Regular sequences of pulsation overtones in young intermediate-mass stars

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Asteroseismology is a powerful tool for probing the internal structures of stars by using their natural pulsation frequencies. It relies on identifying sequences of pulsation modes that can be compared with theoretical models, which has been done with great success for many classes of pulsators including low-mass solar-type stars[1], red giants[2], high-mass stars[3] and white dwarfs[4]. However, a large group of pulsating stars of intermediate mass—the so-called δ Scuti stars—have rich pulsation spectra for which systematic mode identification has not been possible[5–7]. This arises because only a seemingly random subset of possible modes are excited, and because rapid rotation tends to spoil the regular patterns[8–10]. Here we report the detection of remarkably regular sequences of pulsation modes in 60 intermediate-mass main-sequence stars, opening up a new regime in which the power of asteroseismology can be applied. Some of these stars have space motions that indicate they are members of known associations of young stars, and their pulsation spectra confirm that these stars are indeed young.

The δ Scuti variables are stars of intermediate mass (1.5–2.5 $M_\odot$) that pulsate in low-order pressure modes[5–7]. Observations have shown that many δ Scuti stars have regular frequency spacings in their pulsation spectra (references given in the Supplementary Information) but a large sample with unambiguous mode identifications is lacking. Each pulsation mode in a non-rotating star is identified by two integers: the radial order, n, and the degree, l. We expect the strongest observable modes to be of low degree ($l = 0$, 1 and 2), since higher degrees have greatly reduced amplitudes due to cancellation in disk-integrated light. In the so-called asymptotic regime ($n \gg l$), modes with a given degree l are approximately equally spaced. Their frequency separation, $\Delta\nu$, is the inverse of the time taken for sound waves to travel through the star, which is approximately proportional to the square root of the mean stellar density.

The patterns are more complex in a rotating star, with the mode frequencies also depending on the azimuthal order, m. Each nonradial ($l \geq 1$) mode in the pulsation spectrum is split into $2l + 1$ components, where m ranges from $-l$ to l. The relative amplitudes of these components depend on the inclination of the rotation axis to the line of sight. For example, if a star is seen at low inclination (close to pole-on) then the axisymmetric ($m = 0$) mode in each multiplet will dominate, leading to a simpler pulsation spectrum. In very rapidly rotating stars, the oblateness alters the pulsation cavity and further complicates the pattern. However, for rotation rates less than ∼50% of Keplerian break-up, the radial modes ($l = 0$) and the axisymmetric dipolar modes ($l = 1$, $m = 0$) are still expected to follow a regular spacing[11].

To search for regular patterns we have used observations from the *Transiting Exoplanet Survey Satellite* (*TESS*)[12], which provides light curves for many thousands of δ Scuti stars at rapid cadence (120 s sampling). This gives an order-of-magnitude increase over previously available data. We used the first nine 27-day sectors of *TESS* data and focussed on identifying δ Scuti stars that pulsate at high frequencies (above about 30 d^{-1})[13,14]. We also examined stars not previously known to pulsate by calculating the Fourier spectra of *TESS* short-cadence light curves and measuring the skewness of the distribution of peak heights[15] above 30 d^{-1} as a way to flag likely detections. We then inspected the pulsation spectra for regularity using échelle diagrams (described below). In addition, we used data from the *Kepler* spacecraft, which observed about 300 δ Scuti stars at short cadence (60 s sampling) during its four-year nominal mission[15–17]. Stars observed in *Kepler*'s long-cadence mode (29.4-min sampling) were not considered because the Nyquist frequency of 24 d^{-1} makes it very difficult to identify patterns in high-frequency pulsators.

We discovered 60 stars with regular frequency spacings (Table S1 in the Supplementary Information), which define a new group of δ Scuti stars for which mode identification is possible. Figure 1 shows some of the pulsation spectra, which have remarkably regular patterns of peaks. The small amplitudes of the highest-frequency modes may indicate that turbulent pressure, rather than the standard opacity mechanism, is responsible for driving them[18]. Many stars in our sample (e.g., bottom half of Fig. 1) show a strong peak at very low frequency, which is likely to be the fundamental radial pressure mode ($n = 1$, $l = 0$). This identification is strengthened by the fact that these peaks agree with the established period–luminosity relation for the fundamental radial mode in δ Scuti stars[19]. In addition, several stars show a mode that is a factor $\sim 0.78^{-1}$ higher in frequency, consistent with being the first radial overtone ($n = 2$, $l = 0$)[20].

Figure 2 shows the pulsation spectra of several δ Scuti stars in échelle format, where the spectra have been divided into equal segments that are stacked vertically so that the peaks with the same degree fall along ridges. The regularity of the patterns is striking, similar to échelle diagrams of solar-like oscillators[1,2] but at much lower radial orders. Comparison with pulsation frequencies calculated from theoretical models (red symbols in the top row) enables an unambiguous identification of ridges corresponding to sequences of radial modes ($l = 0$) and dipolar modes ($l = 1$), as shown (more examples are shown in Figure S1 in the Supplementary Information). Sequences of $l = 2$ modes do not appear to be present in these stars.

We have placed our sample in the Hertzsprung–Russell (H–R) diagram using effective temperatures and luminosities derived from broadband colors and *Gaia* parallaxes (Fig. 3). The δ Scuti stars with regular frequency spacings tend to be located near the zero-age main-sequence, with masses between 1.5 and 1.8 $M_\odot$. The fact that these stars are relatively young helps to explain their regular pulsation spectra. In more evolved stars, the nonradial modes are expected to be "bumped" from their regular spacings when they undergo avoided crossings due to coupling with gravity (buoyancy) modes in the core[2]. For young stars, this mode bumping only occurs at the lowest frequencies, as can be seen from the models of $l = 1$ modes in Fig. 2 (top row; red triangles at low frequencies).

The large frequency separation, $\Delta\nu$, scales approximately as the square root of the mean stellar density[11,21–23]. However, the mode spacings of stars are not completely regular—even in the asymptotic regime—meaning that $\Delta\nu$ varies with frequency. We used theoretical models to calculate $\Delta\nu$ for δ Scuti stars in the same region that we measured it, namely from radial modes with orders in the range $n = 4$ to 8 (details in the Supplementary Information). We found that

$\Delta\nu$ in the models was typically 15% lower than would be obtained by scaling from the density of the Sun, which is consistent with previous results$^{10,21–23}$. Figure 3b compares the observed large separations of our sample with the densities derived from fitting to evolutionary tracks in the H–R diagram. The results confirm there is a correlation, with most stars lying between the values based on the standard scaling relation (solid red curve) and those from the model calculations (dashed red curve). Some of the spread is probably due to the range of metallicities of the sample, and some will be due to rotation. For example, if a star is oblate then the inclination of its rotation axis affects the observed position in the H–R diagram[24] (and hence the inferred radius, mass and density).

High-resolution spectroscopy can be used to measure the projected rotational velocity of a star, and most intermediate-mass stars have $v \sin i$ values[25] in the range 50–220 $\mathrm{km\,s^{-1}}$. Measurements of $v \sin i$ are available for about one third of our sample, with some being newly measured and others coming from the literature (see Table S1). More than half are below 70 $\mathrm{km\,s^{-1}}$, indicating that this group of δ Scuti stars include many with unusually low projected rotational velocities. This is consistent with the idea that regular frequency spacings are more common in stars seen at high inclinations (close to pole-on).

Some échelle diagrams show the modes along the $l = 1$ ridge to be split into close doublets, as expected for rotating stars (some examples are shown in Figure S1 of the Supplementary Information). Other échelle diagrams show more complicated patterns, with additional ridges at various angles that indicate sequences with slightly different spacings (Fig. 4). The rotation axes of these stars are presumably at lower inclinations than those with simpler pulsation spectra, which would lead us to expect one $l = 0$ ridge and three $l = 1$ ridges. Beyond the usual rotational splitting of $l = 1$ modes, slightly different frequency spacings are expected for each m in an oblate star. This is because modes with different m propagate along different paths through the star, giving different values for the sound-speed crossing time and hence for $\Delta\nu$. In stars with even more ridges, the additional sequences could correspond to modes with higher degrees ($l \geq 2$)—where coupling between modes with different degree may also be important—and perhaps also to chaotic modes[9,26].

The detection of regular pulsation frequency patterns in intermediate-mass stars will expand the reach of asteroseismology to new frontiers. One example is to determine the ages of young moving groups, clusters, and stellar streams, which can vary by up to a factor of two, depending on the method used[27]. Spectroscopic radial velocities and *Gaia* astrometry show that several stars in our sample are members of nearby young associations (references given in Table S1), including the Octans association (HD 44930, HD 29783, HD 42915), the Carina association (HD 89263), the Columba association (HD 37286 = HR 1915), the β Pictoris moving group (β Pic itself) and the recently-discovered Pisces–Eridanus stellar stream (HD 31901). For the latter, gyrochronology yielded an age similar to the Pleiades (~ 130 Myr)[28], in contrast to the initial ~ 1 Gyr age determination from suspected evolved moving group members[29]. Asteroseismic modelling of HD 31901 (Fig. 2c) clearly confirms a young age for this member of the Pisces–Eridanus group, and similar age determinations might be possible for other groups containing intermediate-mass stars.

Four stars in our sample (HD 28548, HD 34282, TYC 5945-497-1, V1790 Ori) exhibit excess emission in the WISE passbands, indicating a circumstellar dust disk. One of these (HD 34282) has a disk that has been resolved by ALMA, showing it to be inclined $60^\circ \pm 1^\circ$ to the line of sight[30]. The constraints on age and inclination of this host star provided by an analysis of its pulsations could illuminate the origin of stellar obliquity[31] and the pace of disk evolution[32].

Finally, we note that six stars in our sample have been classified spectroscopically as λ Bootis stars (references given in Table S1), meaning that their surface chemical abundances show evidence for accretion from circumstellar material. Given that λ Bootis stars are rare, making up only about 2% of A stars[33], the relatively high occurrence rate in our sample lends support to the hypothesis that λ Bootis stars tend to be young, with circumstellar material accreting from a proto-planetary disk.

Future *TESS* observations should reveal more examples of δ Scuti stars that have clear sequences of pulsation overtones. We also suggest that these patterns can be used as a guide for mode identification in the much larger number of δ Scuti stars whose pulsation spectra are not as regular.

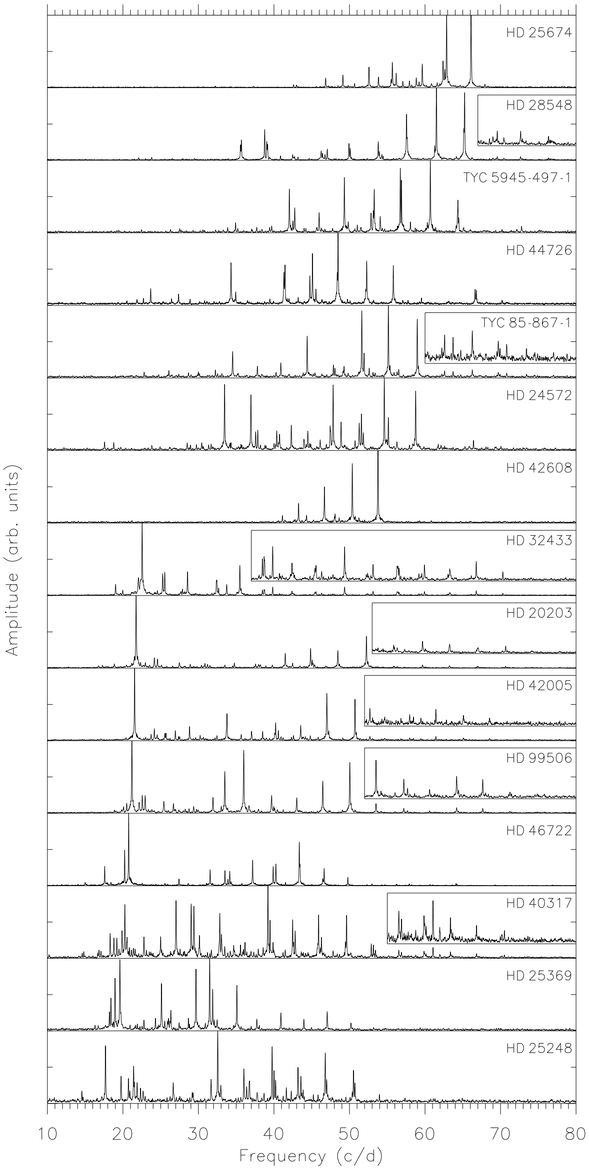

Figure 1 | **pulsation spectra of 15 high-frequency δ Scuti stars observed with *TESS*.** The insets for some stars expand the vertical axis by a factor of 4 to make weaker peaks more visible.

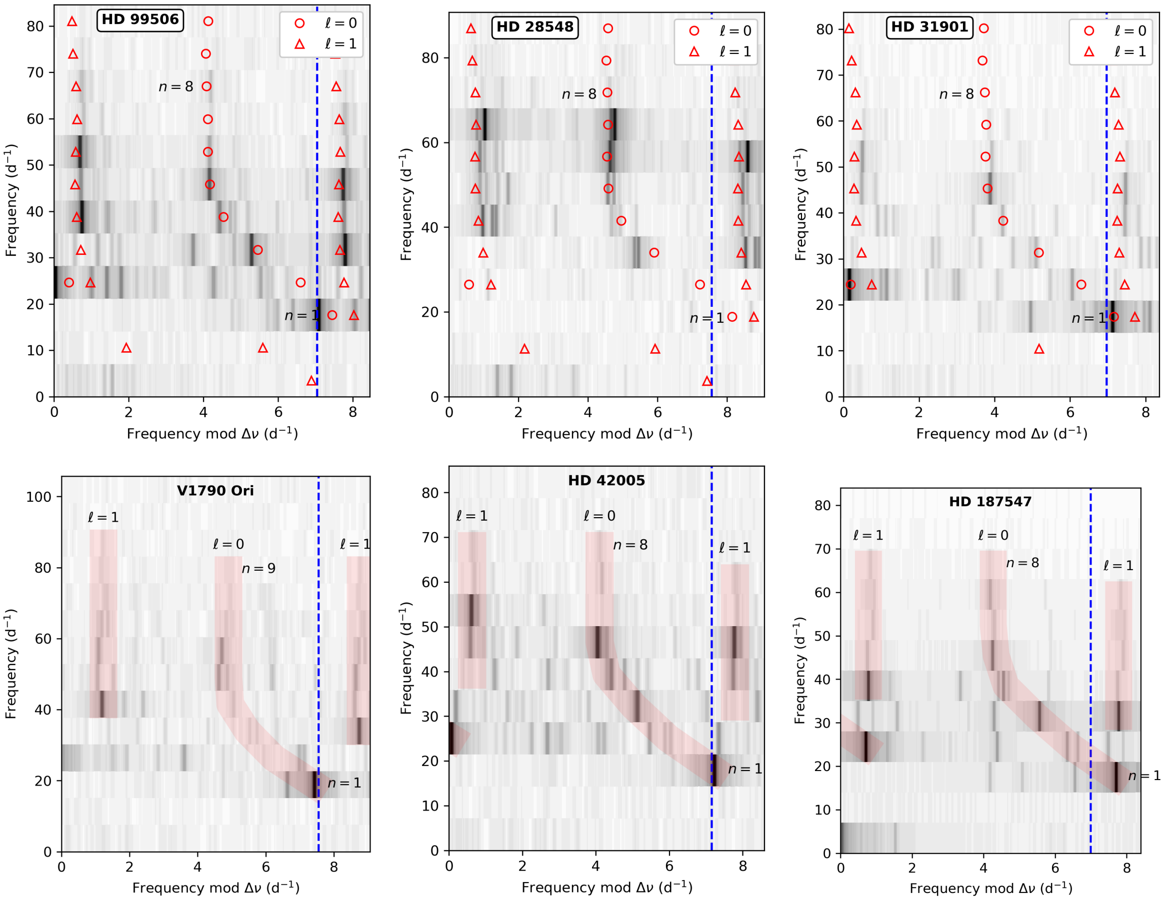

Figure 2 | **Mode identification in δ Scuti stars.** The pulsation spectra are shown in échelle format, with segments of equal length being stacked vertically. The vertical dashed line shows the value of $\Delta\nu$ used in each case, with a repeated overlap region added on the right for clarity. The greyscale shows the observed amplitude spectrum, which in most cases is calculated from one 27-day sector of data from the *TESS* spacecraft. The exception is HD 187547, for which observations were made over 960 d with the *Kepler* spacecraft[18]. Some smoothing was applied to the observed amplitude spectra before plotting. In the top row, the red symbols show mode frequencies calculated from theoretical models of non-rotating stars, chosen to match the observed modes reasonably well (see Supplementary Information for details of the models). These allow mode identifications in other stars, as shown in the bottom row, where the red stripes mark overtone sequences of $l = 0$ and $l = 1$ modes. The parameters of the models shown in the top row are as follows (while noting that other values of the parameters also give fits of similar quality): **a,** HD 99506: mass $1.68\,M_\odot$, metallicity [Fe/H] $= 0.0$, age 200 Myr, effective temperature 8065 K and radius $1.51\,R_\odot$. **b,** HD 28548: mass $1.59\,M_\odot$, metallicity [Fe/H] $= -0.2$, age 270 Myr, effective temperature 8202 K and radius $1.41\,R_\odot$. **c,** HD 31901: mass $1.77\,M_\odot$, metallicity [Fe/H] $= 0.08$, age 102 Myr, effective temperature 8083 K and radius $1.51\,R_\odot$.

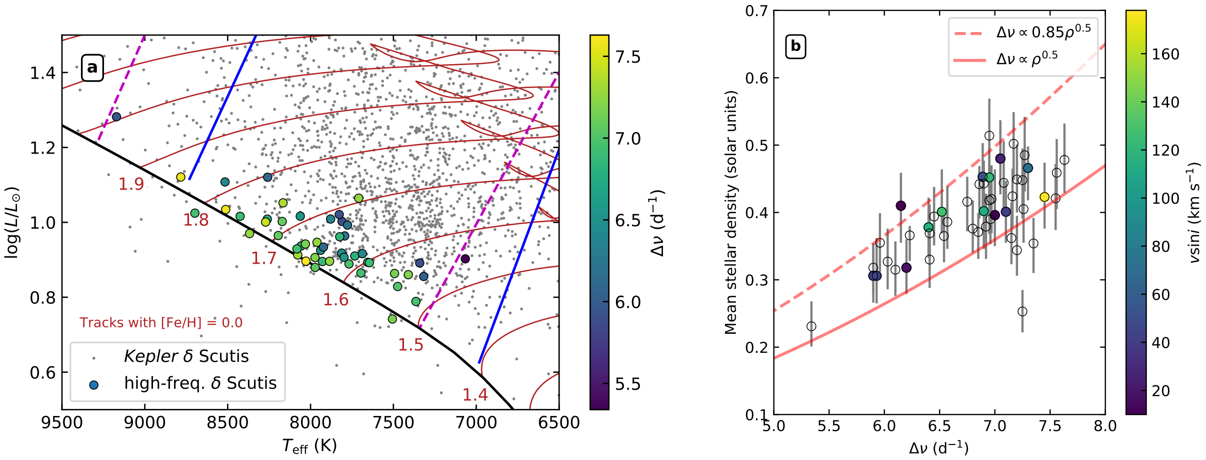

Figure 3 | **Physical properties of high-frequency δ Scuti stars. a,** Location in the H–R diagram, colour-coded by the measured large-frequency separation. The small points show δ Scuti stars observed by the *Kepler* Mission[15] and the red curves (labelled by mass in solar units) are evolutionary tracks calculated for solar metallicity (details in the Supplementary Information). The solid blue lines show the edges of the theoretical δ Scuti instability strip[34] and the dashed magenta lines show the observed instability strip based on *Kepler* stars[15]. **b,** Large-frequency separation versus mean stellar density as determined from observations (symbols), as predicted from the standard scaling relation (solid red line) and from stellar models (red dashed line). Stars with spectroscopic observations are colour-coded by the measured projected rotational velocity ($v \sin i$). Stars with close binary companions have been omitted from both panels (see Supplementary Material).

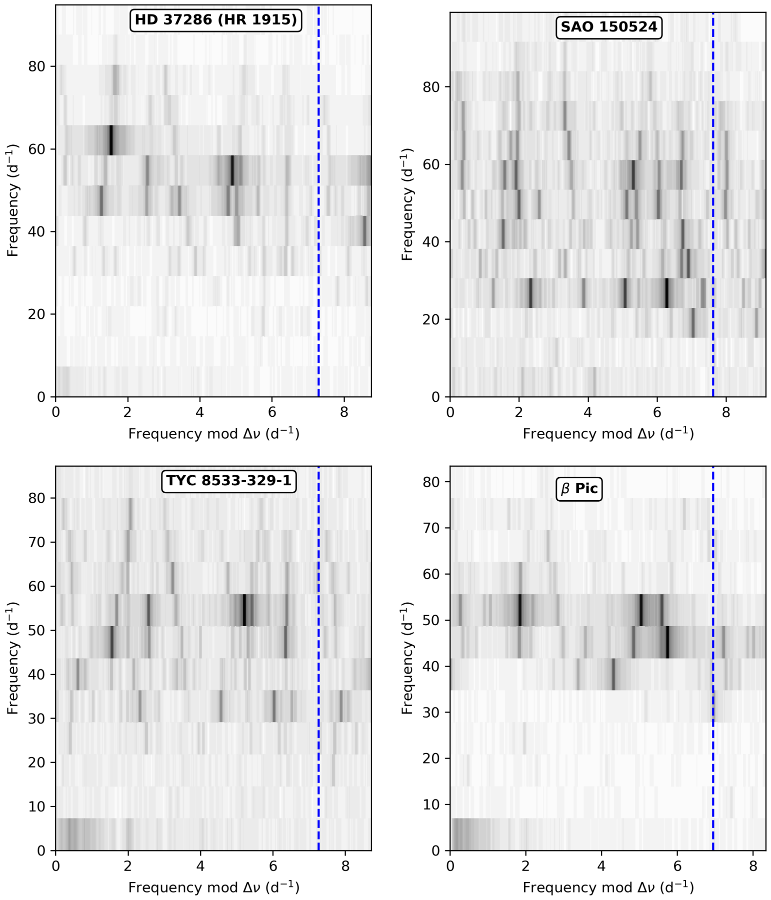

Figure 4 | **Examples of more complicated échelle diagrams of δ Scuti pulsations.** There are several sets of ridges at a range of angles, indicating slightly different spacings. An intermediate value of $\Delta\nu$ was chosen for these diagrams.

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Data Availability *TESS* and *Kepler* data are available from the MAST portal at https://archive.stsci.edu/access-mast-data. All other data are available from the corresponding author upon reasonable request.

Code Availability Codes are available from the corresponding author upon reasonable request.