RED GIANT SEISMOLOGY: SEISMIC SIGNATURES OF CONVECTIVE OVERSHOOT

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ABSTRACT

Most red giant models do not reproduce the position of the observed luminosity bump, a diagnostic of the maximum extension of the convective envelope during the first-dredge up. (see figure 1 based on Khan et al. 2014) Global seismic parameters, the large frequency separation and frequency of maximum oscillation, show that overshoot below the convective envelope helps match red giant model luminosity bump positions to observed bump positions. The global seismic properties, however, cannot be used to probe envelope overshoot in a star-by-star manner. The long time series of Kepler and the TESS continuous viewing zones (CVZ) allow us to determine the individual mode frequencies of many red giants and these individual modes allow us to probe the internal structure of the stars. Red giant mixed modes (modes that are p-like (i.e., acoustic modes) at the surface and g-like (i.e., gravity modes) in the core) contain important information about the interior structure of the star. We present the results of a theoretical study to investigate the seismic signature of convective overshoot in red giants. Our intention is to use these signatures to determine the amount of overshoot needed to model observed frequencies in red giants that have high quality seismic data.

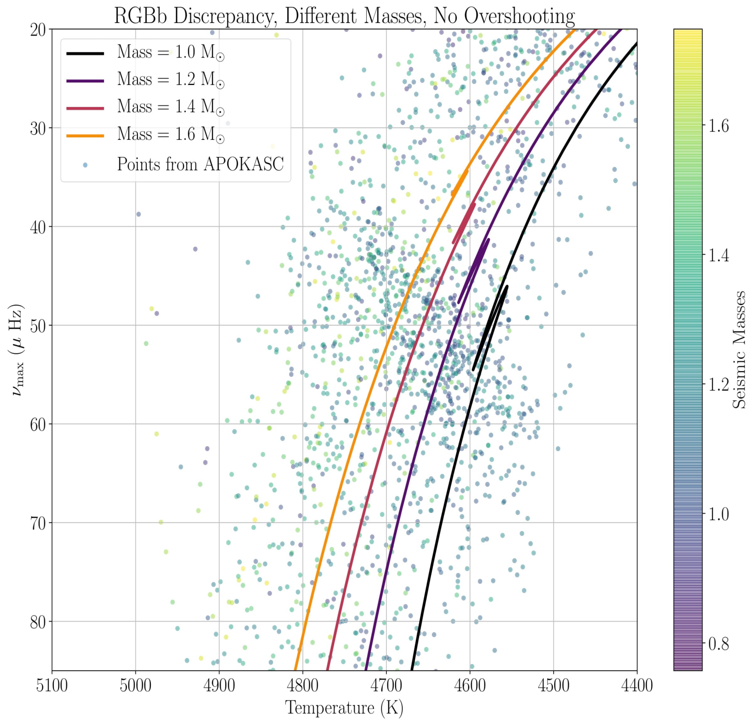


Figure 1 (left,) shows the discrepancy between the position of the red giant branch luminosity bump in red giant models (lines show MESA evolutionary tracks for various mass, solar metallicity red giant models) and the position of the red giant branch luminosity bump from the overdensity of red giants observed in the APOKASC catalogue in a $\nu_{\rm max}$ vs. temperature diagram.

MOTIVATION

WHY RED GIANT SEISMOLOGY

Red giants are intrinsically very bright and can be seen from extremely far distances with high signal to noise. Spaced based photometry missions like CoRoT, Kepler, and TESS have observed tens of thousands of oscillating red-giants stars as the cadence of their observations is favorable for red giant oscillation mode detection. Individual mode parameters can be extracted from many target stars with high quality photometric data. We would like to use these individual modes to determine the input physical parameters for stellar models, particularly convective overshoot, a phenomena that occurs when convective parcels of fluid overshoot convective boundaries due to their momentum. To study the effects of overshoot we employ asteroseismology, a powerful tool which can probe stellar interiors.

POSITION OF THE RED GIANT BRANCH BUMP CHANGES WITH ENVELOPE OVERSHOOT

After a main sequence star exhausts its supply of Hydrogen in the core, it is left with an inert Helium core surrounded by a Hydrogen burning shell which is in turn surrounded by a cool, convective envelope which swells greatly in size during the red giant phase. A star can spend millions to a billion years evolving up the red giant branch depending on its mass, decreasing in surface gravity as it expands and becomes more luminous. An interesting and relevant section of ascending red giant branch evolution is called the red giant branch luminosity bump and appears as a zig-zag shape apparent in a red giant's evolutionary track on the HR diagram. This luminosity bump occurs when the deepening convection zone reaches down to the position of the hydrogen burning shell. The position of the red giant bump in MESA models of varying masses do not match up with the overdensity of red giants observed in catalogs such as the APOKASC catalogue. Figures 1 and 2 show temperature on the x-axis and the frequency of maximum oscillation power ($\nu_{\max}$) on the y-axis. $\nu_{\max}$ is proportional to surface gravity which in turn is proportional to luminosity. Studies such as Khan et al. 2014 have claimed overshooting could potentially explain the red giant branch bump discrepancy. Since the position of this red giant branch bump depends on the deepening convection zone and therefore depends on how convection is modeled, a thorough investigation into how modeling convection changes red giant properties is necessary.

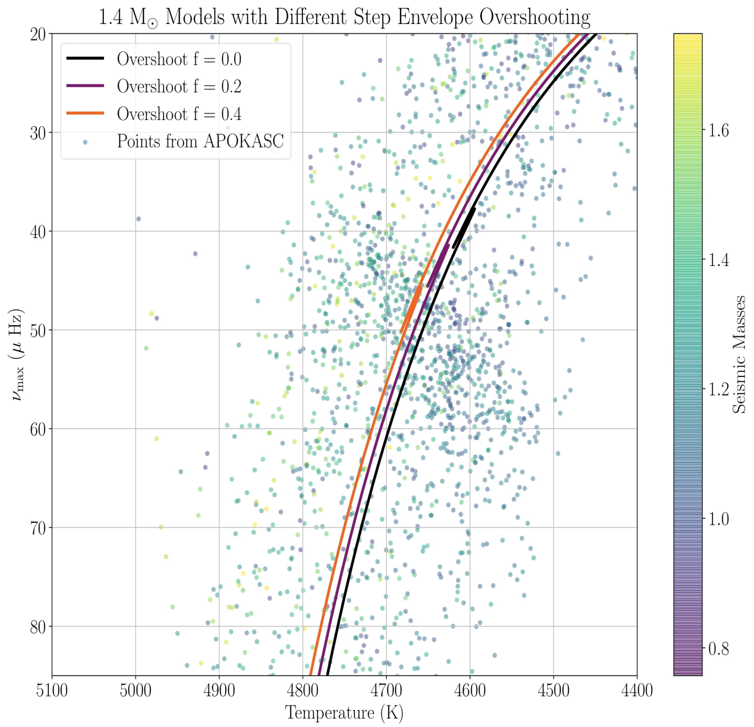


Figure 2 (left,) shows a similar $\nu_{\max}$ vs. temperature diagram to figure 1 but now includes three MESA models for a 1.4 solar mass and metallicity red giant with increasing values of envelope overshoot. The higher step envelope overshoot pulls down the position of the red giant branch bump to be more in line with the observed overdensity in stars as observed by APOKASC.

METHODS

MESA FOR MODELLING CONVECTION

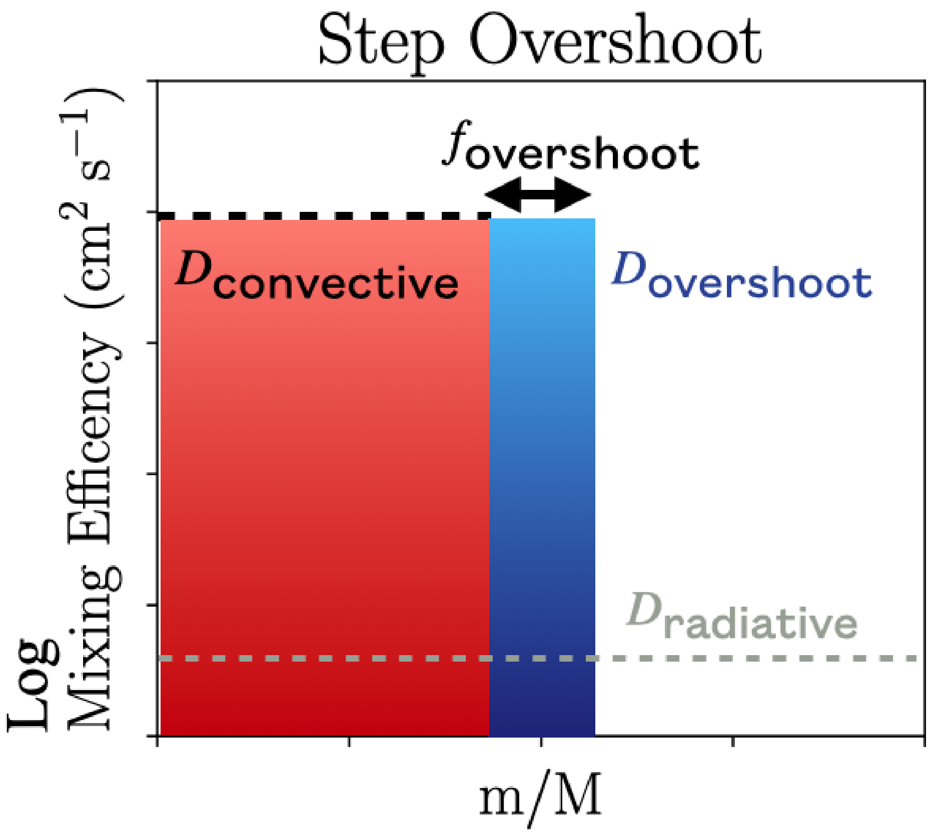


Figure 3 (right,) shows a mixing efficiency versus radius diagram for a convective boundary incorporating step overshoot. The mixing efficiency in the convection zone, $D_{\mathrm{convective}}$, is high and the mixing efficiency in the radiative zone, $D_{\mathrm{radiative}}$, is low. Step overshoot extends the convective, high mixing zone past the convective envelope's boundary by a distance of a free parameter $f_{\mathrm{overshoot}}$ times the pressure scale height at the boundary position. In step overshoot, the mixing efficiency in the overshoot region is $D_{\mathrm{overshoot}} = D_{\mathrm{convective}}$.

Stellar evolution codes like MESA generally use a mixing length approximation to model convection. Mixing length theory is analogous to the concept of mean free path in thermodynamics where a fluid parcel will conserve its characteristics for a certain "mixing length" before being incorporated with the surrounding fluid. This means that within convection zones, the stellar model is fully mixed (no change in element abundances) but no mixing occurs outside of the convective zone boundaries. This is a rough approximation and focusing on the convective boundaries, there should be parcels of fluid overshooting the convective boundaries due to their own momentum. This would mean an effective change in the position of the convective boundaries and how much overshooting there is across boundaries is an important unknown input parameter in stellar modeling. Overshoot in MESA is treated as overmixing and the code includes two options, step overshoot and exponential overshoot.

These two overshoot modeling methods change the mixing efficiency versus interior mass profile of a stellar model in two slightly different ways and for this poster, we focus on the effects of step envelope overshoot. Step overshoot extends the convective, high mixing zone past the convective envelope's boundary by a distance of a free parameter $f_{\mathrm{overshoot}}$ times the pressure scale height at the boundary position as shown in figure 3.

To investigate the effect of different overshoot values, we made stellar models using the evolution code MESA which solves the fully coupled structure and composition equations simultaneously. NOTE: Core overshoot is also important in the main sequence evolution of a star but since the cores of red giants aren't convective, core overshoot manifests as a fossil signature from the main sequence. In future work though, we will look into the signatures of core overshoot.

MIXED MODES

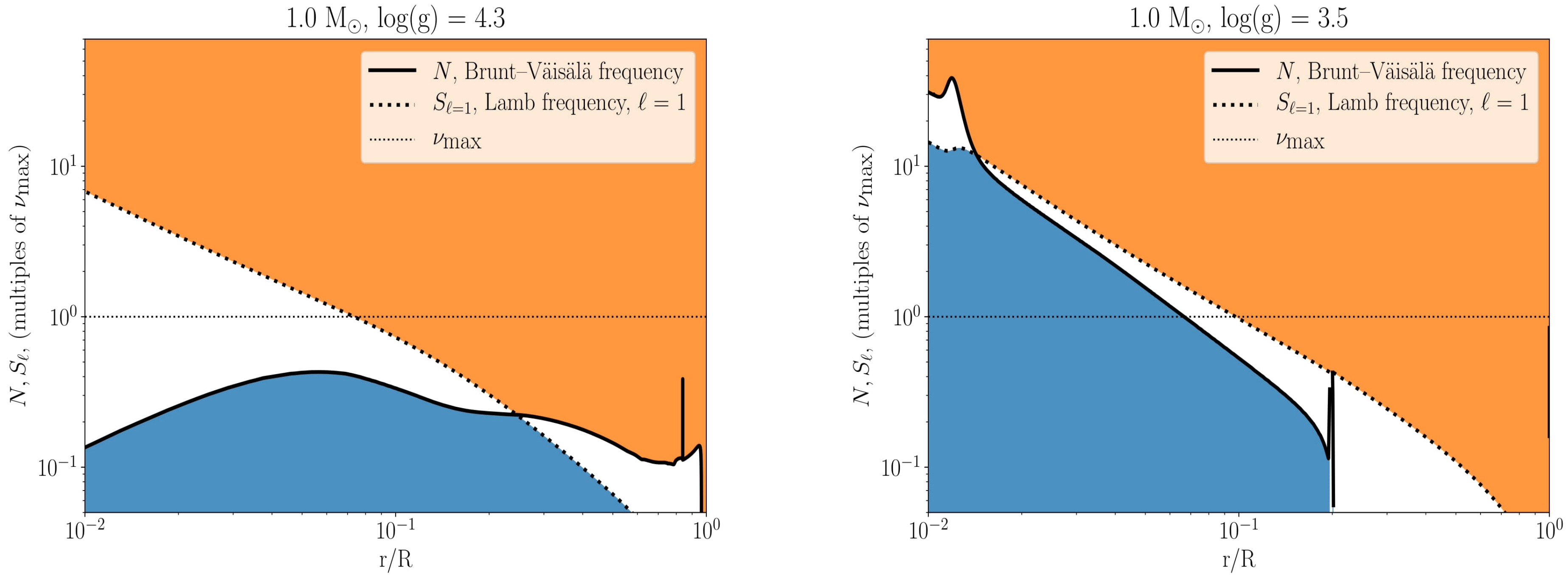


Figure 4 (above,) shows a propagation diagram with Brunt–Väisälä (solid line) or Lamb (dotted line) frequency in units of $\nu_{\max}$ on the y-axis and fractional radius on the x-axis for a 1 solar mass and metallicity stellar model before the red giant branch (left hand side) and during the red giant branch (right hand side.) The cavity in frequency/radius space where p-modes can propagate is highlighted in orange and the g-mode cavity is highlighted in blue.

The asteroseismic pulsations visible on the photospheres of stars by missions like Kepler are produced by standing waves traveling inside the star. Waves where the restoring force is pressure are called p modes and can only exist with frequencies above two characteristic frequencies called the Lamb frequency and the Brunt–Väisälä frequency.

On the other hand, waves where the restoring force is buoyancy are called gravity modes or g modes and exist with frequencies below the Lamb and Brunt–Väisälä frequencies. In regions of a star where the Brunt–Väisälä frequency is imaginary, the stellar fluid is unstable to convection and we have a convection zone. The effective position of the convection zone is changed with the implementation of envelope overshoot.

Between the g and p mode cavities is a classical forbidden region where both g mode and p mode oscillations are damped exponentially. This forbidden region is wide in main sequence stars (see left hand figure above) but as a star evolves into a red giant, the p and g mode cavities close in towards each other and modes in each cavity can couple to each other giving rise to mixed modes (see right figure above.)

EFFECTS OF STEP ENVELOPE OVERSHOOT

STRUCTURAL CHANGES

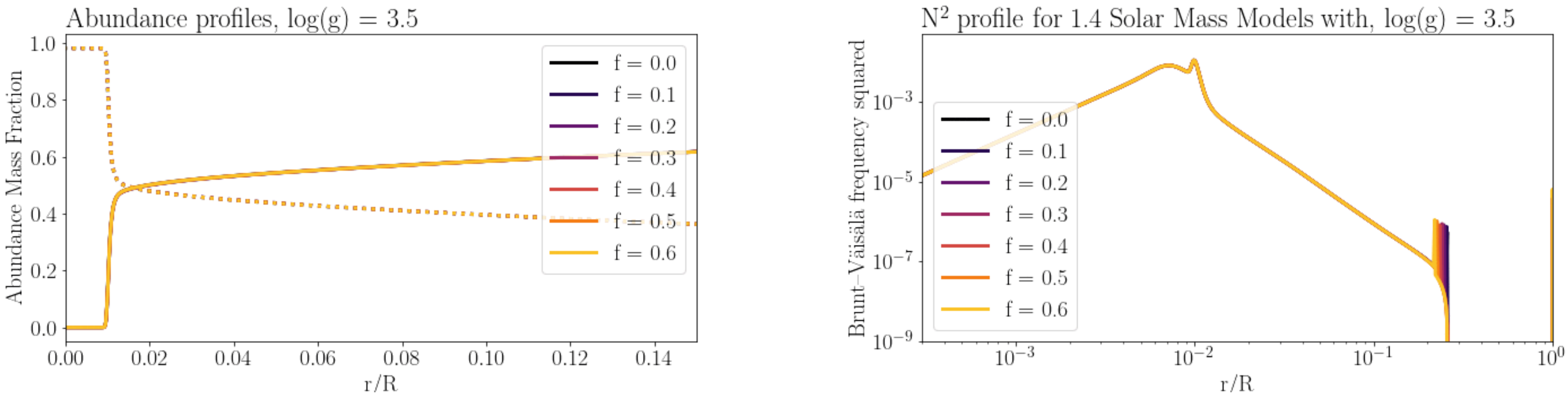
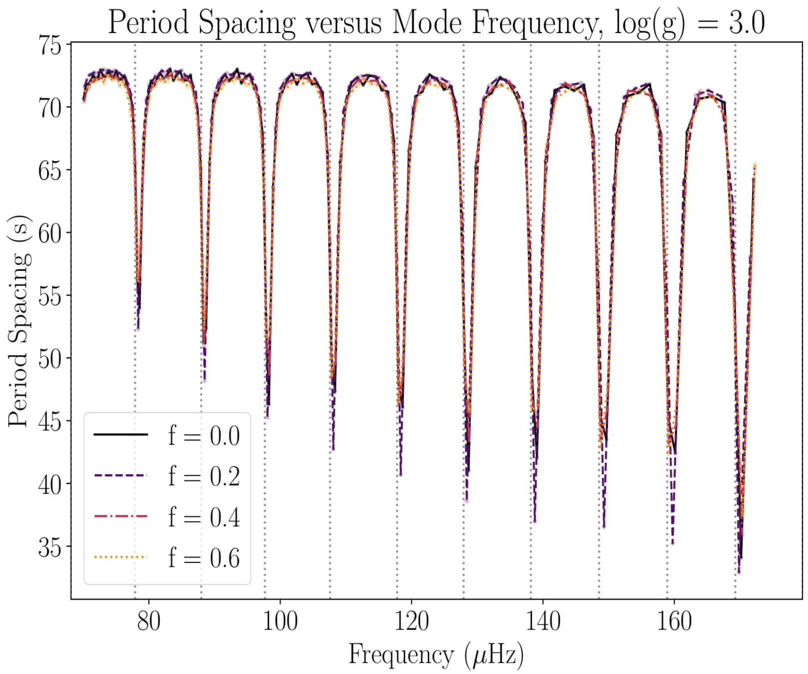


Figure 5 (above,) shows two animations showing how the abundance profiles (left) and Brunt–Väisälä frequency profiles (right) evolve differently up the red giant branch for 1.4 solar mass stellar models with solar metallicity and different amounts of step envelope overshoot. The upper left abundance profile animation shows the Hydrogen abundance (solid lines) and Helium abundance (dashed lines) as a function of stellar radius. Note the abundance profiles are horizontal in the convection zone and models with higher amounts of step envelope overshoot have deeper convection zones at a given value of $\log g$. The difference between abundance profile also means that the Brunt–Väisälä frequency profiles (right animation) for red giant models with different overshoot values will be slightly different since the profile bump signature of the first dredge up changes location based on different values of the step overshoot parameter f.

OSCILLATION MODE PROPERTIES



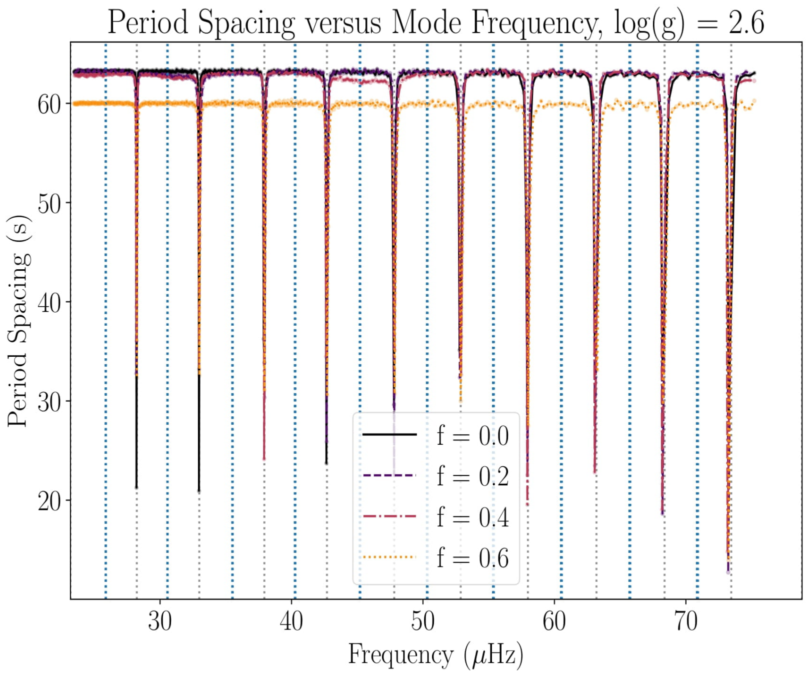


Figure 6 (above,) shows two period spacing versus frequency plots for 1.4 solar mass models with solar metallicity and different amounts of step envelope overshoot. Red giant mode frequencies are generally equally spaced in period so it is informative to plot the period difference between consecutive modes as a function of frequency. The oscillation mode frequencies for our models were calculated with the stellar oscillation code GYRE. The upper left hand figure shows pairwise period difference versus mode frequency for $\log g = 3.0$ and the upper right hand figure shows the same for $\log g = 2.6$ red giant models.

At $\log g = 3.0$, none of the different overshoot red giant models have gone through the red giant branch luminosity bump and therefore the period spacing versus mode frequency plots match up between models of different overshoot. On the other hand, at $\log g = 2.6$, the $f = 0.6$ overshoot model has gone through the red giant branch luminosity bump, resulting in a significant decrease in the median value of the period spacing. Clearly, at a given value of $\log g$, red giant models with different overshoot values have significantly different oscillation properties especially around the red giant branch luminosity bump.

PERIOD ECHELLE DIAGRAM EVOLUTION

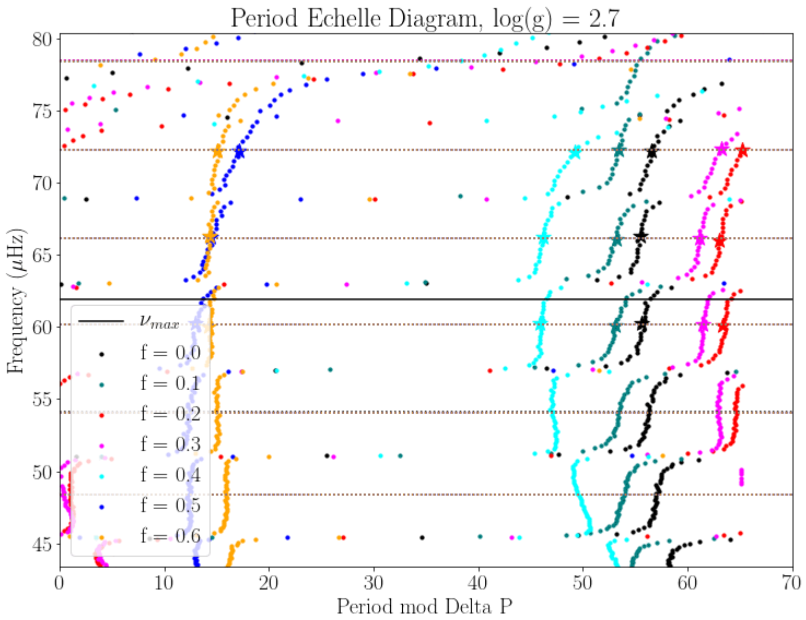
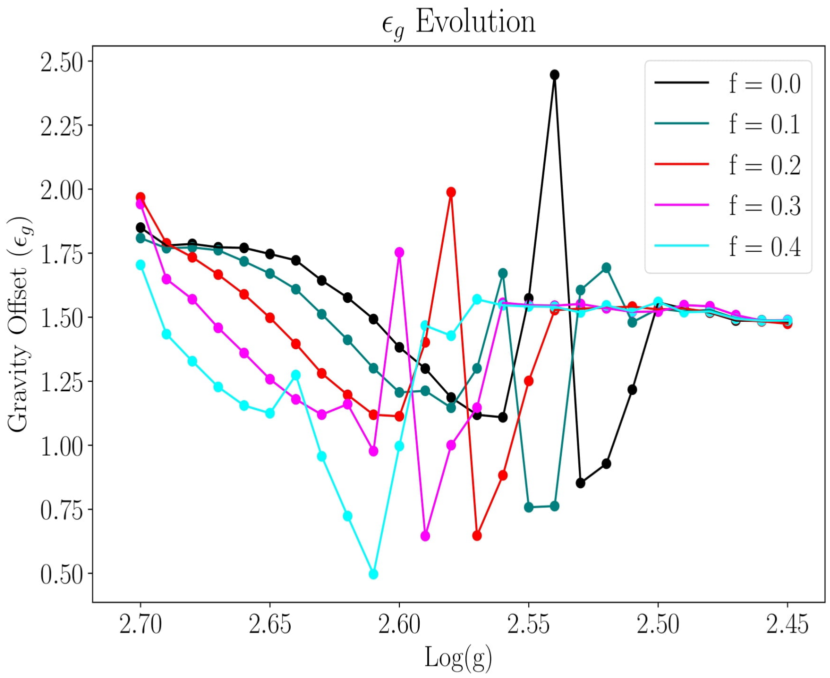


Figure 7 (left,) shows period echelle diagrams with mode period modulo period spacing on the x axis and frequency on the y axis for 1.4 solar mass red giant models with solar metallicity and different overshoot f values. In this work, the period spacing was found for each red giant model of different $\log g$ and overshoot f seperately using a least squares method to find the period spacing which best vertically alligns the section of the period echelle diagram. The animation shows the period echelle diagrams for the different red giant models as the models evolve up the red giant branch and past the luminosity bump. The echelle diagrams looks normal at high $\log g$ when all the models are below the luminosity bump. The diagram then becomes complicated with glitch signatures as each model moves through the luminosity bump, but returns to the normal state again after that. The highest overshoot model goes through the bump first and the one with no overshoot is the last to go through the bump.

ϵ_g, GRAVITY OFFSET EVOLUTION

Figure 8 (left,) shows the evolution of the ϵ_g (gravity offset) values for different overshoot 1.4 solar mass, solar metallicity red giant models at different evolutionary states along the red giant branch.

In this work, we consider that the dipole gravity modes follow the asymptotic comb-like pattern given by Mosser et. al. 2018. This way, since GYRE gives the g-mode radial order, n_g, we can find the ϵ_g (gravity offset) values for the different overshoot red giant models at different evolutionary states along the red giant branch. Plotting the evolution of ϵ_g gives the figure on the right where we can see that the values of ϵ_g for different overshoot red giant models start at about the same point at $\log g = 2.7$, before any of the models have gone throught the red giant branch luminoisty bump. As the red giant models approach the luminosity bump, ϵ_g decreases steadily then spikes up before returning to a steady state. The highest overshoot model goes through the bump first and the model with no overshoot goes through the bump last and we can see the ϵ_g value for the higher overshoot models fall first, then returns to a steady state first. Note that in actual observations, when the radial order of the g-mode is not known, the gravity offset parameter is only known to mod 1 but this ϵ_g behavior of falling near the luminosity bump then returning to a steady value could still be detected.



FINAL COMMENTS

In this poster we have shown that different amounts of step envelope overshoot, as modelled in the stellar evolution code MESA, has an important effect on the internal structure of red giant stars. Due to this internal structure dependence, the oscillation properties of the red giant also change which is apparent after calculating the oscillation modes of the stellar model using GYRE. Using the oscillation mode data, we show period spacing diagrams, period echelle diagrams, and an ϵ_g evolution plot which show that at a given value of $\log g$, red giant models evolved with different amounts of step envelope overshoot show different asteroseismic observables. These differences are related to the evolutionary state of the model before, during, or after the red giant luminosity bump and viewing where the red giant branch luminoisty bump is located (through ϵ_g observations or through searching for H-R diagram overdensities in red giant catalouges) can tell us about how much envelope overshooting should be incorporated in red giant models.

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