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Solar & Solar-Like Oscillations: Insights & Challenges for the Sun and Stars

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Asteroseismology: From Dream to Reality

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Abstract. With the resounding success of Helioseismology in determining the interior structure and rotation of the Sun, and in providing unprecedented studies of the interaction of pulsation and magnetic fields in the solar atmosphere, astronomers have been delighted, after decades of disappointing attempts, with the recent discovery of solar-like oscillations in ξ Hya, β Hyi, α Cen, η Boo and ν Ind. There is now true seismology of a variety of solar-like stars. Asteroseismology also studies stars with a wide variety of interior and surface conditions. For two decades asteroseismic techniques have been applied to many pulsating stars across the HR Diagram. This review describes for non-specialists pulsation modes in stars and discusses a selection of some of the successes already accomplished in asteroseismology.

1. Introduction to asteroseismology

In 1926 in the opening paragraph of his now-classic book, *The Internal Constitution of the Stars*, Sir Arthur Eddington lamented, "What appliance can pierce through the outer layers of a star and test the conditions within?" While he considered theory to be the proper answer to that question, there is now an observational answer: asteroseismology.

Asteroseismology uses the normal oscillation eigenmodes of a star to probe its interior conditions. In the simplest case, where the star can be approximated as spherically symmetric, these modes are described by spherical harmonics. The two main driving forces that cause stellar pulsations are stochastic excitation and the κ-mechanism. Stochastic excitation occurs when the star's eigenmodes resonate with the time scales of the convective motions; this is the case in the Sun and solar-like oscillators. All other known pulsating stars are driven by variable opacity in H, He and sometimes metals, primarily Fe.

There are two main sets of solutions to the equations of motion for a pulsating star, and these lead to two types of pulsations modes: p modes and g modes. For the p modes, or pressure modes, pressure is the primary restoring force for a star perturbed from equilibrium by one of the above driving mechanisms. These p modes are acoustic waves and have gas motions that are primarily vertical. For the g modes, or gravity modes, buoyancy is the restoring force and the gas motions are primarily horizontal.

For the spherically symmetric case, the spherical harmonics that describe the pulsation have three quantum numbers: n, the radial overtone, is the number of radial nodes, each of which is a concentric shell inside the star; ℓ, the degree, gives the number of surface nodes for the mode; m, the azimuthal order, specifies how many of the surface nodes are lines of longitude; for $\ell > |m|$ the rest of the surface nodes are lines of latitude ($-\ell \leq m \leq +\ell$).

Modes with $\ell = 0$ are called radial modes. The star pulsates spherically symmetrically. For known types of pulsating stars these are p modes; e.g. Cepheids and RR Lyrae stars pulsate in radial modes. Modes with $\ell > 0$ are called non-radial modes and may be either p modes or g modes. It is easiest to picture how asteroseismology probes the interiors of stars by imagining a non-radial p mode: A sound wave travels from the surface down into the star along a ray path that is not directed at the center of the star; the wave has an increasing sound speed as it goes deeper, mostly because of increasing temperature and density, hence is refracted back towards the surface of the star where almost all of the energy of the mode is reflected. Modes of different ℓ penetrate to different depths in the star – each mode measuring the integral of the sound speed over its path. The volume of the star that each p mode samples is called the acoustic cavity. With enough modes, as in the Sun, it is possible to invert the observational data to derive the interior sound speed distribution. That can then constrain tightly temperature, density, chemical composition, and rotation as a function of depth.

There are two other important properties of p modes and g modes: 1) as n, the radial overtone increases the frequencies of the p modes increase, but the frequencies of the g modes decrease; 2) the p modes are most sensitive to conditions in the outer part of the star, whereas g modes are most sensitive to the core conditions.

The prime goal of asteroseismology is to study pulsating stars with rich enough frequency spectra to allow inversion of the observations to derive the atmospheric and interior physics of the stars. Thus there is great interest in the study of the newly-discovered solar-like oscillators (the subject of JD12) for this purpose. Other types of pulsating stars have far fewer pulsation modes than the Sun, but the physical conditions in those stars are, in many cases, very different from the Sun and asteroseismology is leading to new, broad understanding of stellar structure.

Some types of stars of interest to asteroseismology are discussed in the following sections to give a flavor of asteroseismic discoveries being made. The solar-like oscillators are discussed in detail by Bedding & Kjeldsen (2003) and Bouchy & Carrier (2003). A basic introduction to the theory of stellar pulsation can be found in the monograph by Cox (1980) and non-radial pulsation is discussed in detail in the monograph by Unno et al. (1989).

2. roAp stars

The roAp stars have been observed photometrically since their discovery over 20 years ago. Frequency analysis of their light curves have yielded rich asteroseismic information on the degrees of the pulsation modes, distortion of the modes from normal modes, magnetic geometries, and luminosities. The latter, in particular, are derived asteroseismically and have been shown to agree well with Hipparcos luminosities (Matthews et al. 1999). New theoretical work on the interaction of pulsation with both rotation and the magnetic field by Bigot & Dziembowski (2002) has presented an entirely new look at the oblique pulsator model of these stars: They find that the pulsation axis is inclined to both the magnetic and rotation axes, and the pulsation modes are complex combinations of spherical harmonics that result in modes that, in many cases, can be traveling waves looking similar to (but are not exactly) sectoral (meaning $|m| = \ell$) m modes. This unique geometry of the pulsation modes in roAp stars allows us to examine their non-radial pulsation modes from varying aspect as can be done with no other type of star.

High-resolution spectra of the roAp stars γ Equ, α Cir and HR 3831 (Ryabchikova et al. 2002; Kochukhov & Ryabchikova 2001) show the extreme stratification effects of abundances and the short vertical wavelength of the pulsation modes in these stars. Lines of Pr and Nd show significant radial velocity variations, while most other lines in the spectrum show none. A plausible interpretation of this phenomenon is that those ions are concentrated in a thin layer by the effects of radiative diffusion, and that this layer lies high in the atmosphere near a vertical anti-node of the pulsation mode. This is consistent with previous observations of strong line-depth dependence (atmospheric height dependence) of the pulsation amplitude in the Hα line (Baldry et al. 1999; Baldry & Bedding 2000), and the strong drop-off of photometric amplitude with increasing wavelength explained by Medupe & Kurtz (1998).

Kurtz, Elkin & Mathys (2003) have resolved the pulsation modes in the roAp star HD 166473 into standing waves and overlying evanescent traveling waves. They have shown for this star that the pulsation modes are standing waves of constant phase in the layers in which the core of the Hα line forms, while they are traveling waves moving outward through the layers above that where the Pr lines form. This is first direct view of outwardly traveling waves in the magneto-acoustic reflective boundary layer in any pulsating star other than the Sun. They also provide the first detailed observational evidence to test new theories of Cunha & Gough (2000) and Bigot et al. (2000) of the complex behavior of the magneto-acoustic modes of the roAp stars in this important boundary layer. Cunha (2001), on the basis of this theory, predicted a solution to a long-standing problem in understanding the asteroseismology of the roAp star HR 1217 that was later observationally confirmed using the Whole Earth Telescope (Kurtz et al. 2002). The time is now ripe for substantial new theoretical developments based on the new kinds of observations being made on roAp stars.

3. White dwarf variables

White dwarfs are g-mode pulsators and are the current champions of asteroseismology. They have more frequencies detected than any other type of pulsating star, other than the Sun, and theory has been more successful in extracting astrophysical information for them than for any other kind of pulsator. There are three main regions of white dwarf pulsation: The DOV, DBV and DAV stars, where the nomenclature is D = white dwarf; V = pulsating variable; and O, B and A refer to spectra that resemble O, B and A stars in the presence of He and H lines.

The best studies of pulsating white dwarfs have been carried out by the Whole Earth Telescope (WET). The WET web site contains a wealth of information and references to published papers from many extended coverage (Xcov) campaigns. An outstanding example is their study of the DOV star PG 1159-035 (Winget et al. 1991) where they found 101 independent pulsations modes. Models yielded a mass of $M = 0.586 \pm 0.003\,M_\odot$; independent tests using distances determined from parallaxes and the mass-radius relation indicate that the quoted precision is probably correct. The periods in PG 1159 are in the range $385 \leq P \leq 1000$ s; they are high-overtone ($n \gg \ell$) g-mode pulsations, as is the case for other pulsating white dwarfs. Asymptotic theory gives a clear prediction of period spacing for such stars, and deviations from that are used to derive the compositional stratification in their atmospheres, i.e. the mass of the surface He and/or H layers – possibly even resolving He^3 and He^4 layers (Wolff et al. 2002). PG 1159 clearly shows $\ell = 1$ and 2 modes, but not $\ell = 3$. The magnetic field strength is less than 6000 G – a very small value for a white dwarf star where field strengths are often MG. Clearly asteroseismology of white dwarf stars is highly successful in extracting astrophysically interesting information.

One of the more striking properties of white dwarfs being studied by asteroseismology now is the C/O interior composition and the potential crystallization of the core in the most massive of the DAV stars in stars such as BPM 37093 (Montgomery et al. 1999) into earth-sized "diamonds". Metcalfe (2003) has even used seismic models of two white dwarfs to measure the $^{12}C\,(\alpha, \gamma)\,^{16}O$ reaction rates, finding a value consistent with laboratory reaction rates.

4. Sub-dwarf B variables

It has been only 7 years since the discovery the EC 14026 stars, the sdBV stars. This group was discovered observationally (Stobie et al. 1997) at the same time that its existence was predicted theoretically (Charpinet et al. 1996). The sdBV stars are low-ℓ, non-radial p-mode pulsators with $65\,\mathrm{s} \leq P \leq 500\,\mathrm{s}$, and amplitudes from 1 mmag up to 0.3 mag. They are all multiperiodic with 2 to 50 modes. Driving is caused by the κ-mechanism operating on a metal line opacity bump in a layer where Fe has been radiatively levitated and concentrated. They are Extreme Horizontal Branch stars that have been stripped of their H envelopes, leaving behind an approximately 0.5–$M_\odot$ He star wrapped in a miniscule H-rich atmosphere with a mass no greater than $10^{-4}\,M_\odot$. They are all in binary systems. Now there is a second group of sdBV stars that pulsate with periods around one hour (Green et al. 2003); these are g-mode pulsators that are slightly separated from the p-mode EC 14026 stars in the HR Diagram.

One of the most exciting of the EC 14026 stars is PG 1336-035. It is an sdBV star in an eclipsing binary with an orbital period of 2.4 hr and with an M dwarf companion of similar radius to the sdBV star. WET devoted two campaigns to this star. During primary eclipse as the M star passes in front of the sdBV star, the pulsation amplitude changes as parts of the non-radial modes are selectively covered. Removal of the eclipse light curve to study these amplitude changes suggests that the pulsation axis may be the tidal axis between the two stars. While there is a wealth of theoretical discussion of tidally induced and modulated stellar pulsation, there have been few observations to test the theory, giving PG 1336 great promise for that.

Another exciting sdBV star, the subject of WET Xcov23 is KPD 1930+2752, an ellipsoidal variable with over 44 periods, and an orbital period of 2.28 hr. The companion is unseen and exceeds the mass of KPD 1930+2752. In fact, the projected orbital velocity of 349 km s^{-1} implies a total mass for the system of *at least* 1.47 $M_{\odot}$ – greater than the Chandrasekhar limit! Gravitational radiation is expected to cause the system to merge in about 200 Myr making KPD 1930+2752 the first good candidate of a Type Ia supernova (SNe Ia) double-degenerate progenitor.

For application of asteroseismology it is necessary to have clear mode identifications of n, ℓ and m for each mode. The combination of line profile and radial velocity studies from spectroscopy and concurrent photometry is best for this. Now in addition to the photometric WET there is the Multi-site Spectroscopic Survey Telescope (MSST). A large campaign by the MSST in 2002 was awarded 113 nights of spectroscopic time to observe the sdBV star PG1605+072 in conjunction with 127 hours of photometric observations obtained by WET in Xcov22. This outstanding data set is still under analysis and promises rich results.

Asteroseismology of sdBV stars was explored for 1.5 days at the recent meeting, "Extreme Horizontal Branch Stars and Related Objects", held in 2003 June at Keele University; recent reviews and latest results can be found in these proceedings (Kurtz 2003).

5. β Cep stars

The β Cep stars are (primarily) p-mode main sequence pulsators of spectral type B0–B2. They have large convective cores which makes them interesting targets for asteroseismology, because of the uncertainty of modeling such cores. Although they are multi-periodic, they are not known to have large numbers of pulsation modes such as are found for solar-like or white dwarf oscillators. Nevertheless, much can be learned from just a few modes, and there have been major recent asteroseismic successes for some β Cep stars.

Aerts et al. (2003) studied 21 years of multi-color photometry for the β Cep star HD 129929 (V836 Cen). They identified an $\ell = 1$ triplet, a doublet they attributed to two m modes of an $\ell = 2$ quintuplet and an $\ell = 0$ radial mode, all with frequencies in the range of 6–7 d^{-1}. The models that best fitted the observed frequencies had a core overshooting parameter of $\alpha_{over} = 0.1$ and non-rigid rotation, with the core rotating four times faster than the surface. If this result stands the test of time, it is the first detection of differential rotation with depth in a star other than the Sun.

For mode identification Handler et al. (2004) and Aerts et al. (2004) have obtained extensive photometric and spectroscopic data sets for the β Cep star ν Eri: 600 hr of differential photometry on 148 nights and 2442 spectra for line profile and radial velocity studies obtained on 118 nights. The frequencies are in the 5–8 d^{-1} range and there is some suggestion from the lowest frequencies of the presence of g modes, as well as p modes. If this is confirmed it will make ν Eri a slowly pulsating B star, as well as a β Cep star.

6. Conclusion

There are many other kinds of pulsating stars that are being studied asteroseismically: The δ Sct stars have, in some cases, dozens of detected p modes. The γ Dor stars are early F, g-mode pulsators with prospect for g-mode studies of cores of stars not very different from the newly discovered solar-like oscillators. Slowly pulsating B stars are mid-to-late B stars pulsating in g modes. All periodically pulsating stars have tremendous promise for new looks at stellar interiors as we hone our theoretical understanding and obtain previously undreamed of observations. Asteroseismology is truly Eddington's "appliance" to see inside the stars. The dream is now a reality.

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