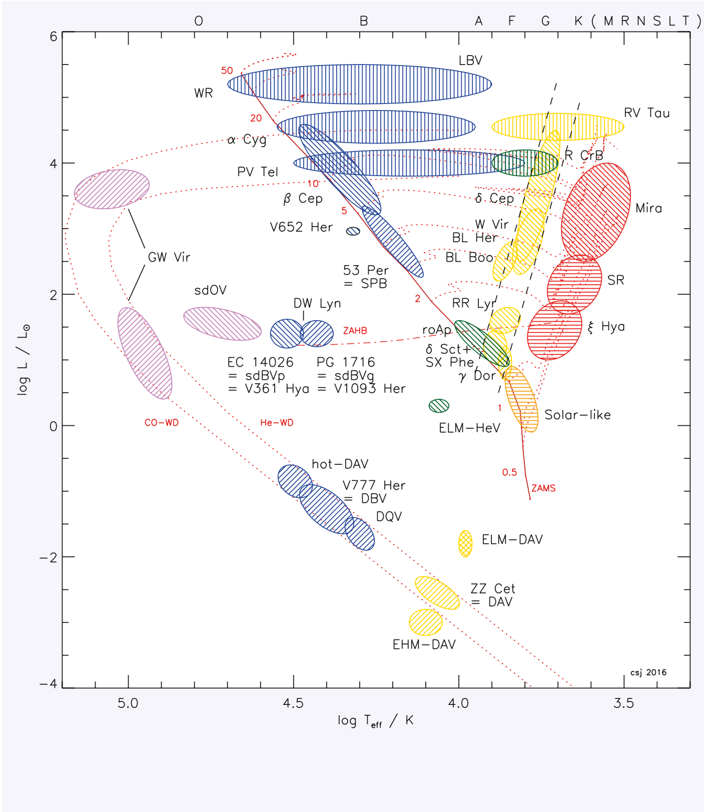
Starquakes spring stellar surprises

Don Kurtz, **Simon Jeffrey** and **Conny Aerts** describe discoveries in the new era of precision asteroseismology.



1 Luminosity–effective temperature (Hertzsprung–Russell) diagram showing locations of major pulsating variables coloured roughly by spectral type, the zero-age main sequence and horizontal branch, the Cepheid instability strip, and evolution tracks for model stars of various masses, indicated by small numbers ($M_\odot$). Shadings represent heat-engine p modes (\\\), g modes (///) and strange modes (|||) and acoustically driven stochastic modes (≡). Rough spectral types are shown on the top axis. (Based on figures by J Christensen-Dalsgaard and then by C S Jeffery. See Jeffery & Saio 2016)

We call it the "Tychonic Principle": a revolutionary improvement in observational precision inevitably leads to discovery. For Tycho Brahe, the improvement was in precision of astrometric position; for us, over the decades since we were students, it has been orders of magnitude improvement in the precision of radial velocity and photometric measurements for stars. Three decades ago, stellar radial velocities were measured to $1\,\mathrm{km\,s^{-1}}$ precision; now, in the best cases they are measured to 10s of $\mathrm{cm\,s^{-1}}$. Three decades ago, stellar light variability was measured to mmag precision (one part per thousand); now in the best cases it is measured to better than μmag precision (one part per million). Stellar astrophysics is being revolutionized by this new ultra-high precision.

The driving force has been the search for exoplanets. The two main techniques for exoplanet searches – radial velocity and transit measurements – require exquisite precision to detect either the tiny perturbative motion of a star being tugged about by a planet, or the slight drop in stellar brightness as a planet transits its star.

The improvement in radial velocity precision came about from brilliant engineering: ground-based spectrographs have been placed in temperature-stabilized vacuums on vibrationally stable platforms with the light from the telescope fibre-fed to the ultra-stable spectrographs. For exoplanet searches the spectroscopic measurements have to provide true radial velocities to feed into Newton's form of Kepler's third law to determine the planets' masses. This carries its own difficulties; at radial velocity precision better than $1\,\mathrm{m\,s^{-1}}$ even the definition of radial velocity is interestingly complex (Lindegren & Dravins 2003). But, for asteroseismology, the fundamental data are the pulsation frequencies, with only secondary information coming from the amplitudes of the radial velocity excursions.

The improvement in the measurement of stellar apparent brightnesses – the μmag revolution – came with space missions that took photometers above the Earth's atmosphere. The highest precision ground-based photometry of one particular star reached 14 μmag – 14 parts per million (Kurtz *et al.* 2005) – in pulsation amplitude, but typically 1 mmag has been considered good. With the advent of the French-led ESA CoRoT mission and the NASA Kepler mission, it has become possible to reach μmag precision for thousands of stars simultaneously.

"Stellar astrophysics is being revolutionized by this new ultra-high precision"

The planet hunters have built beautifully stable spectrographs and ultra-precise photometers in their search for exoplanets; we asteroseismologists have used those precision data for new stellar astrophysics.

Here, we are primarily showing results from the Kepler mission. For asteroseismology this mission provided multifold benefits over ground-based observations. The obvious one is the μmag precision; another is the observation of 200 000 stars simultaneously, instead of just one at a time with old photoelectric photometers, or dozens with CCDs on the ground. The third – and for some purposes the most important – benefit is the nearly continuous observations for four years of about 150 000 stars. For decades, groups of astronomers have organized campaigns to observe pulsating stars contemporaneously from observatories around the world to try to get continuous measurement of the changes in stellar brightness; one project for this is called the "Whole Earth Telescope", (WET; see Provencal *et al.* 2014). But where WET can observe a single target, or a few targets, for several weeks with duty cycles (fraction of time observing out of the full time possible) of, say, 50%, Kepler observations have better than 90% duty cycles for four years for 150 000 stars. For many asteroseismic targets this unprecedented length of observing time has been the key to discovery.

So the planet hunters drove the technology development. We asteroseismologists have put that technology to excellent use. In

Why do stars pulsate?

As a star pulsates, it swells and contracts, heats and cools. The observed pulsation can only continue if there is some part of the interior of the star where as much energy is fed into the oscillation as is damped throughout the rest of the bulk of the star. There are two main drivers of pulsation in single stars: the first is the kappa mechanism, where kappa is the Greek letter κ that represents opacity in studies of stellar structure.

Stars are radially layered. A layer that gains heat during the compression part of the pulsation cycle drives the pulsation; all other layers that lose heat on compression damp the pulsation. If the region gaining heat succeeds in driving the oscillation, the star functions as a heat engine, converting thermal energy into mechanical energy. For the Cepheid variables, RR Lyrae stars and many other types of pulsating stars this heat engine is the kappa mechanism, driven by the opacity of hydrogen and helium.

Simplistically, in the ionization layers for hydrogen and helium, opacity blocks radiation, so that the gas heats and the pressure increases, causing the star to swell past its equilibrium point. But the ionization of the gas reduces the opacity, radiation flows through, the gas cools and can no longer support the weight of the overlying layers, so the star contracts. On contraction the hydrogen or helium recombines and flux is once more absorbed, hence the condition for a heat engine is present: the layer gains heat on compression.

The other major driving mechanism that operates in the Sun, the solar-like oscillators, and in red giant stars, is stochastic driving. In this case, there is enough acoustic energy in the outer convection zone that the star resonates at some of its natural oscillation frequencies; a portion of the stochastic noise is transferred to energy of global oscillation. In a similar way, in a very noisy environment, musical string instruments can sound in resonance with the noise that has the right frequency.

For stars in close binary systems, tidal excitation is a third mechanism, one that occurs when multiples of the orbital frequency come into resonance with intrinsic eigenfrequencies of the binary components.

Stars are three-dimensional, so their natural oscillation modes have nodes in three orthogonal directions. These are described as the distance r from the centre, co-latitude θ and longitude ϕ. The nodes are concentric shells at constant r, cones of constant θ and planes of constant ϕ. For spherically symmetric stars the solutions to the pulsation equations, and hence the stellar pulsation modes, are described by spherical harmonics, functions widely used in electrodynamics and quantum mechanics. For stars there are three quantum numbers to specify these modes: n is the number of radial nodes and is called the overtone of the mode; l is the degree of the mode and specifies the number of surface nodes that are present; m is the azimuthal order of the mode, where $|m|$ specifies how many of the surface nodes are lines of longitude.

Radial modes

The simplest modes are the radial modes with $l=0$, and the simplest of those is the fundamental radial mode with $n=0$. In this mode the star swells and contracts, heats and cools, spherically symmetrically with the core as a node and the surface as a displacement antinode – the analogy is with an organ pipe in its fundamental mode, but in three dimensions. This is the usual mode of pulsation for Cepheid variables and for RR Lyrae stars, among others. The first overtone has $n=1$ with a radial node that is a concentric shell within the star. As we are thinking in terms of the radial displacement, that shell is a node that does not move; the motions above and below the node move in antiphase. The surface of the star is again an antinode, and so on for higher and higher overtones of the radial modes, with larger and larger values of n, the number of radial nodes.

Nonradial modes

The simplest nonradial mode is the axisymmetric dipole mode with $l=1, m=0$. For this mode the equator is a node; one hemisphere heats while the other cools, and vice versa, the northern hemisphere swells up while the southern hemisphere contracts. But there is no change in the circular cross-section of the star, so from the observer's point of view, the star seems to oscillate up and down in space. This can only occur for $n\geq 1$, so in the case of the $l=1$ dipole mode, there is at least one radial node within the star. While the outer shell is displaced upwards from the point of view of the observer, the inner shell is displaced downwards and the

turn, we have developed ways to provide fundamental information about the parent stars critical to the understanding of newly discovered exoplanets. The relationship of the two fields is mutually beneficial, a paragon of scientific cooperation.

Stellar pulsation

There are three main textbooks on stellar pulsation – and now asteroseismology: the *Theory of Stellar Pulsation* (Cox 1980), *Nonradial Oscillations of Stars* (Unno *et al.* 1989) and *Asteroseismology* (Aerts *et al.* 2010). Most stars pulsate in global resonant modes, sometimes also termed starquakes. At the μmag precision of CoRoT and Kepler data, there are some stars on the upper main sequence that seem to be constant, and we wonder why, since most stars in the same part of the Hertzsprung–Russell diagram do pulsate. On the lower main sequence we do not yet know if M dwarfs pulsate; if they do – and we expect that they should – the pulsation signal is currently lost in the background of variability arising from convection and stellar activity.

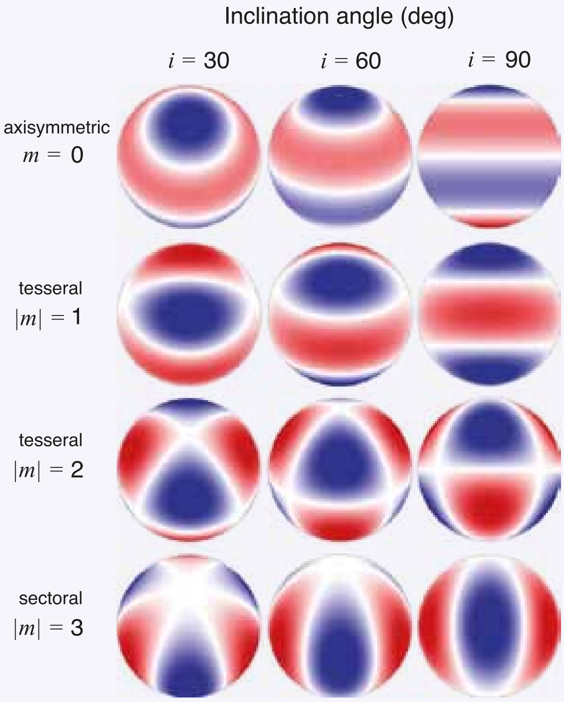
For most of the rest of the stars across the Hertzsprung–Russell diagram we see pulsation from which we can make asteroseismic inferences using the pulsation frequencies. Figure 1 shows a pulsation Hertzsprung–Russell diagram with a veritable zoo of pulsating stars – highlighting the rich coverage of asteroseismology data across almost all stages of stellar evolution for all masses of stars. Aerts *et al.* (2010) give details of the pulsating star classes.

How does asteroseismology work?

Stars naturally oscillate. The Sun, our nearest star, is the starting point for much of the modeling of stellar pulsation, but stellar mass, age and whether the star is in a binary system all affect the internal processes. Asteroseismologists combine theory and the new level of precision observations to unravel processes within stars.

Pulsation modes such as those in the Sun behave as acoustic waves. Reflections within the star set up standing waves with nodes – essentially stationary points – and antinodes – where the displacement is greatest. The structure within a roughly spherical body is complex and the overall pulsation is made up of a series of superimposed modes, described in the box "Why do stars pulsate?". The nonradial modes do not travel purely radially and are hence subject to a temperature gradient across the wave front, the deeper part of the wave becoming hotter and moving faster than the upper part. As a consequence, the wave is refracted back to the surface, where it is then reflected (figure 3). While the number of reflection points is not equal to the degree of the mode, higher l modes have more reflection points. This means that high degree modes penetrate only to a shallow depth, while lower degree modes penetrate more deeply. The frequency of the mode observed at the surface depends on the sound travel time along its ray path, hence on the integral of the sound speed within its "acoustic cavity". Clearly, if many modes that penetrate to all possible depths can be observed on the surface, then it is possible to "invert" the observations to make a map of the sound speed throughout the star, and from that

2 Snapshot of the radial component of the $l=3$ octupole modes. The columns show the modes from different viewing angles; the left column is for an inclination of the pulsation pole of 30°, the middle column is for 60° and the right column is for 90°. The white bands represent the positions of the surface nodes; red and blue represent sections of the star that are moving in (out) and/or heating (cooling) at any given time, then vice versa. The top row shows the axisymmetric octupole mode ($l=3$, $m=0$) where the nodes lie at latitudes ±51° and 0°. The second row shows the tesseral ($0<|m|<l$) $l=3$, $m=\pm1$ mode with two nodes that are lines of latitude and one that is a line of longitude. The third row is the tesseral $l=3$, $m=\pm2$ mode, and the bottom row shows the sectoral mode ($l=|m|$) with $l=3$, $m=\pm3$. Importantly, rotation distinguishes the sign of m and lifts the degeneracy of the frequencies, giving probes of interior rotation in stars.



centre of mass stays fixed. Dipole modes are the dominant modes observed in many other kinds of pulsating stars.

Modes with two surface nodes ($l=2$) are known as quadrupole modes. For the $l=2$, $m=0$ mode the nodes lie at latitudes ±35.26°, so the poles of an $l=2$, $m=0$ mode swell up while the equator contracts, and vice versa. Figure 2 shows a set of octupole modes with $l=3$, giving a mental picture of what the modes look like on the stellar surface, noting that this is generally inclined with respect to the line-of-sight.

The effect of rotation

For modes with $m \neq 0$ there is a phase factor in the time dependence, which implies that the $m \neq 0$ modes are travelling waves; modes with positive m are travelling in the direction of rotation (prograde), and modes with negative m are travelling against the direction of rotation (retrograde).

In the absence of rotation, the frequencies of all $2l+1$ members of a multiplet (such as the octupole septuplet $l=3$, $m=-3, -2, -1, 0, +1, +2, +3$) are the same. Rotation lifts this frequency degeneracy, due to the Coriolis and centrifugal forces. The prograde modes travelling in the direction of rotation have frequencies slightly lower than the $m=0$ axisymmetric mode, and the retrograde modes going against the rotation have slightly higher frequencies, in the co-rotating reference frame of the star, thus the degeneracy of the frequencies of the multiplet is lifted. We end up with a multiplet with $2l+1$ components all separated by the rotational splitting, which to first order is based on a correction depending on the interior structure of the star and on the kind of mode.

The significance for asteroseismology is that where such rotationally split multiplets are observed, the l and m for the modes may be identified and the splitting used to measure the rotation rate inside the star. Where multiplets of modes of different degree or different overtone are observed, it is possible to gain knowledge of the interior rotation profile of the star – something that is not knowable by any other means. This has – in just the last few years – revolutionized our view of angular momentum, and its transport, in the otherwise invisible interior of stars.

deduce its temperature profile, with a few reasonable assumptions about its chemical composition. In the Sun, the sound speed is known to a few parts per thousand over 90% of its radius. To do the same for other stars is an ultimate goal of asteroseismology.

Thus asteroseismology lets us literally see (with sound, like echography) the insides of stars because different modes penetrate to different depths in the star. But stellar oscillations are not just made up of acoustic waves. We can also see inside the stars with gravity waves. In fact, for some stars, and for parts of others, we can only see with these types of modes.

p modes and g modes

There are two main sets of solutions to the equation of motion for a pulsating star, and these lead to two types of pulsation modes: p modes and g modes. For the p (pressure) modes, the pressure force is the primary restoring force for a star perturbed from equilibrium. These p modes are acoustic waves and have gas motions that are primarily vertical. For the g (gravity) modes, buoyancy is the dominant restoring force; the gas motions are primarily horizontal.

There are three other important properties of p modes and g modes. First, as the number of radial nodes increases, the frequencies of the p modes increase, but those of the g modes decrease. Secondly, the p modes are most sensitive to conditions in the outer part of the star, whereas g modes are most sensitive to conditions in the deep interior of the star (except in white dwarfs where the g modes are sensitive mainly to conditions in the stellar envelope) as shown in figure 3. Thirdly, in the limit of high frequencies, the p modes with $n >> l$ are approximately equally spaced in frequency, while in the limit of low frequencies, the g modes with $n >> l$ are approximately equally spaced in period.

These so-called asymptotic relations are very important in many pulsating stars. From Tassoul (1980, 1990) they show that for the p modes, the frequencies are approximately given by

$$\nu_{nl} = \Delta\nu\,(n + l/2 + \tilde{\alpha}) + \varepsilon_{nl} \qquad (1)$$

where $\tilde{\alpha}$ is a constant of order unity, and ε_{nl} is a small correction. $\Delta\nu$ is known as the large separation and is the inverse of the sound travel time for a sound wave from the surface of the star to the core and back again, given by

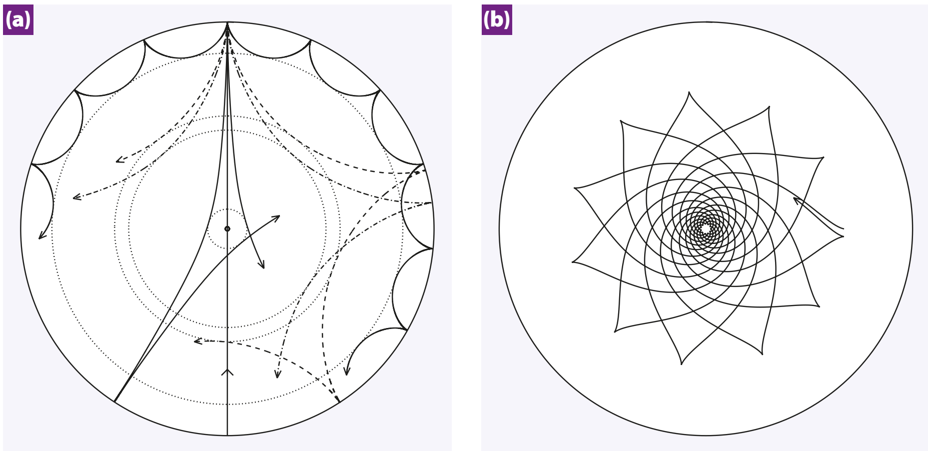
$$\Delta\nu = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1} \propto \sqrt{\bar{\rho}} \propto \sqrt{M/R^3} \qquad (2)$$

where $c(r)$ is the sound speed. The large separation is sensitive to the mass and radius of the star.

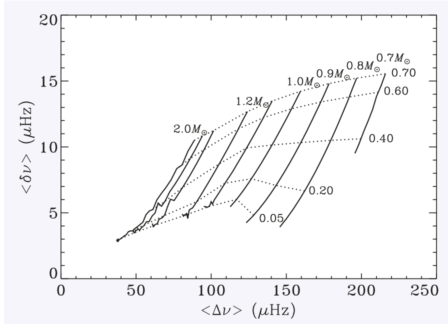
For the solar-like oscillators, Kjeldsen & Bedding (1995) first suggested the empirical scaling relation:

$$\nu_{max} \propto \frac{g}{\sqrt{T_{eff}}} \propto \frac{M}{R^2\sqrt{T_{eff}}} \qquad (3)$$

where ν_{max} is a measure of the frequency of maximum pulsation amplitude of the p mode pulsations. Not surprisingly, as stars evolve ν_{max} decreases for p modes, since the sound waves have further to travel in a star of larger radius, and the sound speed decreases with lower internal temperature through much of the star as it ages. Chaplin & Miglio (2013) present power spectra clearly showing this.



3 Propagation of rays of sound or gravity waves in a cross-section of a Sun-like star. The acoustic ray paths (a) are bent by the increase in sound speed with depth until they reach the inner turning point (dotted circles) where they undergo total internal refraction. At the surface the acoustic waves are reflected by the rapid decrease in density. The g mode ray path (b) corresponds to a mode trapped in the interior. In this example, it does not propagate in the convective outer part. As we shall see, g modes are observed at the surface of other types of pulsators. This figure illustrates that the g modes are sensitive to the conditions in the very core of the star, an important property. (From Cunha *et al.* 2007)



4 This is an asteroseismic "JCD" (for Joergen Christensen-Dalsgaard, who originated it) Hertzsprung–Russell-like diagram. It plots the large and small asteroseismic separations on the abscissa and ordinate, respectively, with modeled lines of constant mass (nearly vertical solid lines) and lines of constant hydrogen core mass (isopleths; nearly horizontal dotted lines). It is easy to see in this format that the large separation decreases with increasing mass – this is because it is proportional to the square root of the mean density of the star – and the small separation decreases with the evolution of the star – this is because of the decreasing hydrogen mass fraction in the core. (From figure 1.11 Aerts *et al.* 2010)

Thus with a spectroscopic measure of T_{eff} and the two constraints in equations 2 and 3, M and R can be determined independently. The term ε_{nl} gives rise to the small separation $\delta\nu$; because this is sensitive to the sound speed gradient caused by the core condensation, it leads to the age of the star. Thus from asteroseismology we can determine three important fundamental parameters – mass, radius and age – for single field stars, with a wealth of applications.

Applications of asteroseismology

Only a little over 20 years ago, "solar-like" oscillations in stars – i.e. stochastically excited p modes in the asymptotic frequency range where $n >> l$ – were unknown. Only the Sun showed the long series of asymptotic p mode frequencies that allowed strong inference of the interior structure and mass motions to be made. Now, with the CoRoT and Kepler data, many hundreds of lower main-sequence stars from spectral type late F, through G and K stars, and thousands of subgiant and red giant stars show solar-like stochastically excited pulsations, with many modes in the asymptotic p mode frequency range (e.g. Chaplin & Miglio 2013).

With spectroscopically determined effective temperatures, the radii and masses of these stars can be determined in the best cases to accuracies of a few percent, although at present there may be systematic effects of up to 10–20%. With time, the systematic errors will be understood and eliminated. The best cases have been well calibrated using eclipsing binary stars, for which model-independent radii and masses can be extracted. Then, because there is a correlation of surface gravity with stellar age – at least on the main-sequence – asteroseismology also delivers stellar age. Figure 4 shows a plot of the large and small separations of equation 1 with model-dependent lines of stellar mass and core hydrogen mass fraction from the zero-age main-sequence to the terminal-age main-sequence. In addition, amazingly, asteroseismology of red giant stars can even distinguish stars that are in the helium core-burning stage from those in the younger hydrogen shell-burning stage (Bedding *et al.* 2011). This comes from the sensitivity of the trapping of modes in the red giant cores to the size and existence of convective cores. Hence asteroseismology can now deliver mass, radius and age for individual field stars.

These new measures of stellar mass, radius and age put new constraints on stellar evolution theory. The mass and radius measurements are mostly model-independent, and will become completely so with better calibrations. The ages are model-dependent, as are traditional isochrone ages, but the method is new.

Exoplanets and asteroseismology

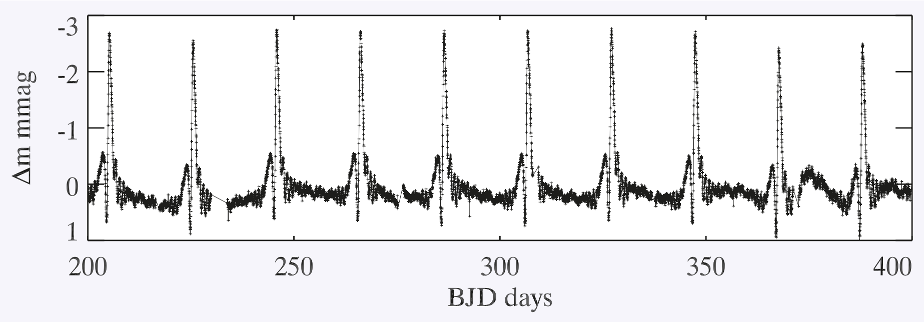
Knowledge of the age of the parent star is very important in the study of exoplanets, the prime goal of which is to find Earth-like planets in the habitable zone. Of course, we are ultimately searching for life elsewhere in the universe. When bio-signatures are found in spectra of exoplanet atmospheres, the age of the planet and star helps to be understand how quickly (or not) life can evolve when conditions are suitable.

Knowledge of planetary mass and radius is indispensable for exoplanet studies. To determine the mass of an exoplanet from radial velocities using Newton's form of Kepler's third law, the mass of the star must be known. An exoplanet transit signal in photometry depends on the cross-sectional area of the planet compared to the cross-sectional area of the star, hence to know the radius of the exoplanet it is necessary to know the radius of the star. Asteroseismology provides these two quantities with a precision much higher than any other available method so far, which is why exoplanetary studies are best combined with asteroseismic studies of their host star.

Galactic archaeology

Just as we like to call our field of study "asteroseismology", instead of the study of stellar pulsations, what used to be known as "galactic chemical evolution" now has a much more exciting name: galactic archaeology. Although an early form of the term was used in the study of white dwarf stars to galactic formation and structure (Wood 1990), it has come into use for galactic chemical evolution in the past decade.

Simplistically, we expect that the first stars in what was to become the Milky Way were made solely of hydrogen and helium from the Big Bang. Interstellar material became enriched in heavier elements by supernovae and mass loss from red giant stars. But how do the current chemical abundances of the metals – defined as elements heavier than helium – depend on position in the galaxy? Spectroscopy can provide the abundances for stars, Gaia will soon produce accurate distances across much of the visible Milky Way; asteroseismology is now providing masses and ages for the stars. This tripod thus holds the potential for remarkable new insight into the chemical evolution of our galaxy in the next few years. That knowledge will inform



5 A section of the four-year (Kepler) data set for the heartbeat star KIC 3749404. The ordinate axis is BJD minus 2 455 000.0. This star is in a 20.31-day orbit with an eccentricity of 0.66. The periastron brightenings (the "heartbeats") are easily visible in this μmag-precision Kepler data, even though the peaks are only just over 2 mmag in height. The changes in brightness at periastron are a consequence of tidal deformation. Even the dip in this light curve is a consequence of the changing cross-section of the stars, not an eclipse. For a look at the beautiful variety of the shapes of the periastron heartbeats, which depend on eccentricity and orientation of the orbit to the line of sight, see Thompson *et al.* (2012) for many more cases, and Kumar *et al.* (1995) for a full theoretical description of possible light curve shapes.

bigger questions of the chemical evolution of the universe, the study of exoplanets and the search for life. Thus asteroseismology connects exoplanetary and galactic studies.

Angular momentum transport

Theories of stellar structure and evolution are triumphs of astrophysics over the past century. With the expanding observational view of stellar interiors afforded by asteroseismology, stellar physics, once purely theoretical, is now also observational. The rotation of stars from their cores to their surfaces, and angular momentum transport mechanisms, both internal and external, significantly affect their structure and evolution. We do not know the interior rotation profiles of stars at birth, but we expect that, after core hydrogen burning has ceased, conservation of angular momentum leads to a spin-up of the contracting helium core and a spin-down of the expanding envelope, leading to radially differential rotation. We also expect that internal energy transport mechanisms lead to latitudinal differential rotation.

These expectations can be tested with observations in visible light for surface differential rotation and by asteroseismology for radial differential rotation with depth. The best-studied case is, of course, the Sun. Surface differential rotation has been known for centuries from sunspot studies; interior rotation has been mapped about halfway down to the core by helioseismology (e.g. Schou *et al.* 1998, Thompson *et al.* 2003, Eff-Darwich *et al.* 2008). The data have shown that the Sun's internal rotation is not as expected; theory suggested rotation on cylinders, but there is unexpected shear in the convection zone while the inner Sun rotates rigidly, implying surprisingly strong angular momentum transport.

In the past few years, we have begun to observe the internal radial rotation profiles of stars with asteroseismology; the results are full of surprises, reviewed by Aerts (2015). Interior rotation properties have been deduced for hydrogen-burning main-sequence phases (Kurtz *et al.* 2014, Saio *et al.* 2015, Triana *et al.* 2015, Murphy *et al.* 2016, Schmid & Aerts 2016) subgiant and red giant phases (Beck *et al.* 2012, Mosser 2012, Deheuvels *et al.* 2012, Deheuvels *et al.* 2014, Deheuvels *et al.* 2015), and the late evolutionary stages of subdwarf B stars (Van Grootel *et al.* 2009) and white dwarfs (Charpinet *et al.* 2009).

Theoretical expectations are often not met: red giant cores rotate much more slowly compared to their surfaces than expected, the main-sequence stars observed so far are nearly rigid rotators with some having slightly, but significantly, faster envelope than core rotation, and white dwarfs have shed their interior angular momentum. The disparity, for example, between theoretical and observed rotation profiles of red giants is two orders of magnitude (Eggenberger *et al.* 2012, Cantiello *et al.* 2014; see Aerts 2015 for an extensive discussion of this matter). All of this indicates that some physics is missing in models: stronger core-to-envelope coupling seems to occur in evolved phases while efficient angular momentum transport must take place in the interiors of some young stars. Remarkably, yet again, asteroseismology provides the answers in terms of angular momentum transport by internal gravity waves, at least for the core hydrogen burning stars (Rogers 2015).

Heartbeat stars

In the box "Asteroseismology, not astroseismology" on page 4.42 we argue that, etymologically, "asteroseismology" is the correct, desirable, but seven-syllable name of our field. The new sub-field investigating interactions between binary partners could be called palirroiasasteroseismology; we call it "tidal asteroseismology".

Thanks to the photometry revolution, we now observe highly eccentric binary stars that generate pulsations by tidal interaction when the two stars come close to collision at periastron passage. The light curve of one of these stars, KIC 3749404 (Hambleton *et al.* 2016, in press), in figure 5 shows why these new variable stars have been named "heartbeat stars", by analogy with an electrocardiogram. Thompson *et al.* (2012) gives an introduction to these new stars; Gaulme *et al.* (2013) and Beck *et al.* (2014) describe spectroscopic and asteroseismic modeling.

Binary stars are of fundamental importance in astronomy because they give essentially model-independent measures of stellar mass and radius. Eccentric binary stars are important because they indicate how tidal interaction transfers angular momentum in both orbital and stellar evolution – knowledge that also informs the important topic of formation and evolution of exoplanetary systems. Now with the discovery of tidally excited g modes in heartbeat stars, we have new probes of the stellar core, both from the pulsations and from the apsidal motion of these binary stars. This is an exciting new field of research that was entirely theoretical until just a few years ago. For a review and status report, see Hambleton (2016, in press).

Tidal excitation of g modes occurs when a harmonic of the orbital frequency is close in frequency to a stellar eigenfrequency. The excitation can be so finely tuned that frequencies near high orbital harmonics can be selectively excited. In a now-classic example – described all of five years ago – Kepler Object of Interest number 54 (KIC 8112039), a 41.8-day orbital period, eccentricity of 0.83, nearly face-on binary system, the highest amplitude g mode pulsations resonate with the 90th and 91st orbital frequency harmonics (Welsh *et al.* 2011). There are more extreme cases – both in eccentricity, and in the high harmonic mode frequencies that are resonant – currently under investigation.

A born-again rocket star

Stellar evolution is usually understood in terms of the lifetime changes in single stars. We calculate and plot evolutionary tracks for single stars on Hertzsprung–Russell diagrams and think about the internal structural changes that the star undergoes in terms of those tracks. Yet binary stars are ubiquitous, and their interaction often have profound effects on their evolution. Type Ia supernovae – the standard candles of cosmology – are binary stars containing at least one white dwarf. One of the most massive stars known, η Carinae, with a mass of perhaps more than 200 $M_\odot$, is a binary star, and the companion will be important to the impending type II supernova it will become (or maybe already has, since it is

Asteroseismology, not astroseismology

Use of the term asteroseismology arose in the 1980s. In a recent web search, we found nearly 9000 instances of "astroseismology", as opposed to 118 000 for the correct term "asteroseismology". Why was one chosen over the other? Seismology (notably geoseismology) long predates asteroseismology. The etymology is Greek: seismology from *seismos* (tremor) and *logos* (discourse). In the construction of the neologism asteroseismology, the Greek form *aster* (star) was preferred to the less common *astron*. The word is spelled as it is – asteroseismology – for the purity of the etymology, which Gough discusses in extensive, erudite and amusing fashion (Gough 1996).

Before asteroseismology, we studied stellar pulsation and the more general field of variable stars. Why change? Most community members will answer that it arises from the much deeper understanding of stellar astrophysics that has become possible in recent decades, i.e. we moved from the detection of a few pulsation modes to astrophysical interpretation of stellar interiors. But astrophysical inference from stellar pulsation is much older than this: see, for example, the classic text *The Internal Constitution of the Stars* (Eddington 1926). Others might argue that the new name catches attention and sounds impressive, hence gives the field and its researchers prestige and authority. Does science work like that? Yes. It is human nature to give yourselves impressive names and titles, and scientists are human. Thus "asteroseismology" it is; misspell this at your peril.

8000 light years away). Think of cataclysmic variable stars, of Roche Lobe overflow and mass transfer, of stellar-mass black holes and X-ray binary stars. Binary stars and binary star evolution matter.

Take V652 Her, the born-again rocket star, as an example. A long, long time ago, in a part of our galaxy that may have been far away then, the more massive component of a binary star grew towards being a red giant, but before it could start helium fusion, its companion's gravity stripped away the hydrogen atmosphere leaving behind a helium white dwarf star. Then the originally lower mass companion began its evolutionary journey to red gianthood, but the helium white dwarf companion was able to reciprocate its mate's previous gravitational assist, and the system became a twin helium white dwarf binary star. Time passed, angular momentum was lost and the two stars eventually merged to become a new, more massive, single white dwarf. But this star was odd: it formed from stars made primarily of helium with very little hydrogen. The merger provided sufficient energy to re-ignite the triple-alpha process and the star was "born again" as a helium shell-burning yellow giant with a difference. For V652 Her, the helium-burning shell surrounds a helium core; the shell is slowly igniting the interior helium and migrating inwards (Saio & Jeffery 2000).

But V652 Her pulsates with a period of 2.6 hr. In the first 15 minutes of the cycle the atmosphere accelerates from –50 to +50 km s^{-1} with a pulse running through the atmosphere at up to 239 km s^{-1}, which is Mach 10 in that environment. The atmosphere then coasts almost ballistically for the rest of the cycle (Jeffery *et al.* 2015). This is a rocket star: its pulsation accelerates like a rocket, then it coasts, again like a rocket.

While this behaviour could be called "yperichitikosasteroseismology", it is just plain old supersonic asteroseismology. V652 Her is in an unusual evolutionary state that can inform us about binary star evolution, about binary mergers of white dwarf stars and hence about type Ia supernovae, and the most extreme pulsational physics we have yet seen.

Conclusions

Asteroseismology is already full of surprises, even though its focus so far has primarily been on low- to intermediate-mass stars. Indeed, there are various types of stars that haven't been studied yet with long-duration space photometry. The Kepler nominal field-of-view hardly contained stars with birth masses above $5\,M_\odot$, and none in an evolved stage. CoRoT observed several young massive stars for five months – not long enough to derive interior rotation information, but enough to have a first look at the near-core regions with g modes. This revealed more chemical mixing and longer lifetimes before supernova explosion than anticipated (Degroote *et al.* 2010, Neiner *et al.* 2012). Kepler did not include supergiants because they are a nuisance for exoplanet hunting; starbirth did not fall into the field-of-view either. Seismic data from these extreme phases of stellar evolution will undoubtedly reveal many more surprises, given that current models for such objects are subject to even larger uncertainties than those for low-mass stars. The methodology is in place, all we need is appropriate seismic data. On the other end of the mass range, we haven't been able to monitor stars with masses below ~$0.7\,M_\odot$, while these are most suitable for exoplanet and archaeology studies. With both the NASA TESS (http://tess.gsfc.nasa.gov, launch 2018) and ESA PLATO (http://sci.esa.int/plato, launch 2024) missions on the horizon, we are heading for a bright future in asteroseismology. ●

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