

Simulating the outer layers of Procyon A: a comparison with the Sun

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ABSTRACT

We compare a new 3D radiative hydrodynamical simulation of the surface layers of Procyon A to a similar 3D simulation of the surface layers of the Sun. Both simulations include realistic input physics and are performed using the same numerical techniques and computer codes.

Convection in the surface layers of Procyon A is very different from the Sun. Compared with the Sun, the atmospheric structure and convective flow in Procyon A exhibit the following characteristics.

(i) The highly superadiabatic transition layer (SAL) is located at a much shallower optical depth; it is in a dynamically active region and its outer region is sometimes located in the optically thin atmosphere.

(ii) The outer region of the SAL moves from an optically thin region to a thick region and back again over a time of 20–30 min. This motion, which is driven by the granulation, takes place in a time approximately half the turnover time of the largest granules.

(iii) The peak rms velocity in the vertical direction is much larger in Procyon A.

The main reason for the radically different radiative–convective behaviour in Procyon A compared with the Sun is the role played by turbulent eddies in determining the overall flow/thermal structure. The turbulent pressure and turbulent kinetic energy can exceed 50 per cent of the local gas pressure (compared with about 10–20 per cent in the Sun). In such regions, the mixing length theory is a poor approximation.

The Procyon A simulation thus reveals two distinct time-scales: the autocorrelation time of the vertical velocity and the characteristic time-scale of the SAL, which is tied to granulation. Just below the surface, the autocorrelation decay time is about 5 min in Procyon A and the SAL motion time-scale is 20–30 min. In the simulations, the peak value of the superadiabaticity varies between 0.5 and 3. When the SAL penetrates the optically thin region, there are efficient radiative losses and the peak of the SAL is low. We speculate that these losses damp out the relative amplitudes in luminosity (temperature fluctuations) compared with velocity (Doppler). Although this will not affect the frequencies of the peaks in the power spectrum, it will probably lower the average amplitude of the peaks relative to the noise background.

Key words: stars: atmospheres – stars: individual: Procyon A – stars: oscillations.

1 INTRODUCTION

Procyon A (hereafter referred to Procyon), one of the brightest stars in the sky, is a well-studied object. Known for its white dwarf companion, its orbit has been well determined by speckle technique and

its mass, long quite uncertain, has now been evaluated to be near $1.5 M_{\odot}$ (Girard et al. 2000). On the basis of evolutionary interior models, the internal structure of Procyon is believed to consist of a convective core, with a radiative envelope and a thin surface convection zone. The mass in its outer convection zone is $10^{-5} M_{\odot}$ at present (Guenther & Demarque 1993). Procyon thus offers an unusual opportunity to study by seismic means both the structure of the outer layers and the efficiency of convective core overshoot

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in intermediate mass stars (Chaboyer, Demarque & Guenther 1999; Straka, Demarque & Guenther 2005).

For all these reasons and in view of theoretical predictions that the p -mode oscillation amplitudes would be relatively large (Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999), Procyon has been a prime candidate for seismic observations from the ground and in space. Interestingly, now that reliable observations are possible, there is an apparent discrepancy between the detection of p -mode oscillations on Procyon, based on radial velocity measurements made from the ground (Eggenberger et al. 2004; Martić et al. 2004), and the high precision intensity measurements described by the Microvariability and Oscillations of Stars (*MOST*) space mission (Walker et al. 2003). In contrast with the ground-based observations, the *MOST* space telescope has failed to detect p -modes from Procyon (Matthews et al. 2004) at its instrumental limit.

This paper focusses on modelling the dynamics and physical conditions in the outer convective layers of Procyon, and in making a comparison with the Sun. We present the results of a 3D radiative hydrodynamic numerical large eddy simulation of the outer layers of Procyon, and compare it to a similar simulation performed previously for the Sun using the same detailed physics input and numerical code (Robinson et al. 2003). The domains of both simulations extend from the observable atmospheric layers in radiative equilibrium and the outer layers of the convection zone, down to a depth at which the temperature gradient exceeds the adiabatic value by only a very small amount (deep convection). The simulation domain in both simulations includes the highly superadiabatic transition layer (hereafter SAL) between the atmosphere and deep convection. It is in the SAL region that the p -modes are believed to be excited by stochastic processes.

In the next section, we describe briefly the starting model and the procedure followed in carrying out the 3D numerical simulation. Section 3 discusses the main results from the Procyon simulation, emphasizing the striking differences in the physical conditions in the atmospheres of Procyon and the Sun. The most surprising result is that the SAL, which in the Sun changes little with time and is placed below the photosphere, is found to vary with time in position and amplitude in Procyon. As a result, the outer layers of the SAL in Procyon are found some of the time in the optically thin atmosphere in Procyon. In this region, radiative losses are large and characteristic time-scales are short, in contrast with the Sun where the SAL is subphotospheric.

The implications of these fundamental differences for the excitation, damping and lifetimes of p -mode oscillations, are discussed in general terms in Section 4, where we analyse the likely consequences for p -mode observations in Procyon and the conditions for the detectability of p -mode oscillations either from the intensity measurements from space (*MOST* mission), or from ground-based radial velocity measurements.

In Section 5, we summarize our results and the direction of future research in the light of our study.

2 3D SIMULATION

The 3D numerical simulation of Procyon was carried out using the same numerical approach and physical assumptions as in our simulations of the outer layers of the Sun (Robinson et al. 2003) and subgiant stars (Robinson et al. 2004). As in the case of the Sun, the same description of the microphysics, i.e. the opacities and equation of state, was assumed in the 3D simulation as in the 1D starting model described below. We used the Alexander & Ferguson (1994) opacities at low temperatures and the OPAL opacities at higher

temperatures (Iglesias & Rogers 1996). The equation of state was the OPAL equation of state (Rogers, Swenson & Iglesias 1996).

2.1 Starting 1D model

The first step was to construct a detailed 1D evolutionary model for Procyon, with the help of the Yale stellar evolution code YREC (Guenther et al. 1992; Guenther & Demarque 1997). This model then provided the starting model for the 3D simulation.

The choice of chemical composition for the simulation is of some interest. Evolutionary models of Procyon show that the mass in the surface convection zone is very small, varying from $10^{-7} M_{\odot}$ at minimum to $10^{-5} M_{\odot}$ at present (Guenther & Demarque 1993). As a consequence, gravitational settling is expected to take place below the convection zone of Procyon, raising questions about the chemical composition to use in modelling the atmosphere of Procyon.

Heavy element diffusion in the envelope is complicated by the fact that both radiative levitation of certain elements and turbulent mixing may also play an important role in inhibiting the gravitational settling (Richer et al. 1998). The Procyon atmosphere typifies the complex transition between the cooler sun-like stars with a deep convection zone and hotter stars along the main sequence where radiation dominates in the envelope. However, from the point of view of this simulation, which considered only the turbulent outermost layers, we could safely ignore these refinements. The metallicity of Procyon has been measured spectroscopically to be close to solar (Takeda et al. 1996; Kato, Watanabe & Sadakane 1996). For simplicity, we adopted the same metallicity mixture as for the Sun (Grevesse & Noels 1993).

The situation is more uncertain regarding the helium abundance because the helium abundance of Procyon cannot be determined spectroscopically. In fact, in the absence of any other effect, applying the treatment of gravitational settling, which is satisfactory for the Sun, would result in the complete depletion of helium in the Procyon atmosphere in less than 10^8 yr (Guenther & Demarque 1993; Provost et al. 2005). It has been suggested by Morel & Thévenin (2002) that the settling efficiency is reduced greatly by radiative diffusivity effects. In view of the above uncertainties, the starting model was constructed under the arbitrary assumption that the efficiency of gravitational settling is decreased by two orders of magnitude. This resulted in a helium content by mass of $Y = 0.07$. We emphasize that the precise value of Y is of little consequence in this study of the structure and dynamics of the atmosphere. In stellar atmospheres of this temperature, helium is ‘dead weight’ and variations in helium content can be mimicked by a small adjustment of the effective gravity. Thus in contrast to the case of the heavy elements, which affect the radiative opacities sensitively, the precise helium abundance is a second-order effect in determining the structure and dynamics of the atmosphere.

2.2 The 3D simulation

The 3D simulation of Procyon is a square-based box of dimensions $14\,500\text{ km} \times 14\,500\text{ km} \times 16\,300\text{ km}$ on a $74 \times 74 \times 160$ uniformly spaced grid. The vertical extent is about 5.5 pressure scaleheights, which includes the helium and hydrogen ionization zones and part of the overlying radiation region. As the simulated granules have diameters of about $10\,000\text{ km}$, one could argue that a larger domain may be required. However, the effect of the box width on the thermal structure or turbulent pressure was shown to be minimal (Robinson et al. 2003), though it may have a small effect on the turbulent kinetic energy near the top. As the focus of our study is on the structure of the

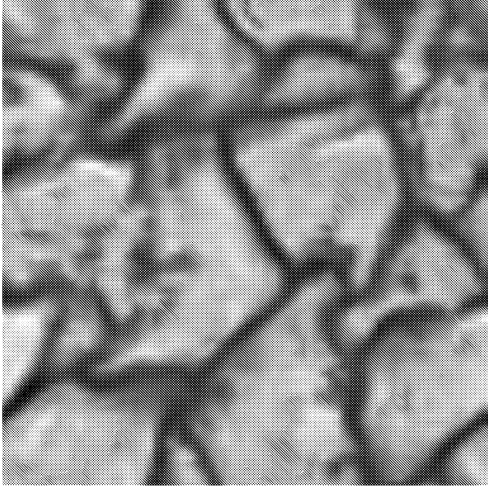


Figure 1. Instantaneous vertical velocity in a horizontal plane located in the SAL of Procyon. Dark regions denote downflows, lighter regions are upflows. The dimensions are 29 000 km \times 29 000 km.

SAL and the vertical velocities, the box width should be adequate. The importance of the depth and width of the box is discussed in detail in appendix A of Robinson et al. (2003). To make sure that the box is indeed big enough, we ran an additional simulation in a box of dimensions 29 000 km \times 29 000 km \times 16 300 km. A grey-scale plot of the instantaneous vertical velocity at a horizontal cross-section located near the peak of the SAL is shown in Fig. 1. The size and shape of the granules does not appear to be affected by the side boundaries of the domain. We confirmed that the average thermal structure and rms velocities (not shown) are almost the same on the 29 000-km-wide box as they are on the 14 500-km-wide box.

The 3D simulation of the Sun is case D in Robinson et al. (2003). This has dimensions 2700 km \times 2700 km \times 2800 km on a $58 \times 58 \times 170$ grid. The Sun simulation does not extend down to the helium ionization zone but still contains about 8.5 pressure scaleheights.

3 COMPARISON WITH THE SUN

3.1 Mean atmospheric structure and superadiabatic layer

We begin by comparing the basic structural parameters of the atmospheres of the Sun and Procyon. Unless otherwise specified, given quantities will be temporal and horizontal averages computed after the simulation has reached a statistically steady state (each horizontal average is taken at fixed height). Fig. 2 shows the mean adiabatic logarithmic gradient ∇_{ad} as a function of depth (expressed in terms of $\log P$), within the two atmospheric simulations. The quantity ∇ , defined in the usual way, i.e.

$$\nabla \equiv \frac{d \ln T}{d \ln P}, \quad (1)$$

is a statistical quantity in the simulation. Partial ionization reduces the value of ∇_{ad} from the monatomic gas value of 0.4, as shown in Fig. 2. We note that in the case of Procyon, both the hydrogen and helium ionization zones are included in the simulation domain. In the case of the Sun, only part of the hydrogen ionization region is included in the simulation domain.

Both Procyon and the Sun exhibit a surface convection zone, which is nearly isentropic in the deep layers. Near the surface, the transition between deep nearly adiabatic convection to the radiative

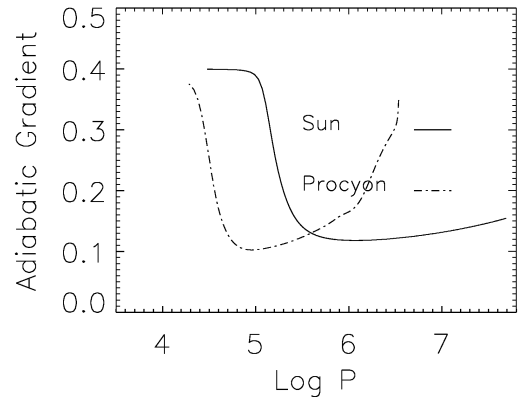


Figure 2. Mean adiabatic gradient in the Sun and Procyon.

atmosphere is characterized by the narrow highly superadiabatic layer, denoted above as SAL. In this layer, the specific entropy rises steeply. This entropy jump is known to be critical in specifying the internal structure of the stellar model, in particular the depth of the convection zone and the model radius, which depend on the specific entropy in the deep adiabatic region. It also affects sensitively the local sound speed near the surface and the observed p -mode frequencies. Most importantly, the SAL is the region where the balance between stochastic excitation from turbulent motions and competing radiative damping takes place, thus determining the amplitudes and lifetimes of p -modes.

The excess of the temperature gradient over the adiabatic gradient, or superadiabaticity, is given by

$$\nabla - \nabla_{\text{ad}} = \frac{d \ln T}{d \ln P} - \nabla_{\text{ad}}, \quad (2)$$

where the subscript ‘ad’ refers to the adiabatic value. Fig. 3 shows the region where the mean superadiabaticity peaks as a function of $\log P$ in the Sun and in Procyon.

A major difference between the two simulations is that the peak of the SAL in Procyon is in a region of much lower density than in the Sun. The SAL peak in the Sun is located below the photosphere in a region that is relatively optically thick and, although the solar photosphere is affected by the convective flows just below, the position of the photospheric surface suffers little change due to the convective motions. This is in sharp contrast with Procyon, where the more violent convective flows are present in the atmosphere and cause the SAL position to vary with time. The SAL moves radially

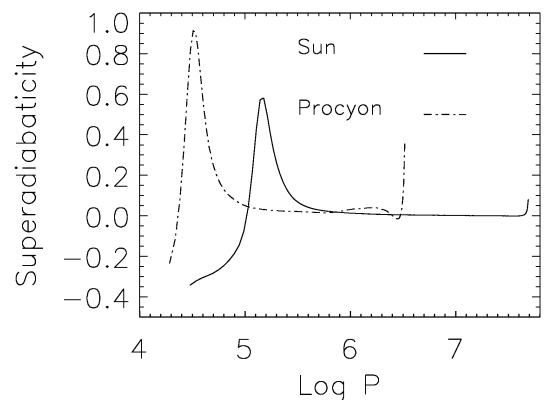


Figure 3. Mean superadiabaticity in the Sun and Procyon. The vertical lines indicate the approximate location of the photosphere.

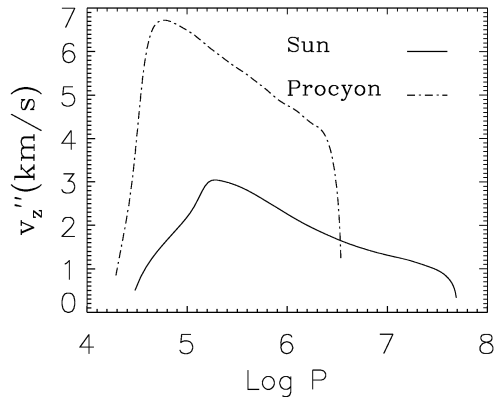


Figure 4. The rms vertical velocity in the Sun and Procyon.

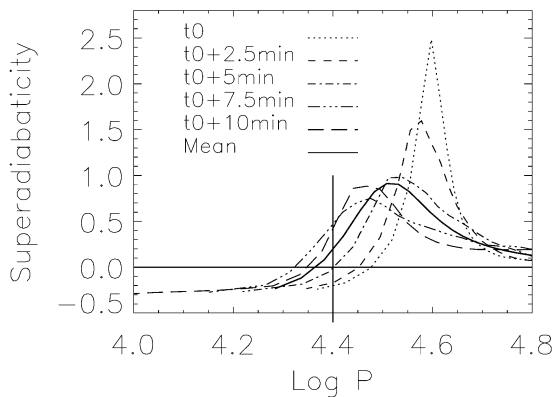


Figure 5. Instantaneous superadiabaticity (horizontally averaged) at 2.5-min intervals. The time average over the entire simulation is also plotted for reference. The solid vertical line approximately indicates the mean location of the photosphere.

back and forth over a time of about 20–30 min and over a distance of up to about half a local pressure scaleheight (about 500 km).

By computing the FWHM of the vertical velocity, we obtain a mean granule diameter of about 10 000 km (details of how we estimate the granule diameter are given in Robinson et al. 2004), while the run of rms vertical velocity (Fig. 4) provides a velocity scale for the granules of 5–7 km s⁻¹. Combining these quantities yields an average time-scale, roughly half the time it takes the largest granules to overturn fully, in the vicinity of 20–30 min. A 42-min movie of granulation in Procyon for the box is presented at www.astro.yale.edu/marjif. The largest granules (seen in the top right-hand corner of the picture) last about 50 min.

The overturning granular motion causes the SAL peak to approach the optically thin layers some of the time. At one point in the simulation, when the SAL is in a particularly shallow region, the very large radiative losses produce a downflowing plume that is able to traverse the entire vertical extent of the computational domain. This is shown clearly in a visualization of the convecting plumes in Procyon given at www.astro.yale.edu/marjif.

To illustrate the response of the SAL to the turbulent overturning granules, we plot the superadiabaticity at five instants in Fig. 5. The photosphere, defined by the location at which the horizontally and temporally averaged temperature equals the effective temperature of the 1D Procyon stellar model, is marked by a solid vertical line. The solid horizontal line shows where the superadiabaticity is zero.

Each plot is separated by 2.5 min in time. The time t_0 is chosen as the time after which the system has reached statistical thermal equilibrium. The figure shows that, over the ‘quasi-periodic’ cycle, the SAL varies both in position and height. During part of the cycle, the outer region of the SAL lies above the photosphere.

By sampling at various instants, we found that this ‘quasi-periodic’ radial movement of the SAL is maintained over at least 250 min (the entire statistical integration time). We note in addition that at certain times the superadiabatic peak in Procyon reaches twice the height of the solar superadiabatic peak. When the outer part of the SAL is in an optically thin region, the photons can more readily carry away excess internal energy from the temperature fluctuations, than they can in optically thick regions. As it loses its excess internal energy at a greater rate compared with its surroundings, the fluctuation is said to be radiatively damped. Because of this damping, it is reasonable to infer that the p -mode intensity amplitudes (which depend on the temperature fluctuation) will be smaller when the SAL is in optically thinner regions.

3.2 Velocity fields, turbulent pressure and turbulent kinetic energy

The rms vertical velocity is plotted as a function of $\log P$ in both the Sun and Procyon in Fig. 4. We see that the turbulent velocity has a much larger amplitude in Procyon than in the Sun. The Procyon simulation predicts vertical velocities and velocity fluctuations in the optically thin atmosphere 2–3 times larger than in the Sun. This is consistent with observation. A recent spectroscopic study of Procyon by Allende et al. (2002) concludes that a comparison of the velocity spans (in line bisectors) for the Sun and Procyon shows that ‘the span of Procyon’s lines exceeds the solar values by more than a factor of 2’.

A grey-scale map of vertical velocities near optical depth unity, as previously shown in Fig. 1, displays a pattern of granulation in Procyon similar to that observed in the Sun, but more chaotic and on a larger scale. The lighter regions denote upflows, while the darker regions at granule boundaries denote downflows. There is a difference of scale: in Procyon, the granule sizes average about 10 000 km, while solar granules average about 1200 km in horizontal scale.

A useful quantity is the ratio R of turbulent pressure P_{turb} to mean gas pressure \bar{P} . The overbar denotes a combined horizontal and temporal average. This ratio can be written

$$R = P_{\text{turb}}/\bar{P} = \bar{\rho} v_z''^2 / \bar{P}, \quad (3)$$

which is a non-dimensional quantity. The quantities ρ and v_z'' are the average density and rms vertical velocity, defined as

$$v_z''^2 = \overline{v_z^2} - (\bar{v}_z)^2, \quad (4)$$

where again the overbar denotes a combined horizontal and temporal average. Fig. 6 is a plot of R as a function of depth for Procyon and the Sun. Unlike the case of the Sun, in Procyon the turbulent pressure varies ‘quasi-periodically’ with the position of the SAL and at times the instantaneous horizontal average of the turbulent pressure divided by the gas pressure can have a peak value of as much as 50 per cent. The instantaneous horizontally averaged turbulent kinetic energy divided by the local gas pressure can also reach 50 per cent near the top of the box (not shown). In the simulation, the maximum Mach number (defined as the maximum v_z'' divided by the local sound speed) is about 2 near the top (in the vicinity of the SAL peak). So motions will be supersonic at small optical depth suggesting short characteristic time-scales.

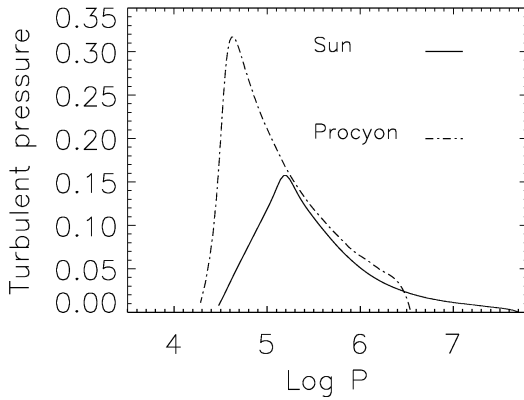


Figure 6. Turbulent pressure divided by the local gas pressure in the Sun and Procyon.

3.3 Overshoot

By comparing the horizontal cross-section of the temperature fluctuation (left panel of Fig. 7) at shallow optical depth ($\tau = 0.001$) with the vertical velocity at optical depth unity just inside the photosphere (right panel of Fig. 7), one can identify regions in which hotter (colder) than average fluid moves down (up). At small optical depth, the downflows appear brighter (hotter; instead of darker below the photosphere) because the fluid is being adiabatically compressed. This is a signature of convective *overshoot* above the photosphere. Note the dark (cold) spot in the upper left-hand corner of the left panel. This indicates upward moving fluid that is colder than the horizontal mean temperature. Generally, only a few such updrafts are sufficiently energetic to be able to continue travelling up even though they are negatively buoyant.

This reversal of the granulation pattern (bright downflows and darker granular upflows) ‘at large height’ was also noted by Nordlund & Dravins (1990) in their study of the Procyon atmospheric granulation.

3.4 Comparison with earlier studies

Our main conclusions regarding the time dependence of granulation and of the SAL in Procyon also appear robust. It is interesting

to compare the results of our simulation to an earlier less detailed hydrodynamic study of the atmospheric structure and granulation of Procyon (Dravins & Nordlund 1990; Nordlund & Dravins 1990). These authors included time-dependent hydrodynamics in their non-grey atmosphere calculations. Even though the models were relatively coarser than ours (the simulation volume included $32 \times 32 \times 32$ elements) and a simplified treatment of the hydrodynamics (the anelastic approximation) was used, the larger temperature contrast of the visible surface was present. Nordlund & Dravins (1990) also noted the position of the granules in the thin atmosphere (‘naked’ granules), in contrast with the Sun. Some features of the striking difference between the properties of convection in an F-type main-sequence stellar atmosphere and the solar atmosphere had already been noted by Nelson (1980) using a simpler model of granulation developed for the Sun (Nelson & Musman 1977).

4 EXCITATION DEPTH OF p -MODES IN THE SUN AND PROCYON

Stochastic fluctuations in the turbulent layers are believed to be responsible for the excitation of p -modes in the Sun and stars with similar convection zones. The 3D numerical simulations of the solar atmosphere have been successful in explaining the excitation mechanism and power distribution of solar p -modes. We have seen that Procyon exhibits a much shallower convection zone than the Sun and it is interesting to query whether the SAL region in Procyon also favours the excitation of p -modes.

The turbulent velocity fluctuations in a convection zone must be stochastically distributed for the excitation of p -modes to take place. We suggest that only when the coherence time for the velocity fluctuations becomes shorter than the period of the oscillation modes where the oscillation power is concentrated, can the fluctuations contribute to the stochastic excitation. To enable stochastic (random motions) excitation of p -modes by turbulence, the turbulent velocity (or temperature) field should be stochastic over a time interval smaller than the p -mode oscillation it is intended to excite. Otherwise it is not temporally stochastic with respect to the oscillation. For the Sun, the relevant oscillation period is $\varphi \sim 5$ min; in Procyon, it is believed to peak around $\varphi \sim 15$ min (Martić et al. 2004).

The autocorrelation coefficient of vertical velocity (which is a function of depth and time) is defined as

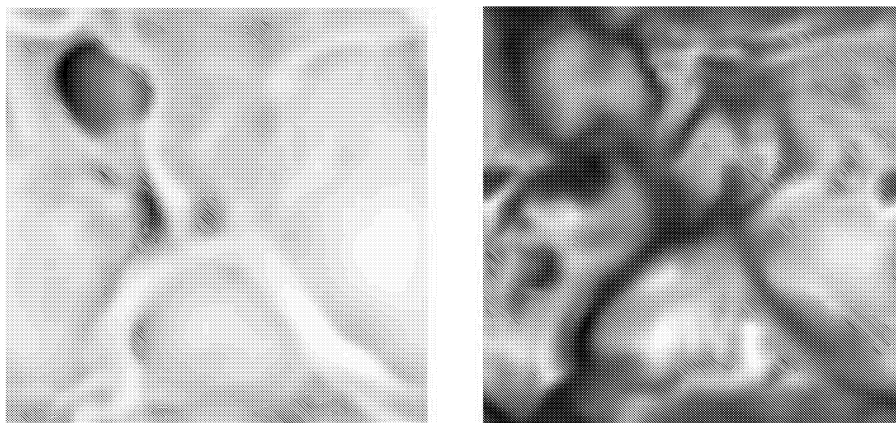


Figure 7. The left panel is a grey-scale plot of the temperature fluctuation in a horizontal plane located in the overshoot region just above the photosphere of Procyon. Lighter regions indicate hotter than average fluid, while darker regions indicate cooler than average fluid. The right panel is the corresponding vertical velocity at the same instant but located just inside the photosphere. Dark regions denote downflows, lighter regions are upflows. The dimensions are $14\,500 \text{ km} \times 14\,500 \text{ km}$.

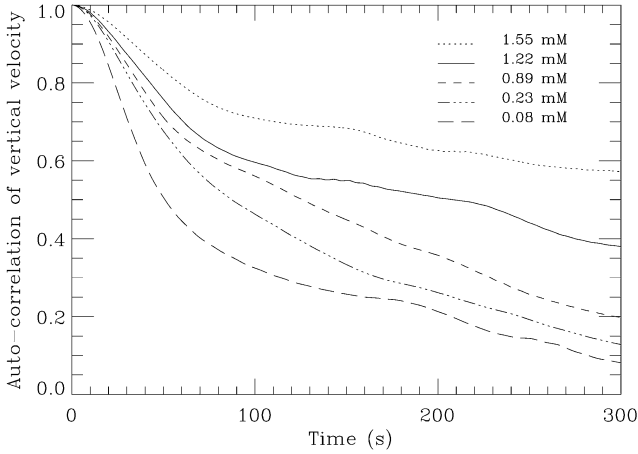


Figure 8. Autocorrelation of vertical velocity at various depths with respect to the photosphere in the Sun. Depth is measured positively inwards from the photospheric surface. After about 5 min, the autocorrelation coefficient is about 0.1 at a depth of about 0.1 Mm below the photosphere.

$$C[v'_z(0)v'_z(t)] = \frac{\langle v_z(0)v_z(t) \rangle - \langle v_z(0) \rangle \langle v_z(t) \rangle}{v''_z(0)v''_z(t)}, \quad (5)$$

where

$$v''_z = \sqrt{\langle v_z^2 \rangle - \langle v_z \rangle^2} \quad (6)$$

and $v'_z = v_z - \langle v_z \rangle$. The angled brackets represent a horizontal average. For brevity of notation, we have written $v_z(x, y, z, 0)$ as $v_z(0)$ and $v_z(x, y, z, t)$ as $v_z(t)$.

Fig. 8 depicts the autocorrelation coefficient of vertical velocity fluctuations, as a function of time and depth, from the 3D numerical simulation of the near-surface layer of the convection zone in the Sun. The autocorrelation coefficient varies between 0 and 1. The vertical velocity fluctuation can be considered to be stochastic when the autocorrelation coefficient becomes small, say of order of 0.1. In the Sun, we find that after 5 min, the autocorrelation coefficient decreases below 0.1 at a depth of about 0.1 Mm below the photosphere. This corresponds to the depth where $\log P \approx 5$. This is near the SAL peak, just below the photosphere, and a depth favourable to p -mode excitation.

An autocorrelation plot started at one instant during the simulation of Procyon is shown in Fig. 9. We see that in the Procyon atmosphere, the vertical velocity fluctuations become stochastic after a time of the order of 300 s; i.e. compared with the oscillation period φ , motions in Procyon are much more stochastic in the shallow layer than in the Sun. At other times during the simulation, the motions become stochastic in a time of between 200 and 600 s. This is because of the radial movement of the SAL described in the previous section. The conditions for stochastic excitation of p -modes would seem to be favourable for modes with periods in the vicinity of 15 min. In fact, several observers who made radial velocity measurements of Procyon from the ground have found evidence for such oscillations (Brown et al. 1991; Eggenberger et al. 2004; Martić et al. 2004).

We emphasize that the above arguments based on the autocorrelation coefficient for the velocity fluctuations suggest only that stochastic excitation can indeed take place in the outer layers of Procyon, at least some of the time, during the quasi-periodic SAL oscillation. This approach does not tell us whether a particular mode is excited or not by the stochastic process. In other words, we use it as a necessary but not a sufficient condition for mode excitation. Mode excitation would require a detailed calculation of the phys-

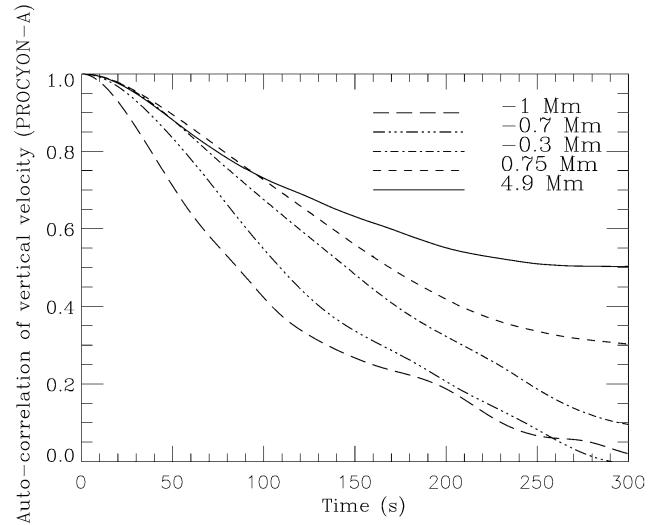


Figure 9. Autocorrelation of vertical velocity at various depths with respect to the photosphere in Procyon. Depth is measured positively inwards from the photospheric surface. After about 5 min, the autocorrelation coefficient near the photosphere is about 0.1. As the position of the SAL varies significantly over the simulation, the details of the plot will depend on the starting time.

ical response of the convective region to the propagation of sound waves within it. Such a calculation, while quite feasible, is outside the scope of the present paper.

However, it is possible to infer on general physical grounds on the differences between the Sun and Procyon. Because large temperature fluctuations due to convection take place in Procyon in regions of lower density, they will come into equilibrium with their surroundings more rapidly than in the Sun, sometimes on a time-scale shorter than the period of the shear motions associated with the acoustic oscillations. This seems to be the case in the simulation, where much happens to the SAL position on a time-scale of say only 10 min (see Fig. 3).

Energy losses by radiation on short time-scales would in all likelihood overwhelm low-amplitude intensity fluctuations with longer periods, such as the p -modes with periods in the vicinity of 15 min. Thus, the detection of intensity fluctuations due to p -mode oscillations in the Procyon atmosphere would seem problematic.

The time-dependent granulation would also introduce a source of noise in radial velocity measurements. However, in the absence of a more detailed knowledge of the relative strength of the excitation and damping mechanism operating in the atmosphere of Procyon, it is difficult to ascertain the precise effect on radial velocity p -mode measurements.

5 SUMMARY AND CONCLUSIONS

We have performed physically realistic numerical 3D simulations of the outer layers of Procyon and have compared the results with a 3D simulation of the solar outer layers performed under the same assumptions. The most striking difference between the Sun and Procyon appears in the atmosphere dynamics. In Procyon, the optically thin atmosphere is subject to quasi-periodic changes on time-scales of between 20 and 30 min. This is roughly half the complete overturn time-scale of the largest granules in the optically thin surface layers. Matthews et al. (2004) present evidence for the detection of unusually strong granulation noise in Procyon in the *MOST* space mission data. Future *MOST* observations of Procyon may be capable

of detecting the signature of the quasi-periodicity in the granulation revealed by our simulation. We emphasize that this atmospheric phenomenon would not have a fixed period because the velocities and dimensions of the granules are stochastic. The presence of granulation in the upper atmosphere of Procyon was also pointed out by Nordlund & Dravins (1990); they refer to the phenomenon as ‘naked granulation’.

What can be further inferred from our simulation regarding p -mode oscillations in Procyon? The highly stochastic nature of the vertical velocity fluctuations in the Procyon atmosphere appears favourable to the excitation of p -modes. On the other hand, the atmosphere is characterized by radiation losses tending to damp out oscillations very efficiently. Based on our simulation results, we speculate on simple physical grounds that, if excited, p -modes may have a short lifetime and smaller relative amplitudes in luminosity (temperature fluctuations) compared with velocity in the Procyon atmosphere.

The task of determining the relative importance of these competing exciting and damping processes in the dynamical and inhomogeneous environment of the atmosphere of Procyon is beyond the scope of this study. Existing theoretical work on the amplitudes of stellar pulsations can perhaps serve as a guide (Houdek et al. 1999). Because it is based on a version of the mixing length theory (MLT; Balmforth 1992), which predicts large convective velocities at the surface in stars like Procyon, the Houdek et al. theory predicts large p -mode oscillation amplitudes. However, the meaning of relating convective velocities to oscillation amplitude is unclear when the stochastic excitation process relates the oscillation amplitudes physically not to the convective flow velocities themselves but to the statistical fluctuations from the mean convective flow in the vertical direction. Predicting the luminosity amplitudes is particularly difficult due to the uncertain coupling between the oscillations and the radiation field. On the basis of their models, Houdek et al. (1999) predict amplitudes in luminosity of about 20 per cent of the velocity amplitudes for the Sun, which is in reasonable agreement with observation (Schrijver, Jiménez & Däppen 1991; Elsworth et al. 1993). Calculating the ratio of velocity to intensity amplitudes in Procyon is a major challenge ahead.

Further observations of Procyon with the *MOST* instrument and improved data from ground-based observatories will be needed to guide future theoretical progress. It is at this point reasonable to conclude that, because of the large intensity contrasts and small time-scale variations taking place in the Procyon atmosphere, detecting the minute intensity fluctuations expected from p -mode oscillations would be a daunting task. This difficulty, in addition to the likelihood of short p -mode lifetimes for Procyon, is a plausible explanation for the inability of the *MOST* space mission to detect p -modes oscillations in Procyon (Matthews et al. 2004).

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REFERENCES

- Alexander D. R., Ferguson J. W., 1994, *ApJ*, 437, 879
 Allende Prieto C., Asplund M., García López R. J., Lambert D. L., 2002, *ApJ*, 567, 544
 Balmforth N. J., 1992, *MNRAS*, 255, 603
 Brown T. M., Gilliland R. L., Noyes R. W., Ramsey L. W., 1991, *ApJ*, 368, 599
 Chaboyer B., Demarque P., Guenther D. B., 1999, *ApJ*, 545, L41
 Christensen-Dalsgaard J., Frandsen S., 1983, *Sol. Phys.*, 82, 469
 Dravins D., Nordlund Å., 1990, *A&A*, 228, 203
 Eggenberger P., Carrier F., Bouchy F., Blecha A., 2004, *A&A*, 422, 247
 Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A., New R., Speake C. C., Wheeler S. J., 1993, *MNRAS*, 265, 888
 Girard T. M. et al., 2000, *AJ*, 119, 2428
 Grevesse N., Noels A., 1993, *Phys. Scr.*, T47, 133
 Guenther D. B., Demarque P., 1993, *ApJ*, 405, 298
 Guenther D. B., Demarque P., 1997, *ApJ*, 484, 937
 Guenther D. B., Demarque P., Kim Y.-C., Pinsonneault M. H., 1992, *ApJ*, 387, 372
 Houdek G., Balmforth N. J., Christensen-Dalsgaard J., Gough D. O., 1999, *A&A*, 351, 582
 Iglesias C. A., Rogers F. J., 1996, *ApJ*, 464, 943
 Kato K.-I., Watanabe Y., Sadakane K., 1996, *PASJ*, 48, 601
 Li L. H., Robinson F. J., Demarque P., Sofia S., Guenther D. B., 2002, *ApJ*, 567, 1192
 Martić M., Lebrun J.-C., Appourchaux T., Korzenik S. G., 2004, *A&A*, 418, 295
 Matthews J. M., Kusching R., Guenther D. B., Walker G. A. H., Moffat A. F. J., Rucinski S. M., Sasselov D., Weiss W. W., 2004, *Nat*, 430, 51
 Morel P., Thévenin F., 2002, *A&A*, 390, 611
 Nelson G. D., 1980, *ApJ*, 238, 659
 Nelson G. D., Musman S., 1977, *ApJ*, 214, 912
 Nordlund Å., Dravins D., 1990, *A&A*, 228, 155
 Provost J., Berthomieu G., Bigot L., Morel P., 2005, *A&A*, 432, 225
 Richer J., Michaud G., Rogers F., Iglesias C., Turcotte S., LeBlanc F., 1998, *ApJ*, 492, 833
 Robinson F. J., Demarque P., Li L. H., Sofia S., Kim Y.-C., Chan K. L., Guenther D. B., 2003, *MNRAS*, 340, 923
 Robinson F. J., Demarque P., Li L. H., Sofia S., Kim Y.-C., Chan K. L., Guenther D. B., 2004, *MNRAS*, 347, 1208
 Rogers F. J., Swenson F. J., Iglesias C. A., 1996, *ApJ*, 456, 902
 Schrijver C. J., Jiménez A., Däppen W., 1991, *A&A*, 251, 655
 Stein R. F., Nordlund Å., 2000, *Sol. Phys.*, 192, 91
 Stein R. F., Georgobiani D., Trampedach R., Ludwig H.-G., Nordlund Å., 2004, *Sol. Phys.*, 220, 229
 Straka C. W., Demarque P., Guenther D. B., 2005, *ApJ*, in press (astro-ph/0505009)
 Takeda Y., Kato K.-I., Watanabe Y., Sadakane K., 1996, *PASJ*, 48, 511
 Walker G. A. H. et al., 2003, *PASP*, 115, 1023 (*MOST* mission)

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