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Determining density and gravity of intermediate-mass stars with Convolutional Neural Networks.

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Abstract

In this work we used a convolutional neural network to determine the mean density and surface gravity of stars from 1.5 to 3 times more massive than the Sun. These physical quantities are key to better understand their structure as well as the physical processes occurring during their evolution. Relying on asteroseismic models we deployed and trained a CNN to detect patterns in the oscillation frequencies. The mean density and surface gravity estimates obtained accurately matched our set of benchmark observations. This method will allow us to analyse massively thousands of A-F stars observed by past, present and future space missions such as CoRoT, Kepler/K2, TESS, and the upcoming PLATO mission.

1 Introduction

In the last decades, the characterisation of the internal structure and evolution of intermediate-mass stars has significantly improved thanks to asteroseismology. More specifically, pattern recognition has been key to significantly constrain models representative of these stars, and thereby to better understand the physics taking place in their interiors. Such patterns have been found in the oscillation spectrum, which allow us to avoid identifying from hundreds to thousands of individual pulsation modes, which is, today, far from being achieved.

For intermediate-mass stars, frequency patterns are not easy to detect. Some theoretical works predicted its existence (e.g. [13, 10, 8]), as well as a scaling relation with the stellar mean density ([15], [14]). Thanks to the ultra-precise photometric lightcurves from the CoRoT ([1]) space mission, quasi-periodic patterns were clearly found in the oscillation spectra of δ Scuti stars (e.g. [6]) and the scaling relation with the mean density was empirically confirmed (see e.g. [5, 7]). This opened the door to multi-variable correlation analyses [9, 3], the study of other patterns, like the rotational splitting [12], to perform certain mode identification in young stars [4], or constrain the age of open clusters [11], to name a few examples.

Statistics- and/or Fourier-based techniques for pattern recognition often yield ambiguous results for intermediate-mass stars. This is because of the small number of frequencies exhibited by these objects on the one side, and the nature of the modes, on the other side, which pulsate around the fundamental radial mode, i.e. far from the asymptotic regime in which solar-like oscillations show clear patterns. Here we tried to overcome those problems using machine learning techniques.

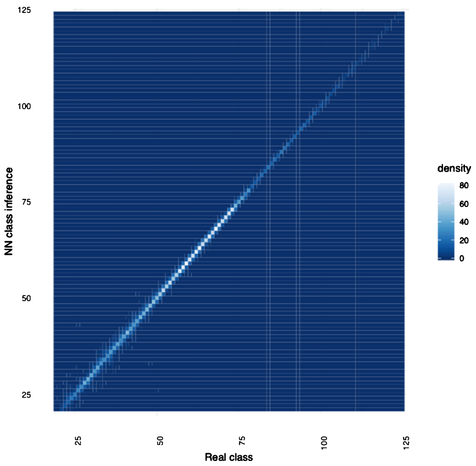

Figure 1: $\Delta\nu$ confusion matrix for the control sample (97% of accuracy for top-1 ranked probabilities).

2 The CNN

To avoid systematic errors due to human criteria, we trained a convolutional neural network (CNN) to identify the large separation, $\Delta\nu$. This pattern is built upon the frequency difference of modes such as

$$\Delta\nu = \nu_{n,\ell} - \nu_{n-1,\ell}. \tag{1}$$

Among intermediate-mass stars, we focused here on a specific type of pulsating stars, the δ Scuti stars, which mainly pulsate with pressure modes (p modes), for which $\Delta\nu$ have been determined with techniques such as the autocorrelation function (AC), the histogram of frequency differences (HDF) and the discrete Fourier transform (DFT).

We built a CNN whose NN are composed by staked layers with convolution, max pooling, and batch normalisation with dropout, all of them combined then into a dense layer with a *Softmax* activation function that normalises the output into a probability distribution that represents a categorical distribution. Each convolution layer of the CNN is fed with a three-dimensional vector composed by the AC, HDF and DFT.

To train the CNN we constructed a dataset composed by 500k asteroseismic models (equilibrium and oscillation frequencies) meant to be representative of δ Scuti stars. To do so, we computed the models varying the mass, metallicity and initial rotation velocity sufficiently dense to reduce uncertainty (and minimise possible selection bias) in the ranges known for these stars. Following [6, 15], for each model we computed the oscillation frequencies in a range covering radial orders from $n = 2$ to $n = 8$, from which the 30 highest-amplitude modes are kept. The amplitude was simulated assuming a visibility law uniquely based on the photometric cancellation effect (up to $\ell = 3$), where the mode visibility decrease for increasing ℓ in the form $A_\ell \sim \ell^{-1/2}$.

From the models dataset we randomly extracted 50k models to be used as our control sample. The CNN provides a probability over the partition class C of mesh p in the interval in which the large separation is expected for δ Scuti stars, i.e. $[0, 100]\,\mu$Hz. The internal accuracy of the machine is tested over 50k models previously extracted from the training dataset[1]. This was done by evaluating the top-k categorical accuracy rate, meaning the success when the target class is within the k predictions ranked by probability. For the control sample, an accuracy of 97% is reached for top-1 probabilities (see Fig. 1).

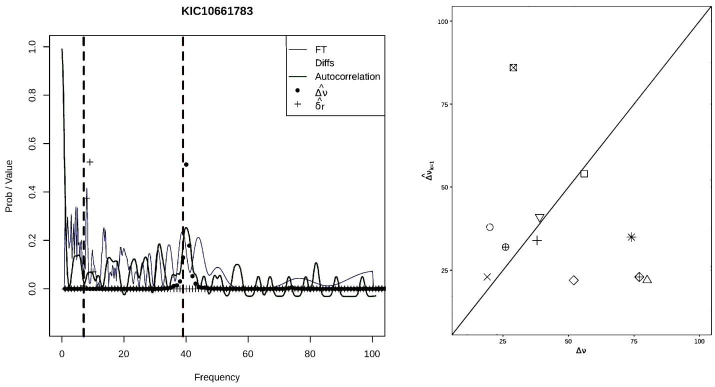

Figure 2: Left: CNN inferences for KIC 10661783 (black dots represent the probability density as a function of the frequency bucket in $\Delta\nu$), together with DFT, AC and HFD predictions. Vertical red line represents the independently observed value. Blue dashed line represents the rotational splitting frequency estimate (for illustrative purpose). Right: comparison between $\Delta\nu$ inferred by the CNN for the benchmark sample of δ Scuti stars in eclipsing binary systems, with those obtained with other methods ([7]). Each symbol represent a different star of the sample. Lines show the 1:1, 0.5:2, and 0.33:3 match relations.

[1]These models were randomly selected assuming uniform distribution along the models grid, which ensures there is no selection bias.

3 The results.

In order to validate the usefulness of the CNN, we applied it to real stars for which we previously had confident values of the large separation and mean density independently: our benchmark sample composed of 17 eclipsing binary systems with a δ Scuti star component (see details in [5, 7]). The confusion matrix shown for these observed stars is shown in Figure 2.

Note that for about 56% of the stars the CNN precisely found (within 1-5% of error) the correct value of the large separation (1:1 line) using top-1 inferences. This implies a RMSE of 28.09 muHz for the complete set of stars. Even more interesting is the fact the for the rest of objects, the results were not randomly distributed in the diagram, but around multiples and submultiples of the 1:1 relation. This implies that the CNN is properly finding $\Delta\nu$ in all the cases, but is not able to *decide* whether is the actual $\Delta\nu$ value or a multiple/submultiple. When these multiples were considered the RMSE of the match significantly decreased to 4.80 muHz.

In other words, the CNN is properly finding $\Delta\nu$ in all the cases, but is not able to *decide* whether is the actual $\Delta\nu$ value or a multiple/submultiple. This problem comes from the lack of information about the visibility of the modes, which, in the range of the observed frequencies, may be prone to display submultiple/multiple instead the actual $\Delta\nu$.

Once inferred robust values for the large separation, it is straightforward to get the mean density [5] and surface gravity [9] of the stars. In addition, the uncertainty coming from the angle of inclination of the stars can be neglected since they stars belong to eclipsing binary systems. For field stars, this might be an important indeed, since the visibility of the modes depend on the angle of inclination, and thereby affecting the number of modes that contribute to the large separation pattern.

4 Discussion and conclusions

The promising results obtained in this work need to be confirmed by the analysis of other stars. The next steps of this investigation are: (1) to apply the CNN to large samples of stars observed by space missions in order to determine their mean density and surface gravity; (2) compare our results with other determinations of $\Delta\nu$ in the literature; (3) include additional information to the analysis that may help us to automatically eliminate the degeneracy with multiples/submultiples of the large separation, like luminosities from Gaia mission, corrections for gravity darkening effects [2] or constraints from other seismic indices like $\nu_{\max}$ [3].

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