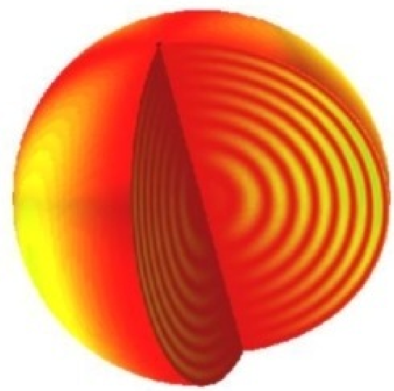
Asteroseismology

The Study of Stellar Oscillations

Understanding stars is central to much of modern astrophysics. Stars are the fundamental entities providing light and energy in the universe and they have produced most of the elements (except hydrogen and helium) from which the Earth is made. In this respect, they are the very source of life on Earth. Stars also provide vital information about the history and the structure of the universe, being the only objects for which we can determine reliable ages.

But we are still very far from a detailed physical understanding of stars, as much of our knowledge is based on limited measurements of the light emitted from the stellar surfaces from which we rely on theoretical models to derive their internal properties.

Although the light from the stars (including the Sun), is created deep within the stellar interior, where the nuclear reactions takes place, its way out of the dense central regions is very long, as it is constantly scattered on the particles in the stellar plasma. It only reaches the surface and escapes the star, after a trip of a few million years. It then carries information about the outer regions from which is emitted, and not about the inner regions, where it was created. Still, the information contained in the starlight can be compared with the theoretical stellar models, but this indirect process is somewhat similar to trying to understand the human body by looking at the skin only.
But pulsating stars offer more possibilities.



Pulsating stars

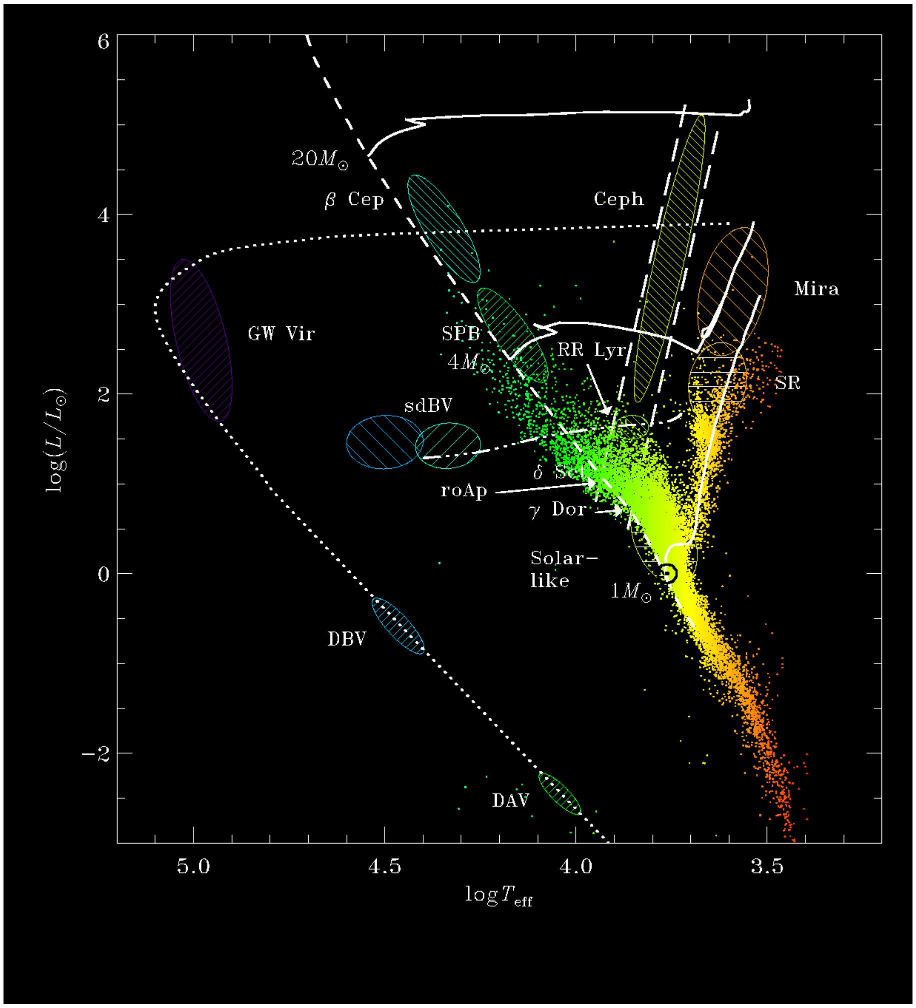
Pulsating stars are stars which size, brightness and temperature vary periodically with time, due to some internal physical processes. As it was already mentioned in "DASC and Kepler", these stars can be categorized according to the manner in which they oscillate, and the stars within the same class of pulsating stars are also physically similar. With the previous discussion on the stellar structure and evolution in mind, we can now show this in more detail.

Pulsations are found in groups of stars all across the Hertzsprung-Russell diagram (or HR diagram). The figure below shows the positions of different groups of pulsating stars in the HR diagram. Most of these groups are named after the first star of each class where pulsations were detected. For instance, the *β Cepheid* stars are named after the second brightest (hence Greek β, the second letter in the Greek alphabet) in the constellation Cepheus, in which variability has been known to astronomers for more than 100 years.

Move the mouse over the different regions of pulsating stars to see an example of the typical pulsations observed in the stars belonging to the group.

For each type of stars, two figures are shown; the upper diagram shows how the stellar brightness changes with time during one day, the lower one shows the results of a mathematical analysis called Fourier analysis, which is used to separate the individual oscillation frequencies - or tones - which are present in the complicated light curve.

This technique for analyzing stellar oscillations in order to extract the frequencies will be described further in the next section "Measuring Stellar Oscillations".



The Hertzsprung-Russell diagram (also referred to as the HR diagram or HRD) shows the relationship between the luminosity and the surface temperature of stars. The diagram, which was first created nearly 100 years ago by Ejnar Hertzsprung and Henry Norris Russell, improved significantly the understanding of stellar evolution, or the 'lives of stars'. In the diagram, hot, luminous stars are found to the upper left, while cool, dim stars are found in the lower right part of the diagram. As illustrated in the Section "Sun-like Stars" a star moves in this diagram as it evolves and hence changes its surface temperature and luminosity. Thus, plotting values of temperature and luminosity for many stars as we measure them at present allows us to determine, for instance, whether a given star is in the main sequence phase of its life, or if it has evolved away from the main sequence to become a red giant.

What this diagram actually shows is that the onset of pulsations in a star is connected to its physical properties - to its luminosity or mass, and to its evolutionary stage or age. These, together, determine the position of the star in the HR diagram.

As the star evolves along its evolutionary track (see the section on stellar evolution), it may pass through one of the marked areas in the figure, and become unstable towards pulsations. This is due to some internal excitation mechanism that can operate in stars in this exact region of the HR diagram, and which can cause the star to pulsate. It then becomes member of the corresponding class of variable stars. Each group typically contains from a few tens to a few hundred stars in which the type of pulsations has been detected. These numbers are expected to be significantly increased by the Kepler mission, as many new variable stars will be detected from the extensive data sets on hundred thousands of stars.

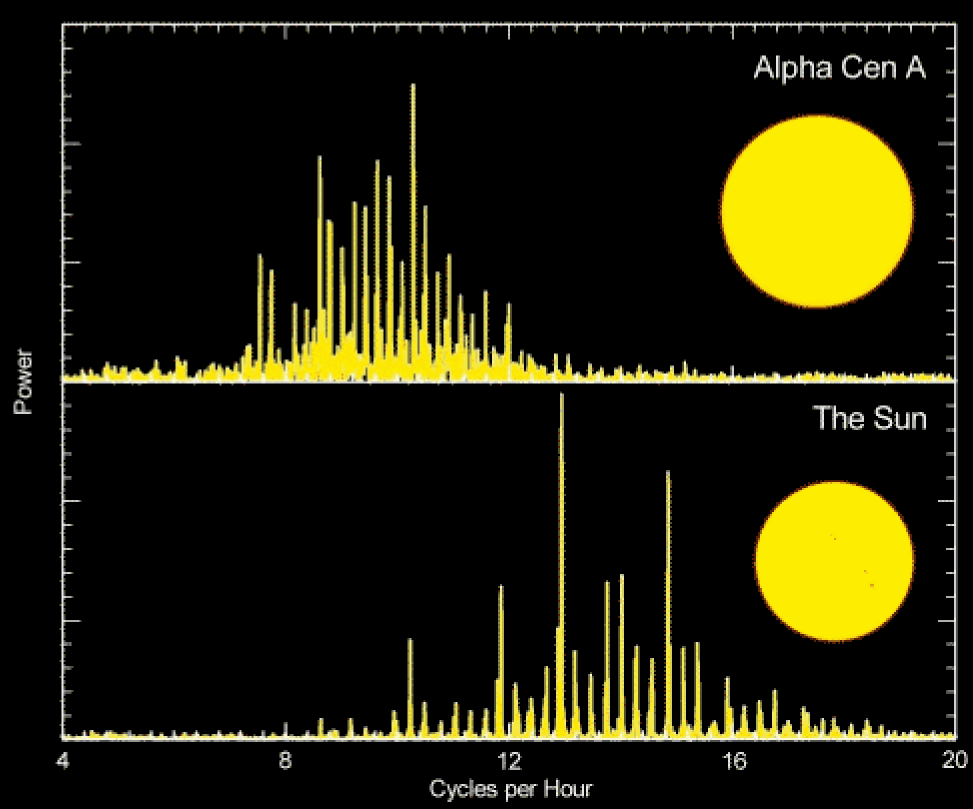
As the star continues to evolve with time, it will eventually leave the unstable region again and stop pulsating. What happens here is that due to changes within the star - such as, for example, a change in density because the entire star expands - the excitation mechanism is no longer efficient and can no longer make the star pulsate. This already tells us a lot about the structure of stars across the HR diagram, as our theoretical models must be able to reproduce the specific type of pulsations found in each one of these specific regions in the HR diagram.

We can now, however, do more than this. Thanks to a fast technological development in instrumentation we can now do ultra-precise and extensive measurements of these "star quakes" in the individual stars, opening up a door to the stellar interior, enabling us to apply the technique of asteroseismology, and actually use the stellar oscillations to look beyond the stellar surface.

The principles in asteroseismology are the same as those geophysicists use to infer the internal structure of the Earth: by using vibrations of the Earth's crust, either brought about naturally by earthquakes or with explosives, in combination with mathematical and physical models, very detailed investigations of the structure of the Earth's interior can be carried out.

Two diagrams showing asteroseismic measurements of the nearby star Alpha Centauri A (4.3 light years away), obtained by the SONG group, compared with data for the Sun.

As the sizes and internal properties of these two stars are different from each other, their oscillations also show different patterns on the two diagrams below.



The study of the stellar structure and evolution through asteroseismology is likewise an interplay between complicated theoretical calculations and ultra-precise observations of stellar oscillations, carried out with the best telescopes and instruments available, at the best astronomical sites in the world.

The background for asteroseismology is, however, found in the Sun.

Helioseismology

The Sun is the best-studied star in the sky. This is because we receive far more light from it than we do from the distant stars, which makes it much easier to collect precise data. Furthermore, it is close enough that we can resolve its surface, which is not the case for the other stars.

There are several telescope networks, set up all around the globe, with the sole purpose of observing the Sun. In each network, 6-8 telescopes are strategically positioned at different longitudes, allowing for precise, continuous observations of the solar surface. At the same time, several satellites observe the Sun, all of which has been taking place for the last several years.

From these measurements, it has been found that the Sun is pulsating simultaneously in millions of different tones. The typical oscillation periods for the individual tones are about 5 minutes, which is far too long for our ears to hear - if we could stand on the surface of the Sun and listen to its ringing. All these tones mean that the overall brightness of the Sun varies in a very complicated manner. But because of very extensive datasets, collected with the telescope networks and the satellites, the individual tones have been determined to high precision. These many tones, or frequencies, can accordingly be used to determine the internal properties of the Sun and be compared with very complicated mathematical and physical computer models of the structure of the Sun, which in turn can be improved and developed, in order better to match the observations.

In this way, a very detailed knowledge of the interior structure of the Sun has emerged, and we have obtained a deep understanding of how a star like the Sun works.

Asteroseismology

However, the problem with helioseismology is that we are only investigating a single star; the Sun. But are younger or older, or more or less massive stars, similar in structure to the Sun? To answer this question, we must observe other stars as well. And the answer to the question is, perhaps not surprisingly, that although the basic principles are the same, there are quite significant differences in structure between stars, in particular between stars of different mass. Stars of about the same mass and age, on the other hand, are quite alike. This means that by doing seismic studies of a number of stars with different properties (mass, age), a more detailed picture of the inner structure of stars can be obtained, and we can investigate how stars evolve. We can, for instance, study stars that are similar in mass to the Sun, but older or younger, and obtain knowledge of both the past and the future of the Sun.

Click on the image to listen to some star sounds

However, although very exciting results are being obtained at present, asteroseismology is still well behind helioseismology. This is because we need to study many stars, which takes time. And again because we receive much less light from the stars. Furthermore, we cannot resolve their surfaces, as we can with the Sun. And since the stellar oscillations manifest themselves in variations in the overall stellar brightness, as well as in complicated local variations across the stellar surface, we simply have less information to work with, as compared to the Sun. This makes it very demanding to obtain sufficient data for determining the tones precisely, which is necessary for doing asteroseismology and to compare observationally determined frequencies with theoretical stellar models.

In the next section, we describe how observations of stellar oscillations are being done, and why a space telescope such as Kepler, offers fantastic possibilities for asteroseismology.

Click here, if you want to read more about asteroseismology.

A short history of helio- and asteroseismology	
1961	First evidence for periodic variation in the surface velocity of selected areas of the Sun.
1979	Solar full-disk observations reveal global oscillations.
1981	The BiSON network starts limited operations. This network is still operating.
1986	The IRIS 7-station network starts operation. Operation ends 2001.
1991	The first evidence for solar-like oscillations in another star (Procyon) is published. Controversial at the time, but later confirmed.
1995	The GONG network for solar oscillation observations starts full operations. Operations are still ongoing.
1995	The first detection of individual oscillation modes is published for the star Eta Bootis. Controversial at the time, but later (2003) confirmed.
2001	First clear detection of excess power in another star (Beta Hyi).
2001	First definite solar-like oscillation measurements in Alpha Cen A
2004	First detection of l=3 modes and measurement of mode lifetime in another star (Alpha Cen A).
2005	Most precise measurements of stellar radial velocities are made with the ESO VLT and the UVES spectrograph (Alpha Cen B).