fig. 1, is that the $l = 3$ modes are much stronger. This occurs because we measure velocities projected onto the line of sight, which gives more sensitivity to the centre of the disk relative to the limb and reduces the tendency for high-degree modes to cancel out (Christensen-Dalsgaard & Gough, 1982). The

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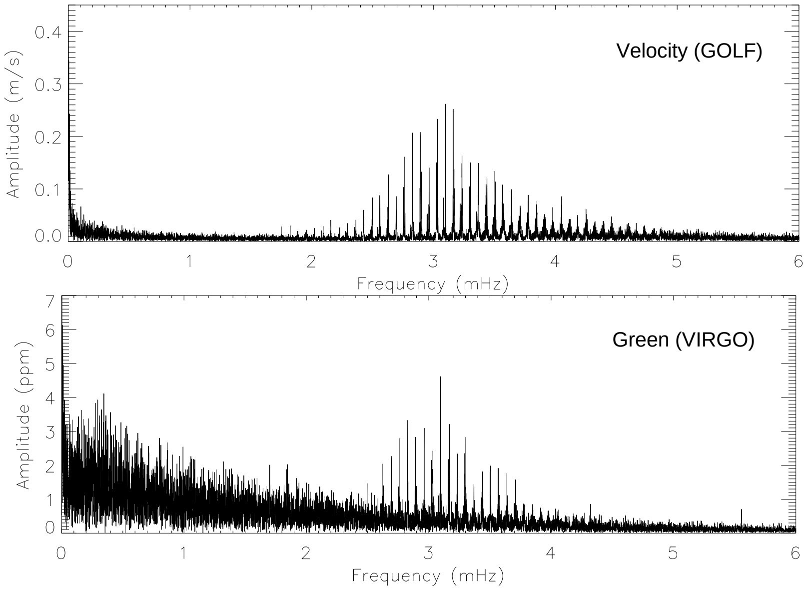

Fig. 1. Amplitude spectra (square root of power) of 20 days of full-disk observations of the Sun from the SOHO spacecraft made in velocity (top) and intensity (bottom). The background is due to fluctuations from solar granulation, which is much stronger in intensity than in velocity. Note that the two observations were not simultaneous.

disadvantage of measuring velocity is that one requires a very stable and sophisticated spectrograph. Such spectrographs are normally mounted on large and heavily oversubscribed telescopes, which makes it difficult to organize multi-site campaigns.

Attempts have been made to measure solar-like oscillations in intensity, but stellar photometry from low-altitude sites is strongly affected by atmospheric scintillation, and the best efforts have so far fallen short of a clear detection (e.g., Gilliland et al., 1993). There is hope that the high Antarctic plateau may offer excellent conditions. If so, the best targets will probably be clusters of stars, and perhaps rapid rotators that are unsuitable for Doppler measurements. Photometry from space is unaffected by scintillation but there are other challenges, in addition to granulation noise, particularly from scattered light from the Sun and Earth. An enormous advantage of space, shared to some extent by Antarctica, is the possibility of long continuous observing runs. For the moment, most of the results in solar-like oscillations are coming from ground-based Doppler measurements, with a growing input from space telescopes such as MOST, WIRE and hopefully COROT, which is due for launch in 2006. In the next sections we review some of the recent results.

3. α Cen A and B

The clear detection of p-mode oscillations in α Cen A by Bouchy & Carrier (2002) using the CORALIE spectrograph represented a key moment in this field. This was followed by a dual-site campaign on this star (Bedding et al., 2004), plus single-site (Carrier & Bourban, 2003) and dual-site (Kjeldsen et al., 2005) observations of the B component. The result is a set of frequencies, together with estimates of mode lifetimes, that should keep theoreticians busy for some time. However, further observations with higher sensitivity are desirable in order to measure modes with low amplitude and hence increase the number of detected modes.

4. Procyon

Procyon has long been a favourite target for oscillation searches. There have been at least eight separate velocity studies, mostly single-site, that have reported a hump of excess power around 0.5–1.5 mHz. However, there is not yet agreement on the oscillation frequencies, although a consensus is emerging that the large separation is about 55 μHz.

Considerable controversy has been generated by the non-detection of oscillations in Procyon from photometry with the MOST satellite, reported by Matthews et al. (2004). Their interpretation has been strongly criticized by Bedding et al. (2005), who maintained that the noise level in the MOST photometry is too high for the signal to be detected. Support for this is given by space-based photometry with the WIRE satellite by Bruntt et al. (2005), who reported a noise level lower than that of MOST. By fitting to the power density spectrum, they extracted parameters for the stellar granulation and found evidence for an excess due to p-mode oscillations. It is clear that Procyon will remain an interesting (and controversial) target. Finally, we point out an interesting feature: all the published velocity power spectra appear to show a dip at 1.0 mHz (see Bouchy et al. 2004 and Claudi et al. 2005 for the most recent examples and Bedding et al. 2005 for a full list of references). This dip is visible in the raw plots but should be even more pronounced if the power spectra are smoothed. An example is shown in Fig. 2, based on velocity measurements of Procyon with the CORALIE spectrograph by Eggenberger et al. (2004), kindly provided by those authors. The dotted curve shows a fit to the background (instrumental, stellar granulation and photon noise). Above this, the excess of power due to p-mode oscillations has a double-humped structure with a dip at 1 mHz. Interestingly, theoretical models by Houdek et al. (1999) of a evolving star with a similar mass and age to Procyon (their Fig. 4) show a dip in the damping rate at a similar frequency. If the dip in Procyon turns out to be real, it opens the possibility of treating the shape of the oscillation envelope as another observable that can be extracted from the power spectrum and compared with theoretical models.

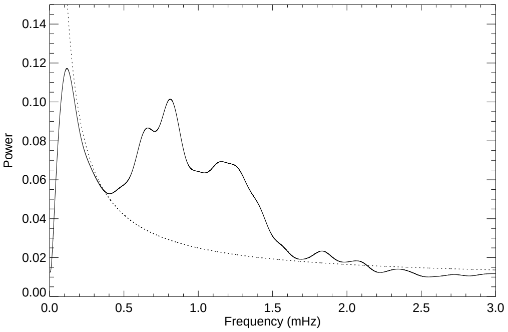

Fig. 2. Smoothed power spectrum of Procyon, based on velocity measurements with the CORALIE spectrograph by Eggenberger et al. (2004). The dotted curve shows a fit to the background (instrumental, stellar granulation and photon noise) and the double-humped excess of power is due to p-mode oscillations.

5. η Boo

This star, being the brightest G-type subgiant in the sky, remains a very interesting target. The claimed detection of oscillations almost decade ago by Kjeldsen et al. (1995), based on fluctuations in Balmer-line equivalent-widths, has now been confirmed by further equivalent-width and velocity measurements by the same group (Kjeldsen et al., 2003) and also by independent velocity measurements with the CORALIE spectrograph (Carrier et al., 2005a). With the benefit of hindsight, we can now say that η Boo was the first star for which the large separation and individual frequencies were measured. However, there is still disagreement on the some of the individual frequencies, which reflects the subjective way in which genuine oscillation modes must be chosen from noise peaks and corrected for daily aliases. Fortunately, the large separation is $\Delta\nu = 40\,\mu$Hz, which is half way between integral multiples of the 11.57-μHz daily splitting (40/11.57 = 3.5). Even so, daily aliases are problematic, especially because some of the modes in η Boo appear to be shifted by avoided crossings. The first spaced-based observations of η Boo, made with the MOST satellite, were presented at this meeting by J. Matthews and the paper has since appeared on astro-ph (Guenther et al., 2005). The results have generated considerable controversy. Guenther et al. (2005) showed an amplitude spectrum (their Fig. 1) that rises towards low frequencies in a fashion that is typical of noise from instrumental and stellar sources. However, they assessed the significance of individual peaks by their strength relative to a fixed horizontal threshold, which naturally led them to assign high significance to peaks at low frequency. They did find a few peaks around $600\,\mu$Hz that agreed with the ground-based data, but they also identified eight of the many peaks at much lower frequency (130–500$\,\mu$Hz), in the region of rising power, as being due to low-overtone p-modes. Those peaks do line up quite well with the regular $40\,\mu$Hz spacing, but extreme caution is needed before these peaks are accepted as genuine. This is especially true given that the orbital frequency of the spacecraft ($164.3\,\mu$Hz) is, by bad luck, close to four times the large separation of η Boo (164.3/40 = 4.1). A full discussion of this issue is beyond the scope of this review, but it is safe to say that the resolution to this controversy will probably have to wait for more observations, both from the ground and from space.

6. μ Ara

This metal-rich G5 V star was already known to host a giant planet in a 2-year orbit (Butler et al., 2001), and was observed for oscillations using HARPS by Bouchy et al. (2005). As a by-product, they found evidence for a second planet of much lower mass, which they confirmed with follow-up observations (Santos et al., 2004). From the oscillation analysis, Bouchy et al. (2005) reported 43 modes with $l = 0$–3, including evidence for rotational splitting of $l = 1$ modes. If confirmed, this would be the first measurement of rotational splitting in a star other than the Sun. Bazot et al. (2005) have compared the oscillations frequencies in μ Ara with theoretical and discussed the possibility of deciding whether the high metallicity in this star is primordial or due to pollution during planet formation. They concluded that it is not possible to decide this question from the current data, although an accurate interferometric measurement of the stellar radius could help.

7. Other results

The F9 V star β Vir has been observed in velocity by two groups: Martic et al. (2004) and Carrier et al. (2005b). Both found excess power from oscillations centred at about 1.5 mHz. Only Carrier et al. (2005b) were able to measure the large separation unambiguously, reporting a value of $72\,\mu$Hz that is consistent with one of the two possibilities suggested by Martic et al. (2004). Carrier et al. (2005b) reported the detection of 31 individual modes, although the single-site nature of these data means that, as always, some caution is needed. This is clearly a star worthy of further study. The F5 V star HD 49933 (HR 2530; $V = 5.7$), which is a target for the COROT space mission, was observed over 10 nights with the HARPS spectrograph by Mosser et al. (2005). The star showed a surprisingly high level of velocity variability on timescales of a few days. This was also present as line-profile variations and is therefore presumably due to stellar activity. The observations showed excess power from p-mode oscillations and the authors determined the large separation ($\Delta\nu = 88.7\,\mu$Hz) but were not able to extract individual frequencies.

Finally, we briefly mention the search for solar-like oscillations in red giant stars with oscillation periods of 2–4 hours. Recent ground-based velocity observations by Barban et al. (2004) with CORALIE and ELODIE spectrographs have shown excess power and a possible large separation for both ϵ Oph and η Ser. Meanwhile, earlier observations of oscillations in ξ Hya by Frandsen et al. (2002) have been further analysed by Stello et al. (2004), who found evidence that the mode lifetime is only about 2 days. If confirmed, this would significantly limit the the prospects for asteroseismology on red giants.

8. Conclusions

We conclude with a few general points:

- Velocity observations are much less sensitive to the stellar granulation background than are intensity observations. The main disadvantage with velocity is the need for sophisticated spectrographs.
- Single-site data have severe limitations and multi-site observations are strongly preferred.
- There are good reasons for trying to get better data for the brightest targets (α Cen A and B, Procyon and η Boo), which are all interesting for different reasons.
- Mode lifetimes have been estimated for a few stars. It is very important to establish this parameter for a wide range of stars, from the main sequence though subgiants to the red giant branch.

Asteroseismology of solar-like stars has a bright future. We must be sure to choose targets carefully and arrange multi-site campaigns wherever possible

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