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The non-detection of oscillations in Procyon by *MOST*: Is it really a surprise?

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Abstract. We argue that the non-detection of oscillations in Procyon by the *MOST* satellite reported by Matthews et al. (2004) is fully consistent with published ground-based velocity observations of this star. We also examine the claims that the *MOST* observations represent the best photometric precision so far reported in the literature by about an order of magnitude and are the most sensitive data set for asteroseismology available for any star other than the Sun. These statements are not correct, with the most notable exceptions being observations of oscillations in α Cen A that are far superior. We further disagree that the hump of excess power seen repeatedly from velocity observations of Procyon can be explained as an artefact caused by gaps in the data. The *MOST* observations failed to reveal oscillations clearly because their noise level is too high, possibly from scattered Earthlight in the instrument. We did find an excess of strong peaks in the *MOST* amplitude spectrum that is inconsistent with a simple noise source such as granulation, and may perhaps indicate oscillations at roughly the expected level.

Key words. stars: oscillations – stars: individual: Procyon – Sun: oscillations

1. Introduction

The *MOST* satellite (Microvariability and Oscillations of Stars; Walker et al. 2003) comprises a 15-cm telescope and CCD detector designed to perform high-precision photometry on bright stars. Matthews et al. (2004, hereafter M04) reported observations of the F5 star Procyon A made almost continuously over 32 days. The Fourier amplitude spectrum showed no evidence for oscillations and M04 concluded that if there are p-modes in Procyon, they must have lifetimes less than 2–3 days and/or peak amplitudes <15 parts per million. We agree completely with this conclusion but we do not agree with some of the other statements in that paper, as outlined in the following sections. For other discussion of the issues raised in M04, see also Elsworth & Thompson (2004).

2. Lowest noise ever?

We have measured the noise level in the *MOST* amplitude spectrum from the data plotted in Fig. 3 of M04, which was provided to us in digital form by the *MOST* team. We find that the noise is about 2 ppm (parts per million) at frequencies above 2 mHz and 2.5 to 4.0 ppm between 2.0 and 0.5 mHz, in agreement with the analysis by the *MOST* team (J. Matthews, priv. comm.).

M04 described the *MOST* result as "the best photometric precision so far reported in the literature (Gilliland et al. 1993; Kurtz et al. 1997; Retter et al. 2004) by about an order of magnitude"[1]. This statement is not correct. The work by Gilliland et al. (1993) was a ground-based photometric campaign to monitor several stars in the open cluster M 67, most of which had spectral types similar to Procyon. Table 11 of that paper gives the final noise levels in the amplitude spectra in the frequency range 2.5–4.5 mHz (Col. 4). Values for the best ten stars (excluding Star 12, which is a red giant) are 6.4–9.7 ppm. These noise levels, obtained after one week, are certainly higher than the 2 ppm reported for the 32-day *MOST*

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[1] Due to an error in typesetting, the reference numbers in the text of Matthews et al. (2004) do not match those in the list of references. The correct numbers are given in the Erratum, which we repeat here for convenience: References 1 to 26 should be, respectively: 1, 10–16, 2, 3, 17–26 and 4–9.

observations, but only by factors of 3–5 and not an order of magnitude. We also note that the noise level for a given observing time is very similar for the two data sets.

The observations by Kurtz et al. (1997) and Retter et al. (2004) cited by M04 targeted Ap stars and were indeed much less precise than the *MOST* data. However, the Retter et al. observations were made from space using the star tracker on the *WIRE* satellite, and the same instrument achieved far better precision (and good evidence for oscillations) on the solar-type star α Cen A (Schou & Buzasi 2001). Indeed, the noise level from those observations was substantially below 1 ppm and therefore considerably better than that from the *MOST* observations of Procyon.

M04 also stated that the duty cycle of 99% for 32 days makes the *MOST* data the most sensitive data set for asteroseismology available for any star other than the Sun. While the duty cycle is certainly tremendously good, one must also take the precision into account and such a grand claim is certainly not justified. The noise at high frequencies (about 2 ppm above 2 mHz) is about half the peak solar signal. Many ground-based velocity campaigns over more than a decade have achieved equivalent noise levels well below this on Procyon (e.g., 8 cm s^{-1} by Martić et al. 2004, which is a third of the peak solar signal) and other stars (for recent reviews, see Bouchy & Carrier 2003; Bedding & Kjeldsen 2003).

Recent ground-based velocity observations of the α Cen binary system are particularly noteworthy. Noise levels have reached 4.3 cm s^{-1} in α Cen A (Bouchy & Carrier 2002), 3.8 cm s^{-1} in α Cen B (Carrier & Bourban 2003) and, most recently, 2.0 cm s^{-1} in α Cen A (Butler et al. 2004). The latter value is a mere tenth of the peak solar oscillation amplitude, and all three campaigns produced data sets that are much more sensitive for asteroseismology than the *MOST* Procyon data. This is reflected in the fact that they actually succeeded in detecting oscillations in stars whose amplitudes are substantially lower than Procyon's.

3. Previous work on Procyon

Several radial-velocity studies of Procyon have detected an excess of power around 0.5–1.5 mHz (Brown et al. 1991; Martić et al. 1999; Bouchy et al. 2002; Kambe et al. 2003; Martić et al. 2004; Eggenberger et al. 2004). The reported peak amplitudes of 50–70 cm s^{-1} (not 1 m s^{-1}, as quoted by M04) are lower than predicted by theoretical models of oscillations (Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999). Even before most of these observations were made, Kjeldsen & Bedding (1995) concluded that F-type stars, namely Procyon and several members of M 67, must oscillate with amplitudes less than has generally been assumed. This point has been raised several times since then (Martić et al. 1999; Samadi & Houdek 2000; Bedding & Kjeldsen 2003; Martić et al. 2004). The knowledge that Procyon oscillates with an amplitude only 2–3 times solar, rather than the theoretically predicted value of at least 4–5 times solar, has therefore been in the literature for many years. The *MOST* upper limit of 15 ppm (four times solar – see Sect. 4) is consistent with this and is therefore hardly a surprise.

It should also be noted that the theoretical predictions are based on our clearly incomplete understanding of stellar convection. Indeed, Christensen-Dalsgaard & Frandsen (1983) noted that mixing-length theory overestimates the convective flux in relatively hot stars and that predictions of oscillation amplitudes may have to be reduced. Interestingly, hydrodynamical simulations of convection for a variety of stellar parameters by Stein et al. (2004) also showed a substantial increase in the energy input from convection to the modes with increasing effective temperature. However, Stein et al. did not estimate the damping rate of the oscillations and hence could not provide estimates of the resulting amplitudes.

Although several independent detections of excess power in Procyon have been made from velocity measurements, it has been difficult to obtain a power spectrum that shows a clear p-mode structure. There is consensus that the so-called large frequency separation is about 55 μHz (Mosser et al. 1998; Martić et al. 1999, 2004; Eggenberger et al. 2004), which agrees well with theoretical models (Barban et al. 1999; Chaboyer et al. 1999; Di Mauro & Christensen-Dalsgaard 2001; Provost et al. 2002; Kervella et al. 2004), but there is not yet agreement on the actual frequencies. This is presumably due either to insufficient high-quality data (i.e., confusion from aliases in the spectral window) or to intrinsic properties of the star (i.e., short mode lifetimes and/or modes shifted from the asymptotic relation by avoided crossings).

4. Could *MOST* have detected oscillations?

For reference in the following discussion, we note that the strongest oscillation modes in the Sun have velocity amplitudes of 20–25 cm s^{-1} and intensity amplitudes in the blue-visual part of the spectrum of 4.5–5.0 ppm. Of course, these peak heights decrease when the observing time becomes significantly longer than the typical lifetime of the modes[2]. Note that M04 quoted mode lifetimes for the Sun of days to weeks, referring to Toutain & Fröhlich (1992). However, the reciprocal linewidths given in Table 6 of Toutain & Fröhlich (1992) must be divided by π to convert to mode lifetimes, as discussed in Sect. 4 of that paper. The dominant modes in the Sun have lifetimes of 2–4 days (see also Chaplin et al. 1997).

We must also keep in mind that intensity variations are a consequence of temperature variations and, while the two are proportional, the constant of proportionality depends on the effective temperature of the star (see Kjeldsen & Bedding 1995, Eq. (5)). In a star with the same physical oscillation amplitude as the Sun (as measured in velocity) but with the effective temperature of Procyon ($T_{\rm eff}$ = 6530 K), we would observe an intensity amplitude at these wavelengths that is $T_{\odot}^2/T_{\rm eff}^2$ = 0.78 times the intensity amplitude we observe in the Sun. Thus, the upper limit of 15 ppm in Procyon reported by M04 corresponds to a "physical" oscillation amplitude of 4 times solar, which translates to a velocity amplitude of just below 1 m s^{-1}. A velocity amplitude of 60 cm s^{-1}, as reported from ground-based Doppler measurements, corresponds to an

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[2] We follow the usual definition that the lifetime of a damped oscillator is the time for the amplitude to decay by a factor of e.
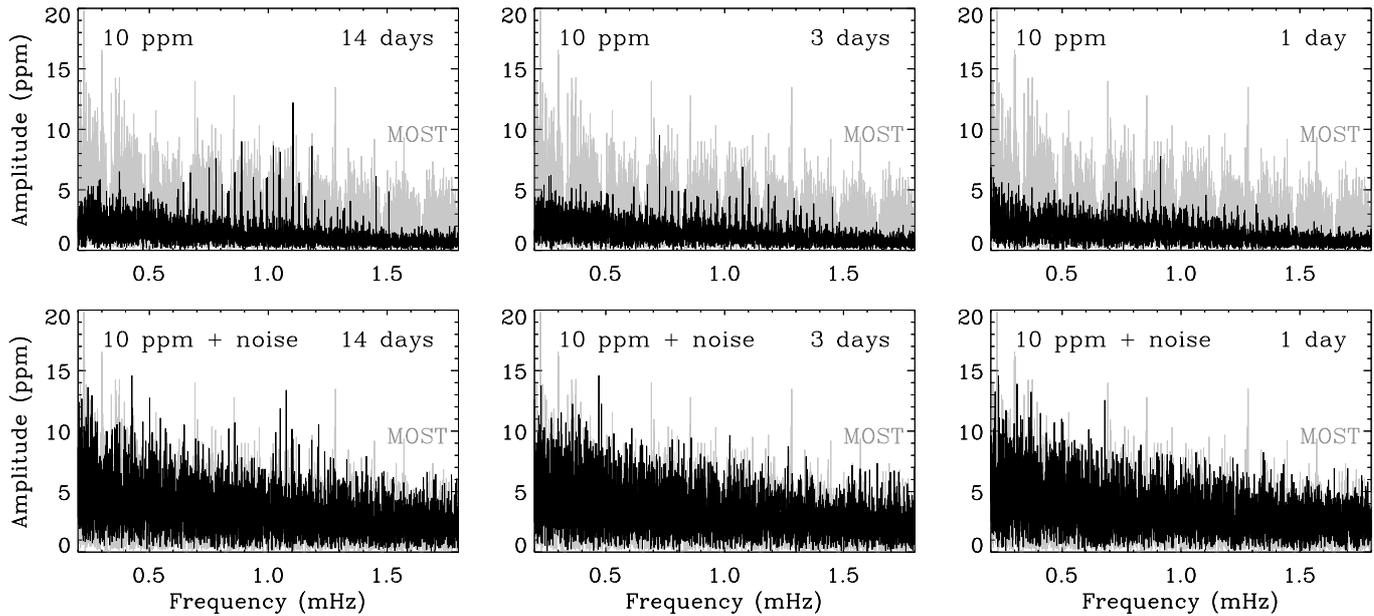
Fig. 1. The amplitude spectrum of Procyon observed by *MOST* (grey), compared with simulations (black) that included oscillations and granulation at the expected levels. The simulations were made for three different mode lifetimes, both with and without instrumental noise.

intensity amplitude of 9.5 ppm, which is below the limit set by M04.

To illustrate some of these points, Fig. 1 compares the *MOST* results with simulations. In each panel, the amplitude spectrum in grey is the spectrum published by M04 (the notches correspond to harmonics of the satellite orbital frequency, where they filtered to removed power from stray light artifacts). The amplitude spectra shown in black are simulations of the signal expected from Procyon if the p-mode oscillations have peak amplitudes of 10 ppm, which matches the level inferred from ground-based velocity observations. We show simulations for three different values of the mode lifetime (14, 3 and 1 d), made using the method described by Stello et al. (2004) and Bedding et al. (2004).

The simulations also included granulation noise at 1.5 times the solar level (see below), which is responsible for the noise floor that rises towards lower frequencies in the upper three panels. In those panels, no photon or instrumental noise was included in the simulation. In the lower three panels, on the other hand, we added sufficient noise to bring the total power up to the level observed by *MOST*. As expected, we see that shortening the mode lifetimes has the effect of lowering the peak heights, making the oscillations even harder to detect, as also found by M04 (Supplemental Material). It is apparent that if Procyon has oscillations with the amplitudes suggested by velocity measurements, we would not expect to see them clearly in the *MOST* spectrum unless the mode lifetimes were much longer than in the Sun.

5. Has *MOST* detected granulation noise?

M04 suggested that the increase in noise towards low frequencies that is seen in their amplitude spectrum could be caused by light variations due to stellar granulation. We would expect
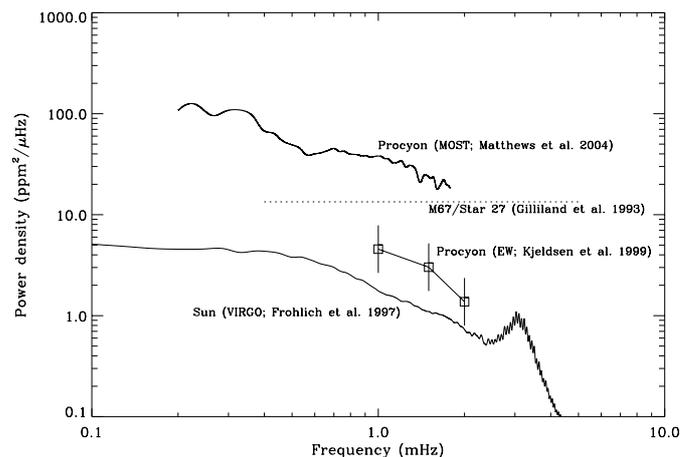

Fig. 2. Smoothed power density spectra from photometry of Procyon (*MOST*), the Sun (*VIRGO*, green channel), and an F-type star in the cluster M 67 (ground-based telescopes). Also shown are Balmer-line equivalent-width measurements of Procyon (EW, with 2-σ error bars).

granulation to be much easier to detect in intensity than velocity, but the level of non-white noise in the *MOST* data seems too high for this.

We illustrate this in Fig. 2, which shows smoothed power density spectra (power per frequency resolution bin). Power density is the appropriate way to compare noise sources, whether the noise arises from granulation, photon statistics or instrumental effects, because it is independent of the length of the observations (see, e.g., Appendix A.1 of Kjeldsen & Bedding 1995). The data for the Sun are full-disk intensity measurements from the green channel of the *VIRGO* three-channel sunphotometer on the *SOHO* spacecraft (Fröhlich et al. 1997; Pallé et al. 1999). The figure shows that the power density of the *MOST* noise is about 16 times higher than the solar

granulation power (4 times in amplitude). This seems implausibly large, especially as Balmer-line equivalent width measurements of Procyon by Kjeldsen et al. (1999) produced an upper limit on granulation – and a tentative detection – of about twice solar in power (1.4 in amplitude). Those points are also shown in Fig. 2, after conversion from equivalent-width to intensity (see Sect. 5 of that paper). We also see that the noise level in the *MOST* spectrum of Procyon is higher than the noise level measured from photometry of F-type stars in M 67 by Gilliland et al. (1993)[3].

Given these comparisons, it seems unlikely that the noise in the *MOST* spectrum is due to granulation in Procyon. We suggest that the most likely origin of the large amount of non-white noise in the *MOST* data is instrumental, possibly from variations in the amount of scattered Earthlight reaching the detector (see M04).

6. Could the ground-based results be artefacts?

M04 suggested the possibility that apparent p-mode power identified by ground-based observers may be an artefact of insufficient gapped sampling of granulation variations. Is it possible that the hump of excess power at 0.5–1.5 mHz that has been seen repeatedly in the velocity data is an artefact? This was in fact suggested by Kjeldsen & Bedding (1995) as a likely cause for the power excess found by Brown et al. (1991), on the basis that the observations were high-pass filtered. Such a filter, when applied to a Fourier spectrum dominated by non-white noise from instrumental effects, will indeed produce a hump. However, subsequent repeated independent confirmations of the power hump, most of which were high-pass filtered much less strongly (or not at all), led Bedding & Kjeldsen (2003) to acknowledge that this excess has a stellar origin.

We also note that in discussing Fig. 7 from Martić et al. (1999), M04 have chosen a figure showing only a subset of the data discussed in that paper, which was deliberately cut to allow comparison with observations of another star (η Cas). On the other hand, Figs. 4 and 8 from Martić et al. (1999) were not high-pass filtered at all and clearly show the excess power.

The suggestion by M04 is that non-white noise from stellar granulation could have produced a hump of power because the ground-based observations have daily gaps. While gaps in the observing window certainly introduce false peaks (aliases), these are always symmetrical about the original peak and are very close to it (small multiples of $\pm 11.6\,\mu$Hz). It is not possible using this mechanism to turn a monotonically varying power spectrum (as produced by granulation or, indeed, by most instrumental effects) into a hump of excess power, as we have verified using simulations. We therefore disagree strongly that the excess power seen by ground-based observers can be explained as an artefact introduced by gaps in the observations.

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[3] Note that all four power density spectra in Fig. 2 were scaled in the same way, such that a sinusoid with an amplitude of 1 ppm observed for 10^6 s gives a peak in power density of height 1 ppm$^2/\mu$Hz. This explains the factor of two between the *VIRGO* power density in the figure and that plotted by Pallé et al. (1999), who used a different scaling convention.
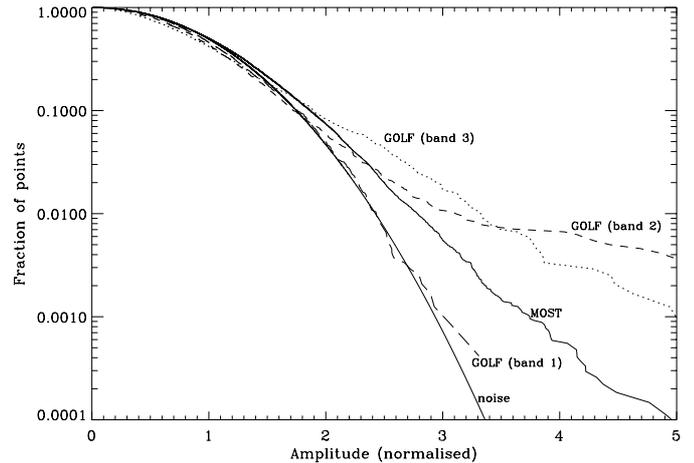

Fig. 3. Distribution of peaks heights in the *MOST* amplitude spectrum of Procyon, compared with pure noise and also with three frequency bands in the *GOLF* solar spectrum (see text).

Finally, we note that in response to M04, Bouchy et al. (2004) have published a short sequence of very high-precision velocity measurements of Procyon obtained with the HARPS spectrograph. These show clear periodicities with typical periods of 18 min and an excess of power in the Fourier spectrum around 1 mHz, in perfect agreement with the previous velocity measurements. Recent evidence for the power excess has also been presented by Claudi et al. (2005) on the basis of observations with a longer timespan but lower precision.

7. Evidence for oscillations in the *MOST* data?

We have examined the *MOST* amplitude spectrum for evidence of oscillations. Based on the ground-based observations, oscillations could be present at low signal-to-noise. Indeed, inspection of Fig. 3 in M04 shows a few peaks that are well above the surrounding noise and it is possible that some of these are due to oscillations.

Comparison with simulations shows that there are many more strong peaks in the amplitude spectrum than would be expected from noise. To quantify this, we examined the cumulative distribution of peak heights, a method that has previously been applied in both helioseismology (e.g., Delache & Scherrer 1983) and asteroseismology (e.g., Brown et al. 1991). We first removed the overall slope by dividing by a smoothed version of the spectrum. This flattens the spectrum and allows us to make meaningful counts of the number of points above a given amplitude. The resulting distribution is shown in Fig. 3, where the horizontal axis is amplitude divided by the mean amplitude.

On the same graph we show the distribution resulting from noise, which we measured by averaging a large number of simulations. It is clear that the *MOST* spectrum has an excess of strong peaks. For example, there are more than ten times as many peaks with height ≥3.5 times the mean than expected from noise.

Also shown in Fig. 3 are distributions of peak heights for the Sun, based on a 30-day series of full-disk velocity observations taken by the *GOLF* instrument on the *SOHO* spacecraft (Ulrich et al. 2000). We show results for three frequency bands

in the solar amplitude spectrum. Band 1 (0.4–1.4 mHz) is at frequencies below the solar oscillations and contains only noise from granulation. We see that this distribution closely matches our noise simulations. Band 2 (1.4–2.4 mHz) contains granulation noise plus the weak low-frequency solar p-modes. Those modes have long lifetimes compared to the length of the time series and so the distribution contains unresolved high peaks. Band 3 (3.8–4.8 mHz) contains the weak highest-frequency solar p-modes, which have short lifetimes. Thus, this band has many resolved modes, which produces a broader distribution of peaks.

Comparing the different curves in Fig. 3, we conclude that the distribution of peak heights in the *MOST* amplitude spectrum is not consistent with being solely due to noise from granulation or similar sources. Rather, there is evidence for an excess of strong peaks that is consistent with the presence of oscillations at approximately the level expected. However, the unusual peak distribution could arise from other causes (as turned out to be the case for the solar measurements analysed by Delache & Scherrer 1983). In particular, the filtering by M04 to remove power at the harmonics of the satellite's orbital frequency may have distorted the peak-height distribution and further analysis of the original time series is needed to help decide this question.

8. Conclusions

Our main conclusions are as follows:

1. The upper limit placed on oscillations in Procyon by the *MOST* satellite is consistent with previous ground-based velocity measurements and with the fact that Procyon oscillates with an amplitude significantly below theoretical predictions, as has been discussed in the literature for many years. The conclusions by M04 that their results "defy expectations from the Sun's oscillations and previous theoretical predictions" and that "target selection for future planned asteroseismology space missions may need to be reconsidered, as will the theory of stellar oscillations" are overstated.

2. The claims by M04 that the *MOST* data represent the best photometric precision so far reported in the literature by about an order of magnitude and are the most sensitive data set for asteroseismology available for any star other than the Sun are both inaccurate. For example, published observations of oscillations in α Cen A in both photometry and velocity are far superior.

3. We find it unlikely that the non-white noise in the *MOST* amplitude spectrum is due to stellar granulation. Instead, the most likely explanation lies in variable amounts of scattered Earthlight reaching the detector. This instrumental noise is probably the reason that oscillations could not be detected in Procyon.

4. The distribution of peak heights in the *MOST* amplitude spectrum is not consistent with a simple noise source such as granulation. The excess of strong peaks may indicate oscillations, but further work is needed before drawing a firm conclusion.

The excellent observing duty cycle of *MOST* makes this a potentially powerful instrument for asteroseismology. It is possible that more sophisticated treatment of the stray light will reduce the noise level enough to reveal a clear detection of oscillations in Procyon. If the non-white noise cannot be reduced, the best targets will be those with larger amplitudes than Procyon, such as more evolved stars (e.g., η Boo) and classical pulsators such as δ Scuti stars and roAp stars. *MOST* has tremendous potential to contribute greatly to the study of these types of stars.

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