The power of asteroseismology

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The power of asteroseismology

Nearly a century ago Arthur Eddington had the foresight to question *“Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?’’* The answer is ***asteroseismology*** – the study of the internal structure of stars through their intrinsic global oscillations. As with musical instruments these oscillations resonate in a cavity specific to the “instrument”, i.e. a star in this case. In this way the oscillations reveal information about the properties of this cavity and thus the star.

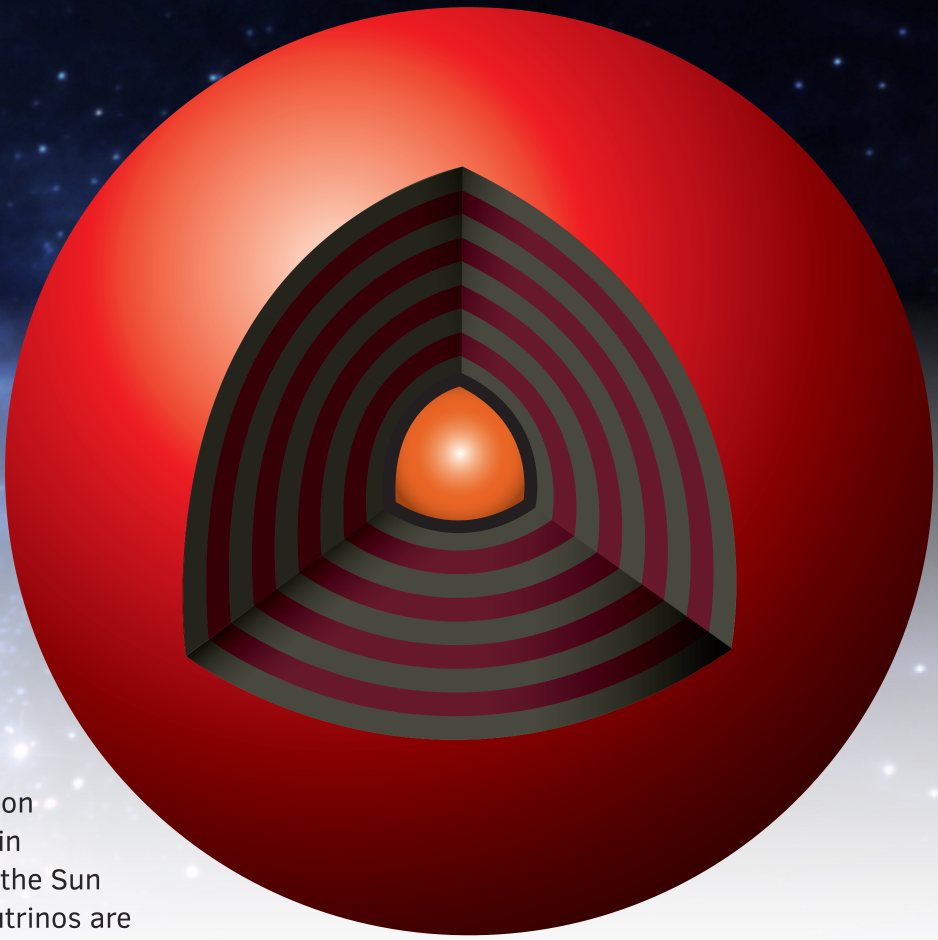
It has been long known that stars can show periodic brightness variations that originate from an intrinsic mechanism in a star. In such a mechanism energy flowing from the core to the surface could be trapped in an opaque layer before reaching the surface. This causes the star to expand. Upon expanding the opaque layer becomes more transparent to the energy flow, which results in the removal of the blockade and making the star contract again (Eddington 1926, Aerts et al. 2010). These breathing oscillations of a star change its radius by a few percent in a coherent manner while at the same time changing its surface temperature and brightness.

History

An early remarkable result from stars with such breathing oscillations (Cepheids) is a relation between the period of the oscillations and the luminosity (absolute brightness) of the stars, the so-called period-luminosity relation (Leavitt and Pickering, 1912). This relation plays an important role in measuring distances of galaxies and star clusters and ultimately the expansion of the universe.

In the 1960s non-coherent oscillations with low amplitudes (much less than a percent) were first discovered in the Sun. These oscillations are stochastically (i.e. in a random way) excited by the turbulent convection in the outer layers of the Sun. Effectively some of the convective energy is transferred into energy of global oscillations. This type of oscillations is referred to as solar-like oscillations.

The oscillations detected in the Sun have provided unprecedented detail of the stellar interior. We now know that the Sun rotates as a solid body in its radiative region up to about 0.7 of its total radius. Above this region there is latitudinal differential rotation in the convective layer, i.e. the outer layers of the Sun rotate faster at the equator than at the poles. At the boundary between solid body rotation and differential rotation there exists a



shear layer, the so-called tachocline. This tachocline could play an important role in the formation of the large magnetic fields present in the Sun. Additionally, seismology of the Sun was pivotal in the discovery that neutrinos are not massless and that low energy neutrinos change flavour (Nobel prize for physics 2015).

Asteroseismic revolution

Other stars with an outer convection zone also excite solar-like oscillations. Among these are stars similar to the Sun, with similar mass and hydrogen fusing to helium in the core, as well as more evolved stars (the future of our Sun). These evolved stars have exhausted their core from hydrogen and either fuse hydrogen in a shell around an inert helium core, or around a core in which helium fusion takes place. These stars are red (cold at the surface) and large (up to 100 times the Sun) and are referred to as red-giant stars (Hekker and Christensen-Dalsgaard 2017). Over the past decade dedicated space telescopes have made it feasible to observe solar-like oscillations in red giants as well as solar-like stars; these observations resulted in an asteroseismic revolution.

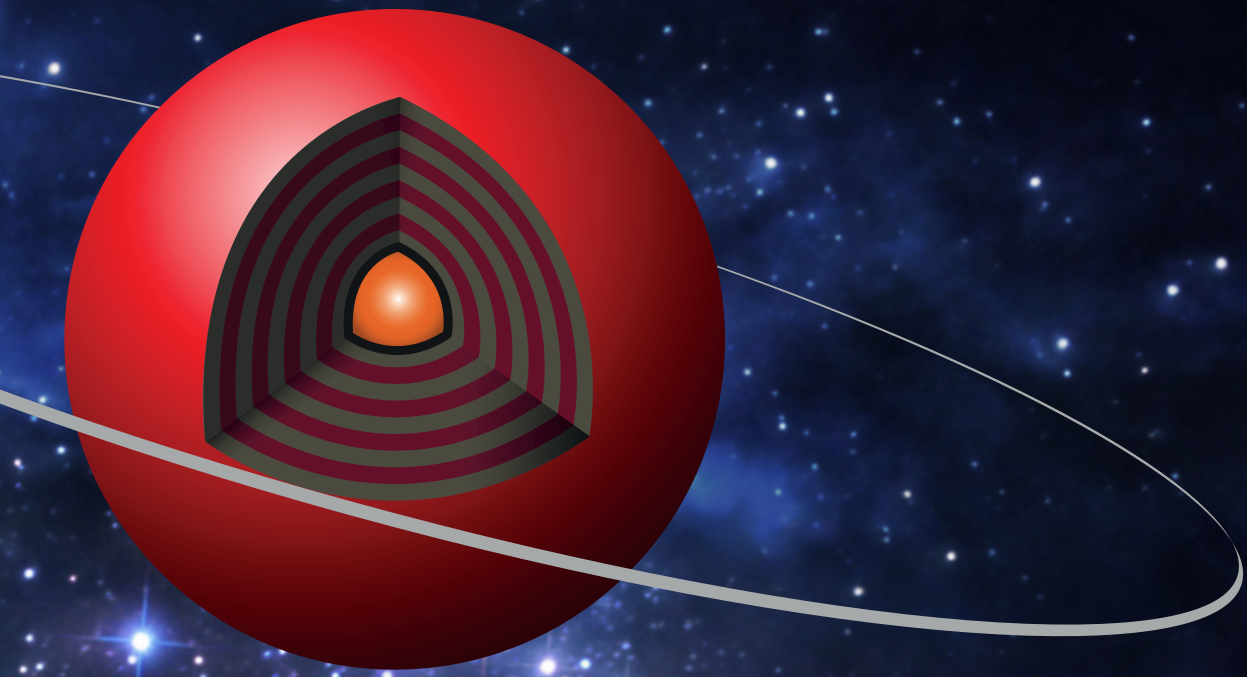
It was discovered that red-giant stars are like musical instruments with two cavities, having one cavity located in the deep interior of the star and one in the outer layers. The oscillations that resonate in both cavities are so-called mixed oscillation modes and provide a direct means to pierce into the cores of red-giant stars and reveal its properties; for instance whether the helium in the core is inert, or fusing (e.g. Bedding et al. 2011). The mixed modes also allow for studies of the rotation of the stellar cores and envelopes. In red giants the cores are rotating about 10 times faster than the envelopes. (e.g. Beck et al. 2012).

Through their sensitivity to the internal structure of the stars, the oscillations combined with surface properties (temperature and chemical composition) can also reveal the stellar mass, radius and age with unprecedented accuracy. Although the ages are depending on comparisons with stellar models, asteroseismic ages are superior to other age determinations in terms of precision and accuracy.

Asteroseismology and computer science

The SAGE (Stellar Ages and Galactic Evolution) group at the Max Planck Institute for Solar System Reseach in Göttingen (Germany) combines asteroseismology with computer science techniques to study stellar structure and evolution and extract the stellar parameters. We have developed a fast and precise tool to determine stellar parameters through the use of machine learning (Bellinger et al. 2016, Angelou et al. 2017). We use random forest regression to measure evolutionary, structural, and chemical stellar attributes from observable features of stars, such as asteroseismic observables. This procedure works by constructing trees that use information theory to create decision rules relating observations to model properties. This approach allows us to rapidly process observables and obtain stellar parameters for large catalogues of stars at different ages and evolutionary states: thus fostering advancement in the theory of stellar evolution.

Additionally, the random forest provides information about so-called *feature importance*, i.e. it indicates what observables are used most often in decisions made by the trees in the random forest. This is essential feedback to know where to focus observational efforts on. Finally, the training time of the random forest is virtually insensitive to the number of free parameters in the underlying stellar model grid. We took advantage of this by varying several parameters such as those for diffusion, convection and convective overshoot, which are most often kept fixed. Hence this allows us to study the importance and effects of these physical mechanisms in stars. Furthermore, the work by Angelou et al.



(2017) also shows the intrinsic accuracy with which stellar parameters can be determined following the information captured in the observables.

Asteroseismology of binary stars
To obtain a handle on the precision and accuracy with which stellar parameters can be determined using asteroseismology, it is essential to compare the same stellar parameters obtained with different independent methods. An excellent test-bed for such a comparison is an eclipsing binary system with at least one oscillating component.

In a binary system two stars are gravitationally bound and therefore the Kepler laws of motion can be applied to infer the orbital parameters (orbital period, distance of the stars from the gravitational center of the binary system expressed as semi-major axis, and eccentricity) and stellar parameters (mass and radius) of the two stars. In case the system is aligned such that from our point of view the stars pass in front of each other, the system is a so-called eclipsing binary system. During an eclipse one of the stars passes in front of, i.e. occults, the other star, and consequently blocks part of the light emitted by the occulted star. This results in a temporary reduction in the intensity of the light that we can measure from the system. From an eclipse it is possible to get a measure of the stellar radius with respect to the semi-major axis of the orbit of the occulting star. From the measurements of a series of eclipses one can infer the radius as a function of semi-major axis of both binary components and the time it takes the stars to complete a full orbit, i.e. the orbital period. In case also Doppler velocities, i.e. the relative velocities of

the stars in our direction, are obtained it is possible to obtain the masses of the stars and semi-major axes of the system by combining our knowledge of the system orientation with the obtained relative velocities. Hence, the stars can be fully characterized in terms of their mass and radius through the measurements of binary signatures.

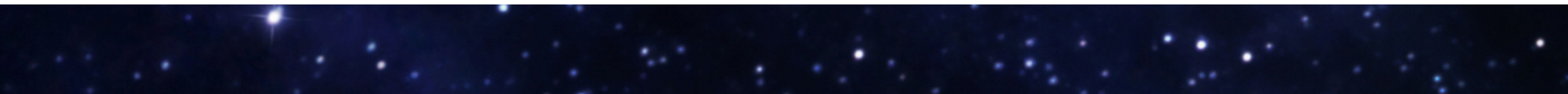
The SAGE group compared the stellar parameters obtained through asteroseismology and from the binary orbital (Themeßl, Hekker et al. submitted). Interestingly the derived masses, radii and mean densities are not consistent within their uncertainties.

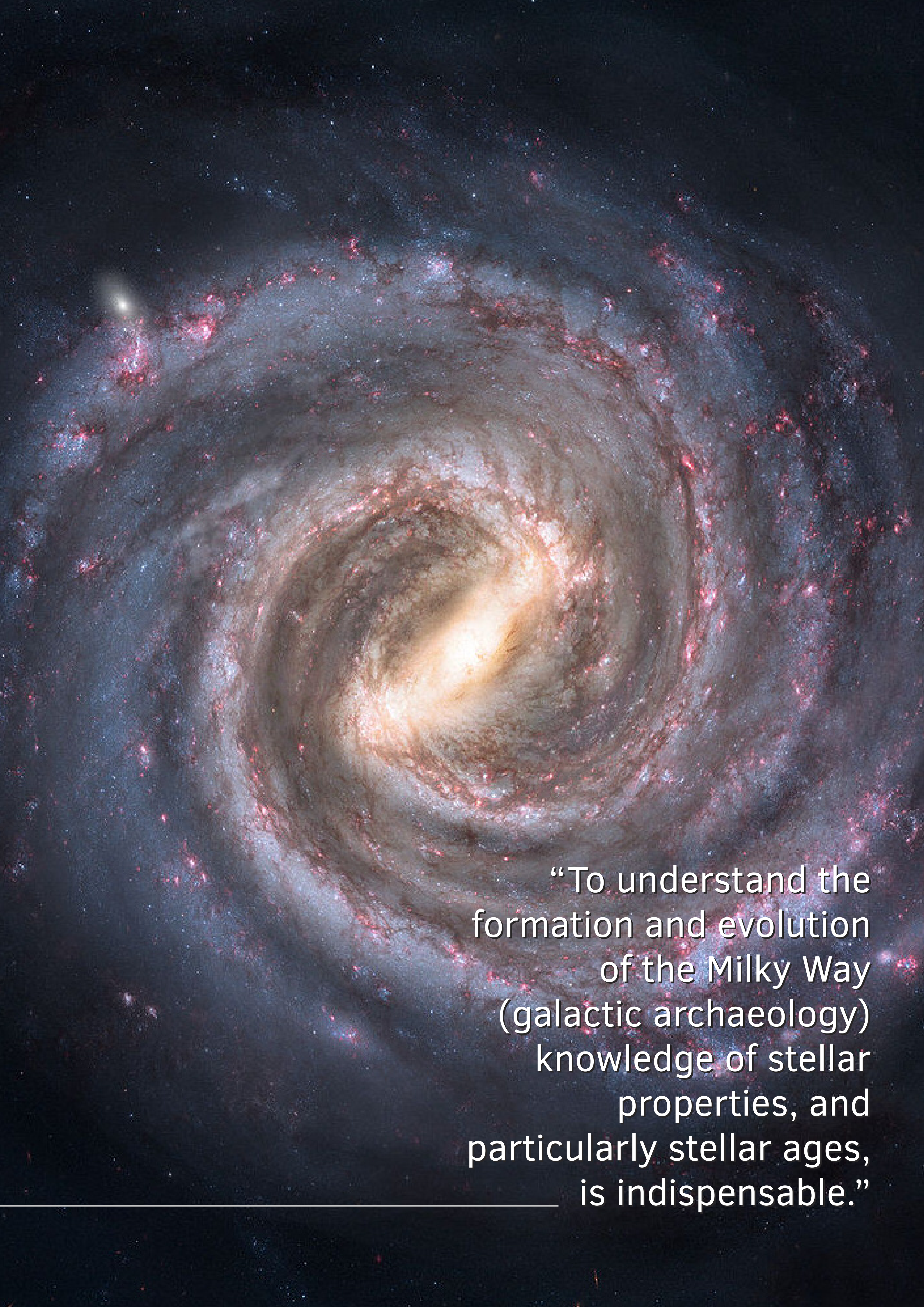
The reason for this inconsistency can be sought in several directions. It could just be a statistical error as we have looked at only a few systems. However, it could also be that the precision of the derived parameters is now so high that we get sensitive to the slightly different intrinsic definitions of masses and radii that are measured using asteroseismology and that can be derived from the binary solution. The impact of the stars in the system on each other could also play a role in this (Themeßl, Hekker, Elsworth 2017).

Asteroseismology and beyond

The power of asteroseismology reaches farther than the structure and properties of stars. It also impacts significant on our knowledge of extra-solar planets, the Milky Way and as mentioned before the expansion of the universe. The determination of the planetary properties (mass, radius and age) critically relies on the knowledge of the same properties of the host star. Indeed, it was thanks to asteroseismology that it was possible to detect earth-mass planets in the habitable zone (e.g. Borucki et al. 2012). Furthermore, stars are a main observable ingredient of the Milky Way and galaxies in general. To understand the formation and evolution of the Milky Way (galactic archaeology) knowledge of stellar properties, and particularly stellar ages, is indispensable. With asteroseismology it now becomes possible to derive stellar masses and ages to an accuracy level that is needed for galactic archaeology.

To utilise the full extent of the power of asteroseismology it is essential to fully understand all the oscillation features that are present in the data and understand their physical origin. This work is still in its infancy and will require many in-depth asteroseismic studies as the field matures.





> “To understand the formation and evolution of the Milky Way (galactic archaeology) knowledge of stellar properties, and particularly stellar ages, is indispensable.”

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