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# THE ROLE OF TURBULENT PRESSURE AS A COHERENT PULSATIONAL DRIVING MECHANISM: THE CASE OF THE $\delta$ SCUTI STAR HD 187547

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## ABSTRACT

HD 187547 was the first candidate that led to the suggestion that solar-like oscillations are present in $\delta$ Scuti stars. Longer observations, however, show that the modes interpreted as solar-like oscillations have either very long mode lifetimes, longer than 960 days, or are coherent. These results are incompatible with the nature of "pure" stochastic excitation as observed in solar-like stars. Nonetheless, one point is certain: the opacity mechanism alone cannot explain the oscillation spectrum of HD 187547. Here we present new theoretical investigations showing that convection dynamics can intrinsically excite coherent pulsations in the chemically peculiar $\delta$ Scuti star HD 187547. More precisely, it is the perturbations of the mean Reynold stresses (turbulent pressure) that drives the pulsations and the excitation takes place predominantly in the hydrogen ionization zone.

*Key words:* asteroseismology – convection – stars: individual (HD 187546) – stars: oscillations – stars: variables: delta Scuti

*Online-only material:* color figures

## 1. INTRODUCTION

Stars of spectral type A and early F cover a very interesting part of the Hertzsprung–Russell diagram, where several astrophysical processes interact. The classical instability strip crosses the granulation boundary between the deep envelopes of efficient convection on the cool side to shallow, inefficient convective layers barely able to transport flux on the warm side. How this transition takes place is not entirely understood. It is of great interest, however, to infer how the stellar structure changes with increasing mass, because convection in the outer layers affects not only the stellar structure, but also the dynamo-generated magnetic fields, activity, and angular momentum transport, etc.

The lower part of the classical instability strip is populated by several classes of pulsators: $\delta$ Scuti ($\delta$ Sct) stars, $\gamma$ Doradus ($\gamma$ Dor), rapidly oscillating Ap (roAp) stars, but also by non-pulsating stars. The main mechanism that is commonly accepted to be responsible for the excitation of pulsations in $\delta$ Sct stars is the $\kappa$ (opacity) mechanism acting like a heat engine in the He II ionization zone, which is located at a layer with temperature $T \simeq 40{,}000$ K. However, there is also a small but measurable contribution from the thin, combined hydrogen (H I) and first ionization zone of helium (He I) to the excitation of oscillations (Castor 1968). This contribution results in an observed phase lag between maximum light and the time of minimum radius obtained from radial velocity measurements. In $\delta$ Sct stars, this phase lag is of the order of 60°, considerably smaller than the 90° in classical Cepheids (Breger et al. 1976). This is because the H I and He I ionization zones are less efficient at driving low-order modes and are closer to the surface in $\delta$ Sct stars compared to classical Cepheids.

Houdek et al. (1999) and Samadi et al. (2002) predicted that the subsurface convection in stars in the classical instability strip is still vigorous enough to stochastically excite solar-like oscillations. The characteristics of solar-like oscillations permit the identification of the geometry of oscillation modes from pattern recognition methods, e.g., from echelle diagrams. This is possible because all modes in a certain frequency range are excited and visible. This is in absolute contrast to oscillations excited by any heat engine mechanism, such as the $\kappa$ mechanism, where the mode selection mechanism is not yet understood (see, e.g., the review by Smolec 2014). The same applies to the oscillation amplitudes. While for solar-like oscillations we can predict their approximate value (e.g., Houdek et al. 1999), this is not the case for heat-engine-driven pulsators, where nonlinear, non-adiabatic codes are needed to estimate their amplitudes.

HD 187547, a $\delta$ Sct star detected with the NASA spacecraft *Kepler*, was the very first of its kind to lead to the conclusion that solar-like oscillations were indeed present in $\delta$ Sct stars (Antoci et al. 2011), as predicted by theory (Houdek et al. 1999; Samadi et al. 2002). The unusual oscillation spectrum of this star (Figure 1) shows a very large range of excited pressure modes at low and high radial orders. Antoci et al.'s (2011) interpretation was based on the striking similarities between the observations and the characteristics of stochastic oscillations. (1) The frequency range observed in HD 187547 cannot be explained by the opacity mechanism as we understand it. (2) The observed pattern at the high-frequency modes is consistent with the large frequency separation, $\Delta\nu$, expected for high radial orders. (3) The scaling relation between the large frequency separation, $\Delta\nu$, and the frequency of maximum power, $\nu_{\rm max}$, correctly predicts the mode with the highest amplitude within the range of modes interpreted as solar-like oscillations (e.g., Huber et al. 2011). (4) The broad peaks are observed only around the modes of high radial orders (Solar-like oscillations are non-coherent because they are intrinsically damped and re-excited oscillations. Opacity-driven pulsations, on the other hand, seem to be stable and coherent over very long timescales.

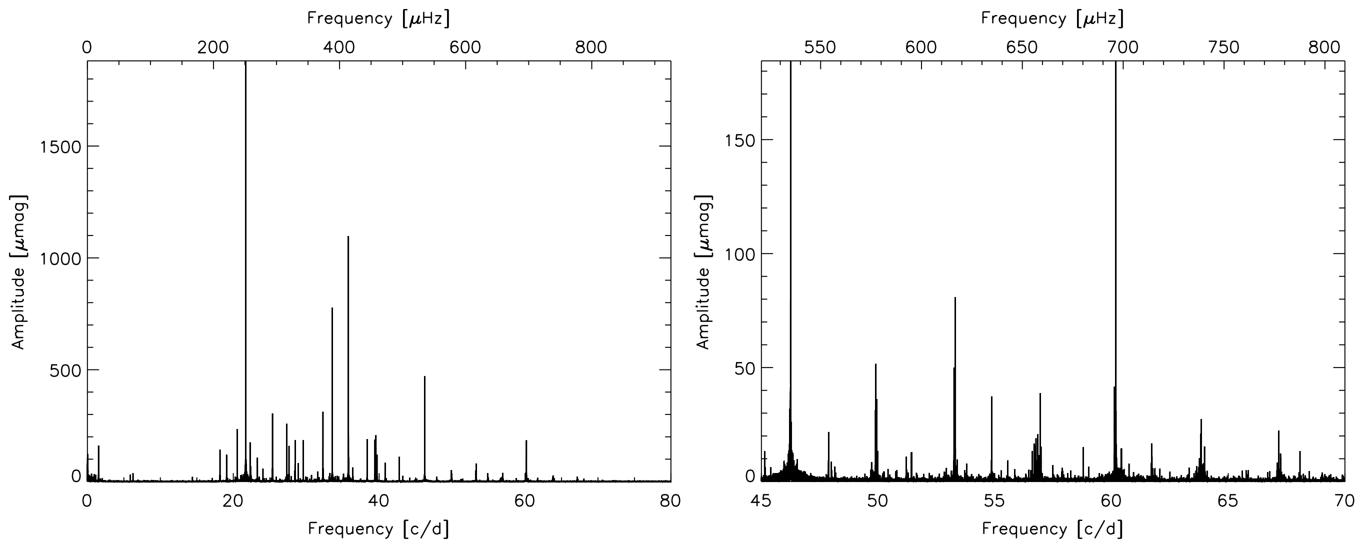


**Figure 1.** Left panel: Fourier spectra of the *Kepler* short cadence data. Right panel: close-up in the frequency region interpreted by Antoci et al. (2011) to be stochastically excited.

Coherent and non-coherent signals can be distinguished in Fourier spectra by comparing the width and the shape of the peak to the window function). (5) The statistical properties of the high-order modes were comparable with those of stochastically excited oscillations (Chang & Gough 1998). This was not the case for the low-frequency modes, excited by the $\kappa$ mechanism.

Abundance analyses of HD 187547 revealed that the star is a chemically peculiar Am star, displaying photospheric overabundances in Ba, Y, and Sr and underabundances in Sc and Ca (Preston 1974). According to Auriere et al. (2011), these stars do not have any large-scale magnetic fields, also confirmed in the case of HD 187547, contrary to the likewise chemically peculiar (ro)Ap stars. The Am phenomenon is related to atomic diffusion, which can efficiently operate because of slow rotation (Charbonneau 1993). The pulsating AmFm stars still represent a mysterious group, as the reason why a large fraction pulsates is not well understood. It is believed that, due to settling of He, this element is not sufficiently abundant in the He II zone for the $\kappa$ mechanism to drive pulsation. The implementation of diffusion of heavy elements in models can explain pulsation in a very constrained instability region (Turcotte et al. 2000). However, observations from the *Kepler* spacecraft and from the ground (Balona et al. 2011; Smalley et al. 2011) demonstrate that pulsating AmFm stars are spread over the entire $\delta$ Sct instability strip. In other words, HD 187547 not only has an unusually large range of pulsation modes excited for a "normal" $\delta$ Sct star, but even more so for a chemically peculiar Am star.

## 2. DATA ANALYSES AND INTERPRETATION

The *Kepler* spacecraft launched in 2009 (Koch et al. 2010) observed our target HD 187547 (KIC 7548479, R.A.$_{2000}$ = 19 48 36.5, decl.$_{2000}$ = 43 06 32.3) for 960 days at short-cadence (1 minute cadence for quarters 3.2 and 7 to 17) and 1470 days at long-cadence observing mode (30 minute cadence for quarters 0–17).

In Figure 1, we show a Fourier spectrum of the entire data set, together with a close-up of the frequency range initially interpreted to be stochastically excited. With more than two years of data, it is now obvious that what Antoci et al. (2011) suggested to be broad peaks with short-mode lifetimes based on one month of data, as expected for solar-like oscillations, are in fact very sharp, well separated, and individually coherent, but closely spaced peaks as shown in Figure 2. The upper row of Figure 2 shows the Fourier spectra of 3 modes computed from 30 days of data, 2 of which were observed in HD 187547 (panels (a) and (b)) and a simulated stochastic mode (panel (c)), demonstrating the similar structure and appearance between the observed and the simulated modes (see also Figure 2 from Antoci et al. 2011). The lower row of Figure 2 illustrates the same modes, but this time computed from 960 d of data. It is clear that the peaks shown in panels (d) and (e) are stable and well resolved, which is in absolute contrast to the stochastic mode in panel (f). The latter shows unresolved peaks and a significantly lower peak height typical for a signal being damped and re-excited.

The stable temporal behavior of the observed modes is not consistent with stochastic excitation, unless the mode lifetimes are longer than the observations, for which the widths of the peaks and the temporal stability provide no evidence, as seen in Figure 2. Furthermore, observations of solar-like oscillators clearly show that the mode lifetimes decrease with increasing effective temperatures, and is of the order of one day for the hottest stars (e.g., White et al. 2012 and references therein). While the observed modes exclude stochastic excitation as seen in Sun-like stars, these do not explain the mechanism triggering the oscillations.

A closer look at the Fourier spectrum reveals an agglomeration of peaks around several of the modes at high radial orders, which is expected for modes of the same degree $l$ of consecutive radial orders. The observed frequency separation (3.5 cd$^{-1}$; 40.5 $\mu$Hz) is consistent with the large frequency separation $\Delta\nu$ for a star with the parameters of HD 187547, i.e., $T_{\rm eff}$ = 7500 $\pm$ 200 K and $\log g$ = 3.9 $\pm$ 0.2 dex. However, there are some problems explaining the peaks around some of the modes (e.g., Figure 2, panels (d) and (e)), which we will address in the next paragraphs.

Rotational splitting of modes: Rotational splitting *alone* cannot explain the above-mentioned agglomeration of peaks. Even under the assumption that *all* modes with $l \leqslant 3$ as well as their associated rotational splittings have observable amplitudes, which is actually unlikely due to geometrical cancellation effects

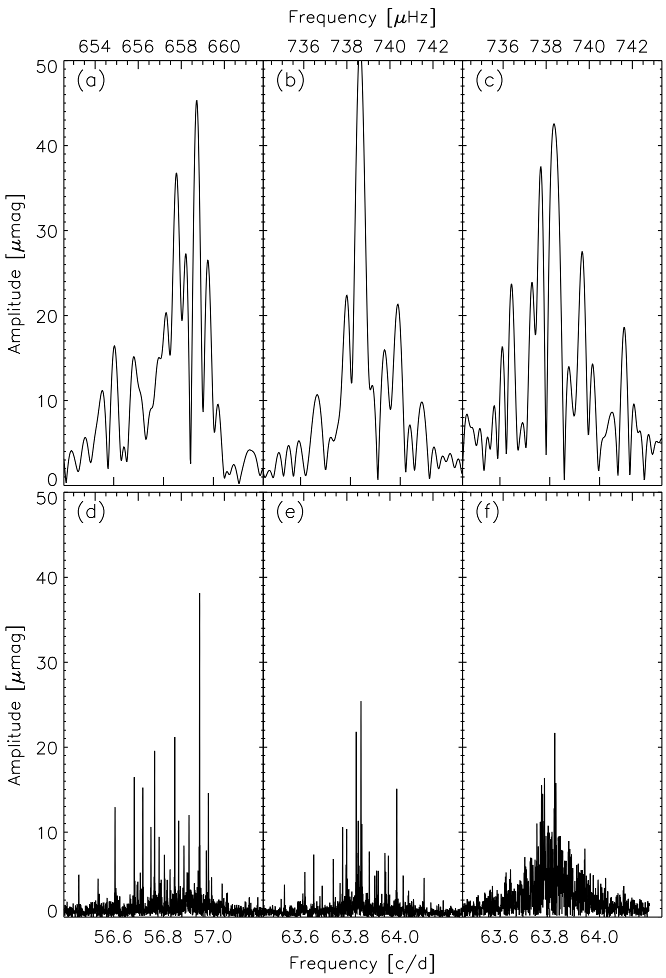


**Figure 2.** In panels (a), (b), (d), and (e), we show Fourier spectra of two oscillation modes observed in HD 187547 and interpreted by Antoci et al. (2011) as being stochastically excited. Panels (c) and (f) depict a simulated stochastic, damped, and re-excited oscillation mode. The Fourier spectra in panels (a), (b), and (c) are based on 30 days of observations (quarter 3.2), the same data set used by Antoci et al. (2011). Panels (d) and (e) illustrate the oscillation spectra of HD 187547 based on 960 days of short-cadence data, clearly showing the temporally stable and well resolved peaks. For comparison, in panel (f) we show the Fourier spectrum of a simulated stochastically excited, i.e., non-coherent, mode with a mode lifetime of 2.8 days using the same duration for the time series as in panels (d) and (e). It can be seen that for a stochastic signal the amplitude decreases with increasing observing time, a characteristic we do not see for the coherent modes, unless beating due to unresolved peaks occurs as illustrated for the mode in panel (b) and (e).

(e.g., Aerts et al. 2010), there are still too many peaks to be accounted for around some of the modes (see Figure 2). Additionally, several of the splittings are too small to be caused by rotation, given the measured $v \sin i$ of $11 \pm 1$ km s$^{-1}$ (Antoci et al. 2011). The Am nature of HD 187547 and the low projected rotational velocity suggest that the star is a slow to moderate rotator, for which fairly equidistant patterns for rotationally split modes associated with modes of degrees 1, 2, and 3 are expected. We used the autocorrelation technique to search for patterns in the smoothed Fourier spectrum of HD 187547. We subdivided the Fourier spectrum into a low- (20–45 cd$^{-1}$) and a high-frequency (45–70 cd$^{-1}$) domain, and checked the frequency region around each high radial order mode separately. No clear dominating or re-occurring pattern, i.e., no re-occurring equidistant peaks, can be found either around the separate modes or in the low- or high-frequency domains. Hence, we conclude that rotational splitting alone is not a viable explanation for the agglomeration, but we do expect that some peaks are indeed rotationally split modes.

High-degree modes: given the high quality of the *Kepler* data, it is plausible that modes of higher degrees ($l \geqslant 4$) are also observed, even if their amplitudes are heavily suppressed due to cancellation effects. Following Ballot et al. (2011) and Lund et al. (2014), we calculate the visibilities with respect to $l = 0$ for modes with degrees from $l = 0$ to $l = 6$ to be 1, 1.48, 0.49, 0.018, 0.0073, 0.0011, and 0.00095, respectively. Assuming that one of the modes with the highest amplitudes is a radial or dipolar mode and adopting the same intrinsic amplitude for all modes, we find it unlikely but cannot rule out that we observe $l > 4$ modes. While $l = 4$ modes might explain the number of observed peaks, these do not explain the observed agglomeration of peaks, as $l = 4$ modes are not expected to align with any of the modes of degree $l \leqslant 3$ in the asymptotic regime, i.e., at high radial orders. The $l = 4$ modes are found in between the ridges of the $l = 0, 2$ and $l = 1, 3$ modes, not only for a model with the parameters of HD 187547, but also for the Sun (Lund et al. 2014).

Mixed modes: mixed modes, i.e., modes behaving as gravity modes in the stellar interior and as pressure modes in the outer envelope, are expected to be observed in pulsating stars as they evolve. However, the evolutionary stage of HD 187547 is not advanced enough (see Antoci et al. 2011) to explain the large number of peaks observed in HD 187547 by mixed modes as found in red giants (e.g., Bedding et al. 2011)

Strong magnetic fields: strong magnetic fields, as observed in roAp stars, could cause rotational amplitude modulation of modes that are aligned with the magnetic axes and not with the rotational axes (oblique pulsator model; Kurtz 1982). This scenario will result in additional peaks in a Fourier spectrum. To investigate whether HD 187547 possesses a magnetic field strong enough to cause an observable mode splitting, we obtained spectropolarimetric measurements of the star on 2012 October 3 using the NARVAL echelle spectrograph in polarimetric mode during DDT time of the Télescope Bernard Lyot (Observatoire du Pic du Midi, France). The spectropolarimeter offers full optical wavelength coverage from 3700–10,000 Å in a single exposure with a resolving power of approximately 65,000. The data were reduced using the LIBRE-ESPRIT automatic reduction software package for spectropolarimetric data, which is based on the ESPRIT reduction package (described in detail in Donati et al. 1997). As the signal-to-noise ratio is too low to detect Zeeman signatures in individual lines, we applied the Least-Squares Deconvolution technique (Donati et al. 1997; Kochukhov et al. 2010), but did not find any polarimetric signal originating from a magnetic field larger than 20 G. Such weak magnetic fields cannot split pulsation modes as observed in roAp stars.

Combination frequencies: many $\delta$ Sct stars show combination frequencies of the form $mf_i \pm nf_j$, where $m$ and $n$ are integer numbers and $f_{ij}$ the observed frequencies, in their oscillations spectra, as a result of the pulsation being nonlinear. In the case of HD 187547, we find several hundreds of statistically significant peaks, which makes it difficult to distinguish clearly between real combination modes and accidental matches. We checked two scenarios in which we required the parent modes to have amplitudes higher than 50 $\mu$mag and 10 $\mu$mag, respectively. We conclude that most of the peaks at high frequencies cannot be reproduced by second-order combination frequencies (i.e., $f_i + f_j$), which are the most likely to occur (Papics 2012). Nevertheless, as a test, we pre-whitened peaks with the same values as second-order combination frequencies and again autocorrelated the Fourier spectrum and found no clear pattern due to rotationally split modes.

Companion: if the star were in a binary or multiple system, it would have a variable velocity with respect to the Earth. This would cause a Doppler shift of each and every pulsation mode, which would be observed as a frequency splitting equal in magnitude to the orbital frequency of the system (Shibahashi & Kurtz 2012). Such orbital frequency splittings are not observed for HD 187547. Additionally, we searched for pulsational phase modulation following the method of Murphy et al. (2014). We used the five highest peaks in the Fourier spectrum, namely, those at 21.7, 35.8, 33.6, 25.4, and 20.6 $\mathrm{cd}^{-1}$, and determined their frequencies, amplitudes, and phases with a nonlinear least-squares fit to the entire *Kepler* long cadence data set (quarters 0 to 17). We then subdivided the time series into 10 day segments, and recalculated the phase at fixed frequencies in each segment. Let us assume the pulsating star is in a binary system. Then we may attribute periodic phase variations to variations in the light arrival time because the path length traveled by the light on its way to Earth varies. We see no periodic variations in phase and thus no periodic variation in the light arrival time delays. Nonetheless, from a Fourier transform of the light arrival time delays, we are able to place an upper limit on a hypothetical binary mass function of $1.1 \times 10^{-5}\, M_{\odot}$. If we assume a primary mass of $1.85\, M_{\odot}$ and an arbitrary inclination angle $i = 45^{\circ}$, we are able to rule out a companion more massive than $0.049\, M_{\odot}$. To provide an upper limit on companion mass, we take the same mass function and assume the primary mass is at the high-mass end of the distribution of masses of $\delta$ Sct stars, at $2.1\, M_{\odot}$, and we assume $i = 15^{\circ}$. With these values we can rule out a companion having a mass $m \geqslant 0.15\, M_{\odot}$.

To conclude, based on the temporal stability and the narrow peaks defined by the window function, the high radial order modes are most likely not stochastically excited. We find an agglomeration of peaks around some of the high radial order modes (Figure 2), but cannot offer a clear explanation to account for all the peaks observed at high frequencies. We can, however, exclude strong magnetic fields to cause additional splitting of modes as observed in roAp stars as well as a companion with a mass larger than $0.049\, M_{\odot}$ to induce additional peaks due to the light time effect. We find very few peaks to have the same values as second-order combination frequencies, which in case combinations frequencies are present are the most likely to occur. Based on the Am nature of the HD 187547, we can assume slow to moderate rotation resulting in more or less equidistantly spaces peaks, but we find no clear pattern to explain rotationally split modes, which does not mean that these are not present, only that they are not clearly identifiable. As far as high degree modes are concerned, we cannot exclude the presence of modes with $l \geqslant 4$, but find them unlikely to explain the agglomeration round some of the high-order modes because of significant geometric cancellation.

## 3. EXCITATION BY THE TURBULENT PRESSURE MECHANISM

In view of the latest *Kepler* data, which suggest that the high-frequency modes observed in HD 187547 are not stochastically excited, we perform a nonadiabatic pulsational stability analyses of two stellar models for this star with the same mass and effective temperature, but different in luminosity. The global properties of the two models are listed in Table 1. The linear stability analyses were carried out in the manner of Balmforth (1992a, 1992b) and Houdek et al. (1999) using, however, the latest OPAL opacity tables (Rogers & Iglesias 1995) supplemented at low temperatures by the Ferguson et al. (2005) tables. In these analyses, the turbulent fluxes are obtained from a nonlocal generalization (Gough 1977a) of Gough's (1977b) time-dependent mixing-length formulation, adopting for the mixing length a value that was calibrated to the Sun. The momentum flux (turbulent pressure) is consistently implemented in both the equilibrium and linear stability calculations, as described by Houdek et al. (1999). The stellar models described above are computed for radial modes only, however, we can assume that the results are also applicable for low-order non-radial modes as well. This is because most non-adiabatic processes take place in the outer thin layers of the star, where the structure of a low-degree modes differ very little from that of radial modes of similar frequencies (as discussed by Balmforth et al. 2001).

**Table 1**
Parameters for the Models Used in This Work are Consistent with the Observations and can Explain the Major Part of the Observed Modes

| | Mass ($M/M_{\odot}$) | $T_{\mathrm{eff}}$ (K) | $L$ ($L/L_{\odot}$) | $\alpha$ |
|---|---|---|---|---|
| Model 1 | 1.85 | 7575 | 16 | 1.7 |
| Model 2 | 1.85 | 7575 | 19 | 1.7 |

In this nonlocal generalization there are three more parameters, $a$, $b$, and $c$, which control the spatial coherence of the ensemble of eddies contributing to the turbulent fluxes of heat ($a$), and momentum ($c$), and the degree to which the turbulent fluxes are coupled to the local stratification ($b$). These parameters control the degree of "nonlocality" of convection: low values imply highly nonlocal solutions, and in the limit $a, b, c \rightarrow \infty$ the system of equations formally reduces to the local formulation (e.g., Houdek et al. 1999), except near the boundaries of the convection zone, where the local equations are singular. Theory suggests values for these nonlocal convection parameters (Gough 1977a), which are of the order of unity, but these values are approximate and to some extent these parameters are free. Balmforth (1992a, 1992b) explored the effect of $a$, $b$, and $c$ on the turbulent fluxes for the solar case and found good agreement between measured solar mode lifetimes and (twice the) estimated linear damping rates using $a^2 = 600$, $b^2 = 600$ and $c^2 = 600$. Houdek & Gough (2002) estimated linear damping rates in the red giant star $\xi$ Hydrae and found mode lifetimes agreeing with observations for $a^2 = 900$, $b^2 = 2000$, and $c^2 = 300$.

The same nonlocal convection model was also applied to roAp stars by Balmforth et al. (2001), who adopted $a^2 = 1000$, $b^2 = 1000$, and $c^2 = 1000$ in the stability analyses of radial p modes. These rather large values for $a$, $b$, and $c$ indicate that convection is more local, which is not inconsistent with the shallow convective envelopes in A- and early F-type stars. These values also reproduce observations of roAp stars best (see, e.g., Cunha et al. 2013). In this paper, we adopt values similar to Balmforth et al. (2001), i.e., $a^2 = 950$, $b^2 = 950$, and $c^2 = 950$, as such high values drive a larger number of modes at higher frequencies, consistent with the observations presented here. Note that Antoci et al. (2011) adopted Balmforth's (1992a, 1992b) solar-calibrated values for the their preliminary estimates of stability properties in HD 187547 and did not find driving at high radial orders.

Our analyses are illustrated in Figure 3 for both models, where we plot the normalized growth rates, i.e., the linear stability

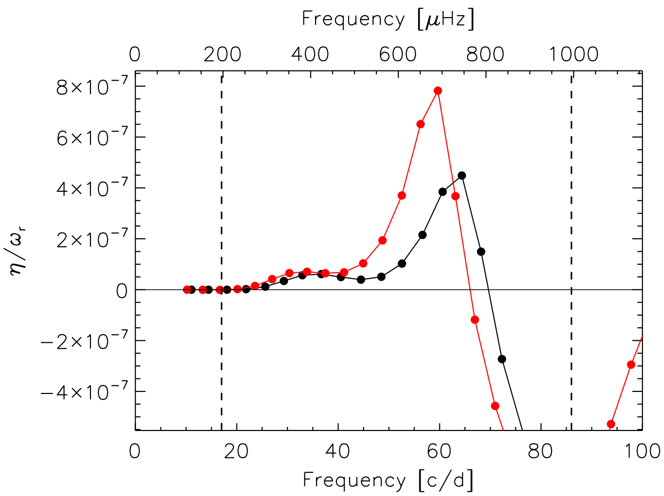


**Figure 3.** Comparison between the theoretically excited range of modes (full circles) and the observed modes delimited by the dashed lines. Here we plot the normalized growth rate as a function of frequency for model 1 (black) and model 2 (gray/red); see Table 1 for details on parameters. A positive growth rate means excited modes, whereas a negative value indicates intrinsically damped modes.

(A color version of this figure is available in the online journal.)

coefficient, $\eta/\omega_{\mathrm{r}}$ as a function of frequency, where the complex angular frequency $\omega = \omega_{\mathrm{r}} + i\eta$. A positive growth rate, $\eta$, indicates intrinsically excited modes, whereas a negative growth rate indicates that the modes are intrinsically damped.

Inspection of the work integrals[7] for these modes shows that it is the perturbation[8] of the turbulent pressure (or momentum flux) which is responsible for driving most of the high-frequency modes. This is reflected in a local increase of the accumulated work integral contribution $W_{\mathrm{t}}$ (solid curve) in Figure 4. The contribution from the gas pressure to the accumulated work integral, $W_{\mathrm{g}}$ (dashed curves in Figure 4), which includes contributions from both the radiative and convective heat flux, also increases locally in the H I ionization zone, but by a much smaller amount than $W_{\mathrm{t}}$. In Figure 4, we show the accumulated work integrals for four different radial orders, $n = 4$, 7, 12, and 16 for both models explored in this article. The mode with $n = 4$ corresponds roughly to the dominant mode observed in HD 187547, which is at approximately 21 cd$^{-1}$. The positive accumulated work integral in Figure 4 (panel (a1)) shows that this mode is primarily excited by gas pressure in the He II ionization zone (see panel (a2) in Figure 4), i.e., by the "classical" opacity mechanism. In this case, the turbulent pressure has a slight damping effect. For the mode with $n = 7$, however, driving in the hydrogen zone occurs by both the gas and the turbulent pressure, but in the He II ionization region only the opacity mechanism is effectively contributing to driving (Figure 4, panels (b1) and (b2)). Interestingly, for the $n = 12$ and 16 modes, depicted in Figure 4 (panels (c1,2) and (d1,2), respectively), the gas pressure is entirely damping while the turbulent pressure in the H I/He I ionization zones is responsible for driving these modes.

The turbulent pressure in the He II ionization layer does not play an important role for either the low- or the high-order modes because, in addition to the very inefficient convection in this ionization zone, the pulsation periods are much shorter compared to the characteristic convection timescale $\tau$. In the H ionization zone, however, $\tau$ is similar to the pulsation periods for frequencies between 60 and 80 cd$^{-1}$ (650 and 800 $\mu$Hz), which is also reflected in Figure 3 by the largest values of the linear growth rates (black and red solid curves).

Similar to the case of the $\kappa$ mechanism, which is responsible for driving the lowest radial orders in the deeper He II ionization region, the driving by the convection dynamics occurs through the pulsationally induced turbulent pressure perturbations $\delta p_{\mathrm{t}}$, where $p_{\mathrm{t}} := \langle \rho w w \rangle$ with $\rho$ being density and $w$ the vertical component of the convective velocity field $\boldsymbol{u} = (u, v, w)$ (angular brackets denote an ensemble average, but in practice horizontal averages are used) and $\delta$ denotes a perturbation in a Lagrangian frame of reference. This leads to intrinsically unstable (self-excited) modes, i.e., to *coherent* modes, which are consistent with the narrow widths of the high-frequency peaks in the observed acoustic oscillation spectrum derived from the longer *Kepler* data set presented here.

There are two distinct ways for the turbulent pressure $p_{\mathrm{t}}$ to excite waves. Solar-like, or stochastic, excitation is caused by localized acoustic random events in the fluctuations of the Reynolds stresses $\rho \boldsymbol{u}\boldsymbol{u}$. This excitation is constrained to a rather thin layer, just below the stellar surface, where convection reaches the highest turbulent Mach numbers. These convective fluctuations have random phases with respect to the modes and therefore constitute a stochastic driving. A rather different mechanism is offered by the coherent excitation by the horizontally averaged turbulent pressure $p_{\mathrm{t}}$ due to a phase lag in the response of $p_{\mathrm{t}}$ to an incident (acoustic) wave or density perturbation, similar to the phase lag between gas pressure $p$ and density $\rho$ in the case of the $\kappa$ mechanism. The phase lag is such that it provides either coherent excitation, or damping, but does not fluctuate in time, as is the case in the stochastic excitation mechanism. Instead it depends only on the structure of the star.

Previous calculations with a time-dependent convection formulation already indicated that the turbulent pressure can act as a driving agent in various types of pulsating stars. The first evidence that the phase of $\delta p_{\mathrm{t}}$ can be such as to drive pulsations was reported by Gough (1966) for Mira stars. Later, Houdek (2000) found intrinsically unstable modes with radial orders $7 \lesssim n \lesssim 10$ in $\delta$ Scuti stars for a certain set of convection parameters and, more recently, Xiong & Deng (2007) reported an instability strip for red giants whose location in the HR diagram was determined by the turbulent pressure contribution to the work integral.

We conclude that driving by turbulent pressure perturbations in an appropriate stellar model does reproduce up to 85% of the observed range of unstable modes in HD 187547. This driving mechanism is therefore a promising candidate for explaining high-order p modes in $\delta$ Scuti stars.

### *3.1. Insights from 3D Simulations of Convection*

In one-dimensional (1D) models of convection, including mixing length treatment (MLT) as well as nonlocal and time-dependent flavors of it, the convective flux is inseparably linked to the velocities through simple proportionality. Small convective fluxes therefore mean small convective velocities. In Gough's (1977a, 1977b) nonlocal mixing-lengths formulation, the differential equations (of sixth order) for the turbulent fluxes are solved as a boundary value problem, with exponentially

[7] A detailed discussion of the work integrals $W_{\mathrm{t}}$ and $W_{\mathrm{g}}$ is given in, e.g., Balmforth (1992a, 1992b).

[8] We use the word *perturbation* to denote a variation of a quantity induced by the pulsation and the word *fluctuation* for the variation of a quantity induced by the convective motion.

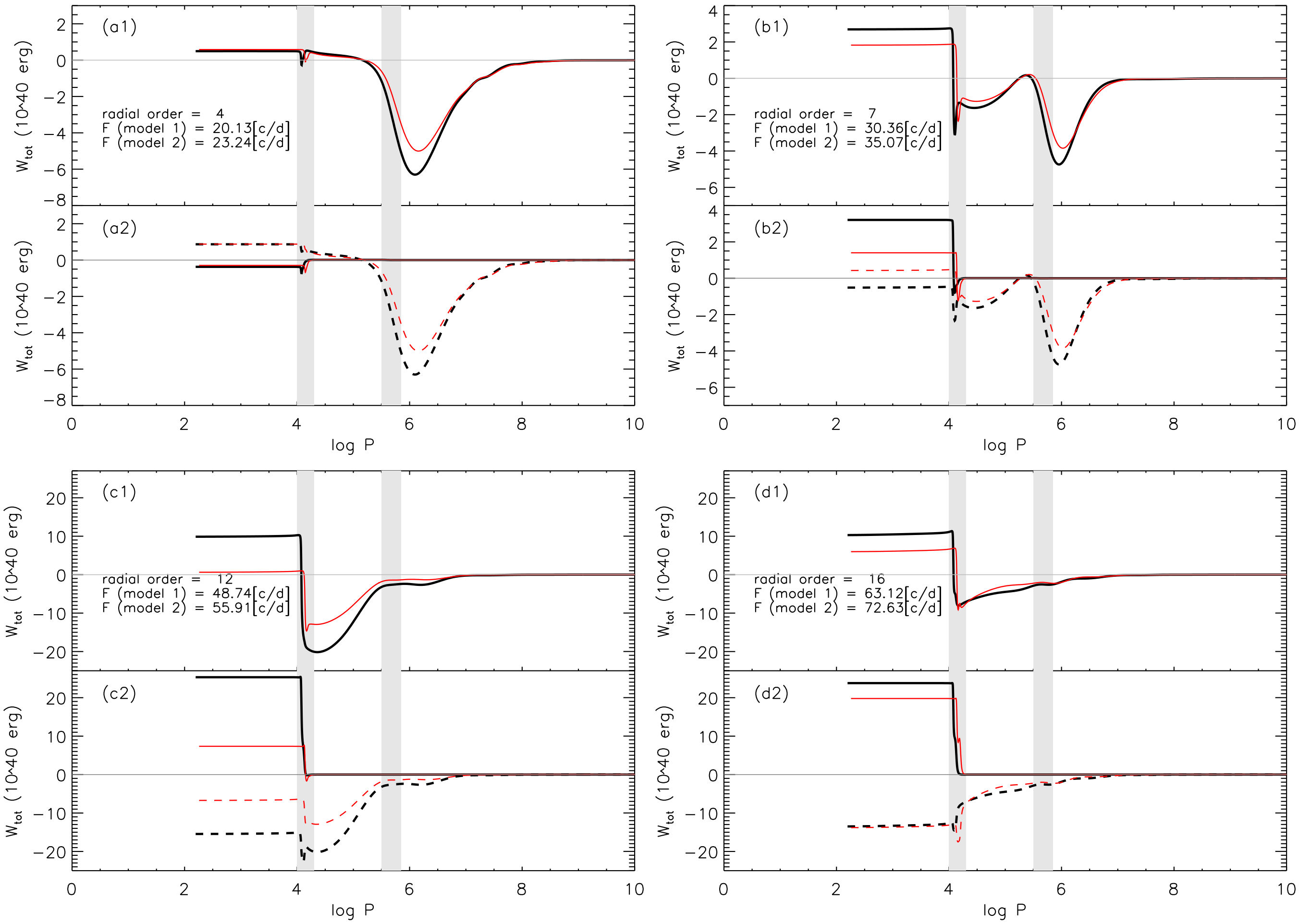


**Figure 4.** Accumulated work integrals as a function of total pressure for modes of different radial orders $n$. Model 1 is depicted in black and model 2 in red (gray in the print journal). The parameters are described in Table 1. The gray region at $\log P \simeq 6$ indicates the He II ionization region, and at $\log P \simeq 4$ the H I and He I ionization zones. Panels (a1), (b1), (c1), and (d1) illustrate the total accumulated work integrals, while panels (a2), (b2), (c2), and (d2) show the accumulated work integrals for the turbulent pressure (continuous line) and the gas pressure (dashed line).

(A color version of this figure is available in the online journal.)

decaying (positive) fluxes into the overshooting, convectively stable layers. From realistic three-dimensional (3D) hydrodynamic simulations of convection (Trampedach et al. 2013), on the other hand, we know that the velocity field is almost decoupled from the fluxes, and the latter are governed not only by correlations between flow direction and temperature contrast, but also by the fractional area (filling factor) covered by each flow direction. Since large fluxes are going in each direction, even a slight change in filling factor can profoundly change the convective fluxes. This is what decouples the convective velocities from the convective fluxes, and makes current 1D formulations of convection inadequate for predicting velocity fields from overshooting and from very inefficient convection, as found in A stars.

At the borders of convection zones, the Schwarzschild criterion tells us that the correlation between temperature contrast and flow direction changes sign, and the overshoot flux is actually negative, as observed in the simulations. This overshoot flux is also small as the upflow filling factor abruptly changes from 65% in the convection zone to less than 50% above it, causing the opposing fluxes to nearly cancel and fall off exponentially with height. The velocities, on the other hand, display no sign of this profound transition. Since the turbulent pressure is $\langle \varrho w w \rangle$ and $\varrho$ does not change abruptly either, the turbulent pressure extends well beyond the convection zones, despite the fluxes forming a well-defined boundary of convection. Thin and close convection zones, as found in A stars, therefore have efficient mixing between them, despite the two zones being clearly separated. They also have very inefficient convection, with high velocities transporting only a fraction of the full flux, $\sigma T_{\rm eff}^4$ (Freytag et al. 1996; Freytag & Steffen 2004; Trampedach 2004; Kupka et al. 2009).

The decline of convective fluxes occurs at cooler temperatures compared to the decline of the convective velocities, whereas in the case of 1D MLT models, the velocities and fluxes are proportional to each other. In other words, the outer layers of A-type stars are still convective. In the case of high effective temperatures, however, convection mixes material but does not transport energy efficiently. Despite the free parameters of analytical formulations of convection, no combinations of parameters can reproduce these results of 3D simulations due to their built-in assumptions. Compared to such a model, a preliminary convection simulation of HD 187547 has a larger and more extended turbulent pressure peak, providing even more excitation than the 1D model, despite transporting little flux by convection.

## 4. DISCUSSION AND CONCLUSION

Based on more than two years of *Kepler* data, we can conclude that the high radial order modes observed in HD 187547, initially interpreted by Antoci et al. (2011) as being stochastically excited, show no temporal variability and are coherent and intrinsically unstable (i.e., self-excited). The long data set was required to resolve the very closely spaced peaks and to show that there is no temporal variability, inconsistent with pure stochastic oscillations that have mode lifetimes significantly shorter than the observing period of 960 days.

There is no clear explanation for the observed agglomeration of peaks around the high radial order modes, as we cannot account for all the peaks using only modes with $l \leqslant 3$ and their associated $m$ modes. Modes with $l = 4$ are not expected to cluster around high-order modes with $l \leqslant 3$, at least not for the observed parameters of HD 187547 and are thus also insufficient. We cannot exclude the presence of modes with $l > 4$, but the geometrical cancelation effects for such modes are very high, which would imply that the intrinsic amplitude of these high-degree modes are higher than those of radial or dipolar modes—a hypothesis that we find unlikely and that has no other observational support. From polarimetric observations we set an upper limit of 20 G for the strength of the magnetic field, which excludes the possibility of magnetically split modes like those seen in roAp stars.

Our models, using a time-dependent, nonlocal convection treatment, suggest that convection excites oscillations in HD 187547, however, not stochastically. It is the turbulent pressure that is the main driving agent and can reproduce 85% of the observed frequency range. We find that the adopted nonlocal convection parameters, $a^2 = 950$, $b^2 = 950$, and $c^2 = 950$, can reproduce observations of oscillating A-type stars and therefore assume that they represent realistic values for describing the convection dynamics in A-type stars when using the nonlocal convection model by Gough (1977a, 1977b). Preliminary results from 3D hydrodynamic simulations of convection for HD 187547 show that the amount of turbulent pressure is even larger than in our 1D models, which provides further evidence in favor of this excitation mechanism provided the turbulent pressure has a suitable phase lag with respect to the oscillations.

Similar values for the $a$, $b$, and $c$ parameters, as adopted in this work, were used in the study of the excitation mechanism in roAp stars conducted by Balmforth et al. (2001), equally motivated by the fact that in these pulsators the convective envelope is very shallow. Balmforth et al. (2001) found that driving of high-frequency modes in roAp stars takes place in the H I ionization region, however, the driving results from the opacity mechanism and is present only in models where convection is suppressed by a magnetic field. Thus, the values of $a$, $b$, and $c$ play no direct role in the excitation of the oscillations discussed by Balmforth et al. (2001). Nevertheless, based on a detailed comparison with observations, Cunha et al. (2013) recently provided strong evidence that the opacity mechanism in models similar to those suggested by Balmforth et al. (2001) fails to drive the very high-frequency oscillations observed in a number of roAp stars. As an alternative, Cunha et al. (2013) suggested that the perturbation to the turbulent pressure may be the principle driving agent for these modes, similarly to our independent findings for models of HD 187547. However, since the oscillations observed in roAp stars are of significantly higher radial orders and, consequently, more sensitive to the details of the outer stellar layers—which are particularly difficult to model in roAp stars due to the presence of strong magnetic fields and strong chemical peculiarities—the authors were very conservative in their conclusions about this possibility. Our results for intermediate radial order modes in a star with a much less complex outer envelope and atmosphere support the possibility that the turbulent pressure can be a driving agent for classical pulsators in a particular region of the HR diagram.

For the future, we plan to explore the entire parameter space in the classical instability strip and investigate how the values of $a$, $b$, $c$ affect the mode stability within the entire instability strip, i.e., for different stellar masses, metallicities, and changing the stratification in the stellar atmospheres using the models presented in this paper. Additionally, we have started 3D simulations of convective atmospheric models for the parameters of HD 187547, which will allow to better understand the stellar convective envelope in $\delta$ Sct and related stars.

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