PERSPECTIVES: ASTRONOMY

# The Birth of Asteroseismology

Douglas Gough

In the wake of the success enjoyed by helioseismologists in inferring the interior structure of the sun, astronomers have recently begun to search for seismic oscillations in other stars. A variety of techniques have been tried, but until recently none was successful. In 1999, however, Martic *et al.* (*1*) found good evidence for oscillations in the bright star Procyon. Perhaps the most convincing evidence to date comes from recent observations of β Hydri, the brightest star in the southern constellation Hydrus (the Lesser or Little Water Snake) (see the figure).

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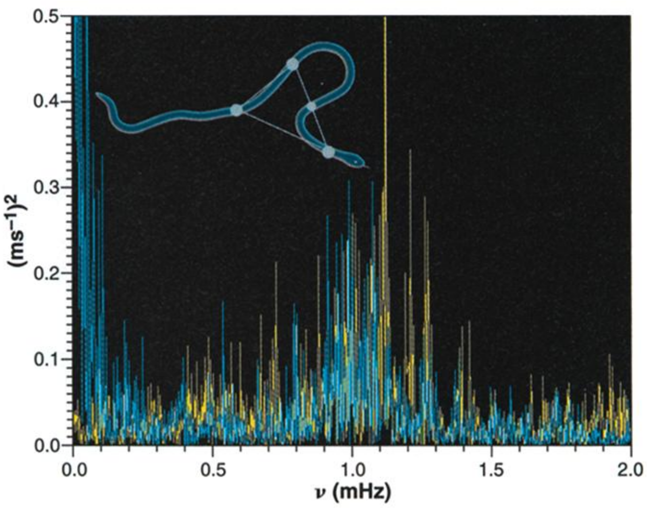
β Hydri is particularly interesting because it is similar to the sun yet is believed to be substantially older; it thus augurs what our sun will be like once it has consumed all its hydrogen fuel at the center and begins its passage toward old age. Bedding *et al.* have carried out seismic observations of this star using the 3.9-m Anglo-Australian Telescope in Siding Springs, New South Wales. The results, which will be published shortly in *Astrophysical Journal Letters* (*2*), herald the birth of asteroseismology.

The sun is typical of sunlike stars. It can be divided into three principal regions: a relatively quiescent region that occupies the inner 70% of the solar radius, a turbulent convection zone that extends to the visible surface, and a cool diffuse atmosphere supporting a hot surrounding corona that, except at times of eclipse, is invisible to the eye. Heat generated from thermonuclear reactions in the dense (150 times the density of water), hot (15 million K) core of the inner region is transported to the surface, from where it is radiated into space. The outer layers are diffuse (1 millionth the density of water) and relatively cool (5800 K); the density declines very rapidly near the surface, causing seismic waves to be reflected. The waves are thus trapped in the sun, but the visible layers near the surface respond to the oscillations, enabling them to be observed.

Oscillatory stellar variability was first recognized by Fabricius in 1596 in the star Mira Ceti (*3*). Since then, tens of thousands of large-amplitude pulsating stars have been discovered. Like Mira, they pulsate in usually one or at most very few modes of oscillation. The best known pulsating stars are the Cepheid variables, which are bright and have a well-defined relation between their periods of oscillation and their luminosities (*4*). By measuring the period of a distant Cepheid, its luminosity can be inferred, which combined with its apparent brightness allows its distance to be inferred. This procedure is the first stage of setting up the distance scale for mapping the visible universe.




**A distant sunlike star meets expectations.** Power spectrum of the Doppler measurements of β Hydri (blue). The yellow spectrum is a theoretical expectation, obtained by first scaling solar data (*16*) according to the theory of Houdek *et al.* (*17*) and then reducing the amplitude of the resulting artificial signal by a factor of 1.9 to render the total power in the frequency interval 0.67 mHz < ν < 1.5 mHz the same as that of the β Hydri spectrum (*18*, *19*).

As is the case for many large-amplitude pulsating stars, the natural modes of oscillation of the sun are standing acoustic waves. However, unlike in Cepheids, whose pulsations are self-driven through an instability, the waves in the sun are intrinsically stable and need to be driven continually by some separate agent. The driving force comes from the turbulent convection in the outer layers of the star, which radiates acoustic power just as do flames in a roaring furnace. The trapped waves form a rich spectrum of essentially discrete resonant modes. Their frequencies contain information about the convection zone and the radiative interior but are insensitive to the structure of the atmosphere. Thousands of these modes have been measured in the sun, and millions are believed to be present. Their properties can be analyzed in much the same way as geophysicists study the oscillations of Earth. Knowledge of the sun's modes has enabled the determination of the sound speed to within 0.1% throughout most of the interior (*5*) and a (less accurate) determination of the angular velocity and some aspects of meridional flow in and beneath the convection zone (*6*).

Distant sunlike stars are believed to have similar oscillations. Most of these oscillations cannot be detected by present techniques, however, because not only the spatial but also the temporal variation is oscillatory and therefore signals from neighboring out-of-phase regions of the stellar surface largely cancel. A potentially measurable signal is expected only for the modes with the largest wavelengths—essentially $4\pi R/(2l+1)$, where $R$ is the stellar radius and $l$ takes the values (*7*) 0, 1, 2, or 3—for which cancellation over the visible portion of the surface is sufficiently incomplete. In the case of the sun, there are only about 70 such modes (*8*). Evidently, only restricted inferences can be drawn from such a small subset. Nevertheless, the information they provide beyond what can be inferred from other astronomical data is enormous.

To understand what can be achieved by asteroseismology, consider what could have been learned from helioseismology had the sun been observed only as a distant star. Data from light integrated over the visible disc have been obtained as Doppler shifts (*9*–*11*) and white-light intensity variations (*12*), from which one can estimate the mode frequencies. In addition to gross properties such as the sound travel time τ from center to surface, these data allow the helium abundance and the depth of the convection zone to be estimated (these properties were first, and more accurately, determined from spatially resolved observations). One can also obtain from these whole-disc data a measure of the stratification of the energy-generating core, which is influenced by nuclear transmutation, and use this information to calibrate theoretical models to estimate the age of the sun (*13*). Moreover, from mode amplitudes and acoustic spectral line widths, one can learn something about the convection that drives the modes.

The recent observations of β Hydri reported by Bedding *et al.* (*2*) were carried out over five consecutive nights last June.

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In all, nearly 1200 Doppler measurements were made (*14*). The spectrum from β Hydri contains a concentration of power quite similar to that of the sun. Indeed, the overall shape of the power spectrum is in striking agreement with what one would expect by appropriately scaling the solar spectrum (see the figure), and the value of the total power is more or less consistent too. The deviations from theoretical expectation will help us to improve our understanding of the interaction between convection and pulsation.

It is difficult to associate individual peaks in the power spectrum with specific modes because the inevitable daytime gaps in data obtained from only a single observing site add extra periodicities to the signal, introducing many more peaks (called the window function) into the spectrum. Nevertheless, a value of a mean of the so-called large frequency separation Δ between adjacent mode frequencies ν of like degree $l$ ($\nu_{n,l}$ and $\nu_{n-1,l}$) could be derived. The measured value for Δ (which is a measure of τ) is very close to that expected for β Hydri. Furthermore, the measured offset $\varepsilon = \nu_{0,0}/\Delta$, which is determined by the outermost layers of the convection zone, is similar to that of the sun. The mean value of the small frequency separation $\delta = \nu_{n,l} - \nu_{n-1,l+2}$, which measures the stratification of the core, indicates a well-evolved star, as β Hydri is believed to be.

Bedding *et al.* (*2*) report that complementary, albeit poorer data were obtained essentially at the same time from the smaller Leonard Euler Swiss telescope at La Silla in Chile, some 140° east of the Anglo-Australian Telescope. If all the data can successfully be combined, a nearly continuous data set will be achieved; the window function and consequently the mode identification will thereby be improved. But already, these observations point the way toward a future when a coordinated network of observatories around the world, such as the Whole Earth Telescope (*15*), will enable continuous Doppler observations of sunlike oscillations of a variety of stars in different phases of their evolution. Then asteroseismology will truly be under way.

**References and Notes**


1. M. Martic *et al.*, *Astron. Astrophys.* **351**, 993 (1999).
2. T. Bedding *et al.*, *Astrophys. J. Lett.* **549**, 105 (2001).
3. R. Wolf, *Handb. Astron.* **2**, 549 (1892).
4. The luminosity is the total rate of radiation of energy.
5. A. G. Kosovichev *et al.*, *Sol. Phys.* **170**, 43 (1997).
6. J. Schou *et al.*, *Astrophys. J.* **505**, 390 (1998).
7. The modes have a spherical-harmonic structure, with $l$ being the degree of the harmonic. There are $2l + 1$ harmonics of degree $l$ with different azimuthal orders $m$ satisfying $-l \le m \le l$; these constitute a multiplet. If the star were perfectly spherical, the frequencies of the members of a multiplet would be degenerate. The degeneracy is lifted by symmetry-breaking agents such as rotation. If the frequency splitting can be measured, it can be used to infer the internal angular velocity of the star.
8. Here I ignore degeneracy splitting. There are about 18 observable multiplet frequencies associated with each (low) value of $l$. They are labeled by the order $n$ of the mode, which in the sun satisfies $10 \le k \le 27$, where $k = n + 0.5l$. (The modes "observed" in β Hydri satisfy $12 \le k \le 20$.) Modes with lower $k$ are confined too deeply in the stellar interior for their surface manifestation to be detected against the stellar noise; modes with higher $k$ approach and even penetrate the visible surface (photosphere) and are scattered so severely by the intense turbulence in the surface layers that their frequencies are too ill determined to be of immediate use for diagnosing the stellar interior.
9. A. Claverie *et al.*, *Nature* **282**, 591 (1979).
10. G. Grec, E. Fossat, M. Pommerantz, *Nature* **288**, 541 (1980).
11. A. H. Gabriel *et al.*, *Sol. Phys.* **175**, 207 (1997).
12. C. Fröhlich *et al.*, *Sol. Phys.* **170**, 1 (1997).
13. D. O. Gough, E. Novotny, *Sol. Phys.* **128**, 143 (1990).
14. The first successful whole-disc detections of solar oscillations were also accomplished with Doppler data (*9*, *10*), although the instrumental techniques were quite different.
15. R. E. Nather *et al.*, *Astrophys. J.* **361**, 309 (1990).
16. W. C. Chaplin *et al.*, *Mon. Not. R. Astron. Soc.* **298**, L7 (1998).
17. G. Houdek *et al.*, *Astron. Astrophys.* **351**, 582 (1999).
18. In the theoretical spectrum, the amplitude of the artificial signal has been reduced by a factor of 1.9, which represents a discrepancy between theory and observation. Most of that discrepancy was overlooked by Bedding *et al.* (*2*), who compared solar mean amplitudes (having frequencies near the peak of mean power) with the greatest of the amplitudes of the β Hydri modes.
19. Homology arguments suggest that the frequency dependence of the amplitude spectrum of acoustic modes of sunlike stars scales as the acoustic cutoff frequency $\nu_c \propto ML^{-1}T_e^{3.5}$ in the atmosphere of the star, where $M$ is the mass, $L$ is the luminosity, and $T_e$ is the (effective) surface temperature of the star. Accordingly, artificial β Hydri data were constructed by first scaling the frequency of the Fourier transform of solar whole-disc Doppler data (*16*) to that expected of β Hydri and adjusting the amplitude according to the theory of Houdek *et al.* (*17*). The transform was then inverted to obtain a time series to which was added Gaussian-distributed random noise with variance, relative to the mean amplitude of the final signal, chosen (by iteration) to be equal to that estimated by Bedding *et al.* (*2*). The signal was then "observed" through the same temporal window as was β Hydri. The resulting power spectrum (*18*) is shown in yellow in the figure. The high power at very low frequencies in the β Hydri spectrum (blue) results from slow uncorrected instrumental drift, which was not incorporated into the scaled solar spectrum.


PERSPECTIVES: DEVELOPMENT

# The Path to the Heart and the Road Not Taken

**Eric N. Olson**

Life is full of decisions. One of the earliest is that facing embryonic mesoderm, which must decide whether to become heart or blood. Three papers from the Lassar and Mercola groups published in a recent issue of *Genes & Development* show that this decision is influenced by opposing gradients of positive and negative signals that intersect to create a specific heart-forming zone in the embryo (*1–3*). The idea that overlapping gradients of signaling molecules can generate sharp boundaries of gene expression in the embryo is not new. What makes these papers interesting, however, is that they shed light on the signaling molecules responsible for the formation of heart and blood, the first specialized mesodermal tissues to develop in vertebrate embryos. They also suggest potential strategies for the eventual therapeutic manipulation of cardiac and blood cell fates.

The heart forms soon after gastrulation in a specific region of the anterior mesoderm adjacent to the endoderm; blood cells arise from the posterior mesoderm (*4*). Experiments with surgically manipulated embryos suggest that antagonistic signals control the decision of early mesodermal cells to become heart or blood (*5–7*). The heart does not form if anterior endoderm is extirpated from embryos, pointing to an instructive role for anterior endoderm in this process. Furthermore, when combined with posterior mesoderm in vitro, anterior but not posterior endoderm induces heart formation at the expense of blood development (*5*, *6*).

Several peptide growth factors mimic the heart-inducing activity of anterior endoderm. The most potent of these are bone morphogenetic proteins (BMPs) 2 and 4. Beads soaked in these BMPs, or fibroblasts engineered to express them, induce anterior mesodermal cells that would otherwise give rise to the head to adopt a cardiac cell fate (*7*). BMPs are expressed in the lateral endoderm along the entire anterior-posterior axis of the embryo, whereas heart induction is restricted to the anterior mesodermal region. This implies that additional factors, either positive or negative, cooperate with BMPs to activate the cardiac program in vivo.

The neural tube and adjacent notochord are especially potent sources of signals that repress cardiogenesis in neighboring mesoderm. Surgical removal of the anterior neural tube leads to heart formation in head mesenchyme, and co-

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