51. Asteroseismology – and star distances

Even with the largest of astronomy's arsenal of ground and space telescopes, most stars apart from our Sun are only observed as point sources of light. It is then perhaps surprising that we know anything at all about their inner structure, or inner workings.

Close-up studies of our Sun reveal its surface temperature and chemical composition from spectroscopy, details of surface features and convection cells from high-resolution imaging, along with time variability of its magnetic field, sunspots, flares, and coronal mass ejections from various remote-sensing instruments.

Detailed models of the inner structure of our Sun and other stars are based on numerous nuclear reaction rates which depend on the star's chemical composition and age, its density, pressure, and temperature, and adding in dependencies on their internal rotation, conditions in their radiative and convective zones, and many other detailed physical effects.

Spectroscopy of even very distant stars provides clues to their chemical composition, temperature, and surface gravity. But accurate knowledge of the distance to each star is critical in transforming *observed* properties, such as brightness and angular radius, into *intrinsic* properties, such as luminosity and physical size. A star's mass is of crucial importance for stellar models, but it is generally only measurable for certain stars in binary systems. Otherwise it is typically estimated from the position of the star in the Hertzsprung–Russell diagram.

An important tool in probing the internal structure of our Sun came with the advent of *helioseismology*, viz. inferring its internal structure from the 'shock' waves that can propagate through it. These waves are analogous to the seismic waves which propagate through the Earth's interior as a result of earthquakes or tsunamis.

On Earth, 'elastic waves' that can propagate in the solid crust and deeper into its interior are of two main types: 'pressure waves' or primary waves (P-waves), longitudinal waves of compression and expansion, and the slower 'shear waves' or secondary waves (S-waves) that move perpendicular to the direction of propagation.

Seismic waves provide high-resolution probes for studying the Earth's interior. One of the earliest discoveries (demonstrated by Harold Jeffreys in 1926) was that the outer core of the Earth is liquid. Since S-waves do not pass through liquids, the liquid core causes a 'shadow' on the side of the planet opposite the earthquake where no direct S-waves are observed. Processing readings from many seismometers using seismic tomography, the mantle of the Earth has been mapped with a resolution of several hundred kilometres, allowing the identification of convection cells and other large-scale features of its core and mantle.

Large earthquakes can also set the entire Earth 'ringing' like a bell. A mix of 'normal modes', with discrete frequencies and periods of around one hour, lead to resonant signatures observable even a month after a major seismic event.

The realisation that analogous studies can be made of the Sun's internal structure came in the 1960–70s, with the discovery of tiny quasi-periodic oscillations in its intensity and line-of-sight velocity, with periods of about 5 minutes. The entirely fluid interior of the Sun leads to somewhat different oscillation modes compared to the Earth: the dominant pressure modes or P-modes, but also gravity modes (g-modes) most prominent in its radiative interior, and surface gravity modes (f-modes). These oscillations are principally caused by sound waves that are continuously driven and damped by convection near the Sun's surface.

Helioseismology observations made from the ground over several decades, with GONG and BiSON, and space observations from SoHO and SDO, has shown that the Sun has a rotation profile with a rigidly-rotating radiative (i.e. non-convective) interior zone; a thin shear layer, the 'tachocline', which separates the rigidly-rotating interior and the differentially-rotating convective envelope; a convective envelope in which the rotation rate varies both with depth and latitude; and a final shear layer just beneath the surface, in which the rotation rate slows down towards the surface.

ASTEROSEISMOLOGY extends the principles of helioseismology to more distant stars, although less information is accessible because their surfaces are unresolved. Oscillations are monitored through high-accuracy photometry over weeks or months.

Mechanisms other than convection can excite stellar oscillations, depending on a star's mass and spectral type: large-amplitude Cepheid and RR Lyrae variables are driven by a variation of radiation opacity with temperature (the 'κ-mechanism'), while tidal forces can drive oscillations in eccentric binary systems.

Over the past decade, a wealth of asteroseismic observations have been acquired on thousands of stars from space, most notably from the Kepler satellite as part of its search for exoplanet transits.

AMPLITUDES AND PHASES of the stellar oscillations are largely controlled by near-surface layers. For example, frequencies are determined by the bulk sound speed and the internal density profile. Convective motions within the differentially rotating outer convective zone modify the star's temperature, density and velocity structure. *Convective overshooting*, caused by the momentum of cool sinking material into the deeper radiative regions, alters the structure of the tachocline, the transition region between the two.

Stellar rotation further influences the details of the frequency spectrum through its variation with radius, and because of the resulting flows and instabilities which are also a function of the star's evolutionary state.

The detailed interpretation of an observed frequency spectrum proceeds via a comparison with theoretical models. For solar-type oscillations, for example, state-of-the-art asteroseismic models, based on the latest space-based observations, yield typical uncertainties of around 3–5% on stellar masses and 1–3% on stellar radii based on certain 'scaling relations'.

Uncertainties of typically 5–10% on luminosities follow from estimates of the radii from these models, and these in turn yield an asteroseismic distance, which can then be compared with accurate trigonometric distances from Gaia. As a result, the Gaia parallaxes therefore provide a powerful test of asteroseismic (and hence stellar evolution) models.

SEVERAL STUDIES using the early parallaxes from Gaia DR1 showed that the good agreement between asteroseismic and astrometric distances for solar-like oscillators (both dwarf and subgiants), which had already been demonstrated with the Hipparcos data, also hold true for the more accurate distances from the Tycho–Gaia Astrometric Solution, while the more accurate asteroseismic distances for pulsating red giants from Kepler yielded early insights into systematics in the DR1 parallaxes (e.g. De Ridder et al., 2016; Davies et al., 2017; Huber et al., 2017).

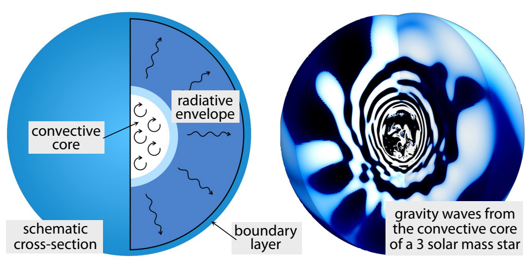
More detailed analyses became possible with the release of Gaia DR2. For example, Sahlholdt et al. (2018) used a sample of 93 dwarfs to show that the asteroseismic radii are 1% smaller than Gaia radii on average, possibly explained by a negative bias of 30 μas in the DR1 parallaxes. They argued that asteroseismic radii are generally accurate to within 1%, but are perhaps overestimated by 5% or more at the highest temperatures. Several other studies have further examined the implications for Gaia systematics or asteroseismic models (e.g. Hall et al., 2019; Khan et al., 2019; Zinn et al., 2019).

I WILL LOOK AT one particular study using the DR2 data in a little more detail, which illustrates the insights into the physics of stellar interiors that is being gained.

Pedersen et al. (2021) studied 26 'slowly-pulsating B stars', a class of star between 3–10 solar masses which are known to be rapidly rotating. Over this mass range, higher core temperatures lead to H–to–He fusion occurring primarily via the temperature-sensitive CNO cycle, which leads to the core being convective, while the outer envelope is ionised, transparent to ultraviolet radiation, and is consequently radiative.

The extent to which the convective core mixes with the radiative envelope in turn affects the amount of H fuel that can be accessed for core H burning, and in consequence allows the stars to live for longer, changing their evolutionary paths. But the degree of mixing, and its effect on the boundary layer and the radiative envelope, has so far remained unknown.

The Gaia distances provide strong constraints on the asteroseismic models. These show that the internal mixing among the 26 stars is far from uniform, with some having almost no mixing, while others show levels a million times higher. The mixing shows no clear dependence on the star's mass or age, but does appear to be correlated with the rotation. But this is not the only physical process at work, and improvements in the theory of the internal mixing of massive stars will follow.



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THERE CAN BE LITTLE DOUBT that many new and interesting insights into stellar structure, stellar evolution, and the state-of-the-art computational models being used to interpret observations of stellar oscillations, will come from the improved astrometric solutions from Gaia in the future.