MYSTERIOUS OSCILLATIONS

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THE INTERNAL STRUCTURE OF STARS

SASKIA HEKKER

Life on Earth is intimately connected with the Sun and the stars around us. To understand the habitability of our planet we need to appreciate its cosmic surroundings, such as the solar system and the Milky Way. Stars are mysterious entities, but understanding their physics inevitably proves enlightening. Using the technique of asteroseismology – the study of the internal structure of stars through their global oscillations – we are on our way to unravelling the physics and evolution of these celestial bodies.

“The Cosmos is within us. We are all made of stardust. We are a way for the universe to know itself.” This famous quote by American astronomer Carl Sagan (1934–1996) expresses in a nutshell the fact that we are intimately connected with the stars. Every person on Earth, as well as our planet itself, the solar system, the stars, and even the galaxies consist of atoms that come from outer space. In fact, any atom in our universe more complex than hydrogen, helium, and lithium was produced inside a star. Stars not only provide the building blocks for life on Earth. Our own star – the Sun – is the major source of energy and light on which humanity thrives. Similarly, other stars might provide energy and light for extraterrestrial life.

Stars are at once enlightening and mysterious. While we may perceive them as fixed points of reference in our night skies, they do, in fact, have a life and evolution of their own. Stars, like people, are born, age, and die. One central concern in astrophysics today is to understand what exactly happens inside stars as they go through this process and how the physical conditions below the surface change as they evolve. Using the light that stars emit, we study their surface properties such as temperature, gravity, and chemical composition. Until quite recently, however, we were unable to look inside to investigate what is causing light to be emitted in the first place. British astronomer Sir Arthur Eddington (1882–1944), who was the first to suggest that

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nuclear fusion of a light element (hydrogen) into a more massive element (helium) may fuel the stars, addressed this problem as early as 1926, asking: “What appliance can pierce through the outer layers of stars and test the conditions within?” Nearly a century later we have found ways to answer this question by using approaches and methods from seismology.

Studying the natural vibrations of stars

Seismology is the study of earthquakes and the propagation of seismic waves through the Earth and similar planet-like bodies. It is based on the detection and analysis of the subtle vibrations – small departures around the equilibrium – that travel through these bodies due to certain events that take place below the surface. When applied to our Sun, this method of study is called helioseismology, and when applied to the study of far-away stars, it is called asteroseismology. Stars, like musical instruments, vibrate at very distinct frequencies. With a violin or guitar, air vibrates in a cavity, the inner part of the instrument. The shape of the cavity determines and characterises the typical sound of the instrument. Vibrations in stars occur when the stellar matter is excited as a result of certain internal or external mechanisms – like the turbulent convection in the outer stellar layers or the gravitational forces exerted by other celestial bodies orbiting close by. Depending on their age, mass, size and composition, stars too give out unique, signature "sounds" – these "sounds" are a star's natural frequencies or "eigenfrequencies".

We cannot hear these sounds, but we can appreciate them nonetheless by detecting and analysing the small changes they produce in a star's brightness. These changes reflect the inner structure of the star, giving us vital clues about what transpires within. In this way, stars provide us with a symphony of "typical sounds" or vibrations that we can "listen" to to draw inferences about what fuels these celestial bodies and how light travels from the core to the surface. This information in turn helps to understand how the building blocks of the universe are generated, the origins of energy and light for humankind – and possibly for extraterrestrial life – and how our own star, the Sun, is likely to evolve, and with what repercussions for life on Earth.

The ages of stars

In stars like our Sun, core fusion starts with hydrogen, which slowly fuses into helium. This phase is what is known as the main sequence, in which stars reside for 90 percent of their total lifetime and do not undergo significant changes. The Sun will remain on the main sequence for the next five billion years or so. Once hydrogen is depleted after billions and billions of years, hydrogen fusion continues in a shell around the helium core. During this shell-burning phase the temperature and density in the core continue to rise. Eventually, helium in the core starts fusing into carbon, with hydrogen fusion continuing in the surrounding shells. Depending on the mass and composition of the star, this sequence of core and shell fusion events repeats itself with oxygen and other heavier elements, all the way up to iron. Evolved low and intermediate mass stars (with masses up to about eight times the mass of the Sun) are known as red-giant stars, which are cool, large, red, bright stars that will eventually disintegrate into planetary nebulae, providing the raw materials for the next generation of stars and planets. Since red-giant stars are bright, their oscillations are more pronounced than those of main-sequence stars like the Sun, for instance. This makes it easier to collect asteroseismic information and hence to learn about the physical conditions inside.

Red-giant stars are the main focus of study in the 'Theory and Observations of Stars' (TOS) group based at the Heidelberg Institute for Theoretical Studies (HITS) and the Landessternwarte (LSW) Heidelberg. One major challenge in asteroseismology is that stars other than the Sun essentially appear to us as point sources – that is, we cannot see the details of the stellar surface. This makes it harder, if not impossible, to obtain detailed information on the layers just below the surface. By contrast, the increased density in the core of red giants allows oscillations from the core to reach the surface. It is thus much easier to study the deep interior of red giants than it is to study the deep interior of the Sun. Red giants are particularly interesting for asteroseismologists because they are intrinsically bright, abundant, and can have different internal structures. By measuring the brightness of these stars every half hour for several months or even years – by recording what is known as time series data – we are able to track the variations in their brightness, which can help us gain insights into their internal structure.

Making windows into stars

Over the past 15 years, various space missions – such as CoRoT (Convection Rotation and planetary Transits), Kepler, K2, and, currently, TESS (Transiting Exoplanet Survey Satellite), as well as global networks of small ground-based telescopes such as SONG (Stellar Oscillations Network Group) – have provided data ideally suited for asteroseismology. These data open new windows onto stars that have already led to ground-breaking discoveries.

For instance, we can now see whether a star has a helium core that is not yet fusing, or a core in which helium fusion has started. This is a particularly important quality because core-helium fusing stars all possess nearly the same intrinsic brightness, making them useful as distance indicators. A distance indicator, or "standard candle", is an astronomical object that is close enough to measure its real distance from the Earth. Such not-too-distant objects are used as stepping-stones to determine the distances of objects that are even further away. Hence, these stars form the first step of the cosmic distance ladder, in which each rung of the ladder provides information needed to determine the distances of objects at the next distance level.

There is also a list of open questions that asteroseismology can help us tackle. In many cases, these questions arise from the discrepancies between what we observe and what the stellar models predict. One example is the actual size of stellar cores, which, in some instances, have been found to deviate quite substantially from what the models had suggested. Asteroseismology also enables us to define and

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Zentrum für Astronomie: Landessternwarte Königstuhl
Die Landessternwarte Königstuhl (LSW) wurde am 20. Juni 1898 als „Großherzogliche Bergsternwarte“ durch den Großherzog Friedrich I. von Baden eingeweiht. Sie befindet sich auf dem Westgipfel des Königstuhls und verfügt über sechs mit Teleskopen ausgestattete Beobachtungskuppeln. Seit 2005 ist sie nicht mehr Landesinstitut, sondern – zusammen mit dem Astronomischen Rechen-Institut (ARI) und dem Institut für Theoretische Astrophysik (ITA) – Teil des Zentrums für Astronomie (ZAH) der Universität Heidelberg. Geleitet wird sie von Prof. Dr. Andreas Quirrenbach. Die Wissenschaftler*innen der Landessternwarte forschen auf den Gebieten der stellaren, extragalaktischen und theoretischen Astrophysik und beteiligen sich an der Entwicklung und am Bau astronomischer Instrumente. Arbeitsgruppen der Stellarphysik beschäftigen sich mit Planeten außerhalb des Sonnensystems, metallarmen und heißen Sternen, der Hochenergie-Astrophysik sowie aktiven Galaxien. Darüber hinaus sind die LSW-Wissenschaftler*innen an internationalen Projekten wie dem Large Binocular Telescope oder dem H.E.S.S.-Teleskop für die Beobachtung höchstenergetischer Gammastrahlen beteiligt.

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characterise the speeds at which the cores of stars rotate. For instance, in recent years we discovered that the core of a red giant rotates about ten times faster than its surface. While this is an important observational insight in its own right, it is not consistent with the theoretical predictions. In observed stars, the core was found to rotate ten to 100 times slower than stellar modelling had predicted. This suggests that some transport of angular momentum is missing in the models. Identifying the angular momentum transport mechanisms that are active in stars is currently an important aim in stellar research. This enhanced knowledge of angular momentum transport mechanisms provides fundamental insights into such mechanisms in conditions that cannot be reproduced on Earth and may be applicable in other (unrelated) contexts as well.

Apart from these breakthroughs, there has also been incremental progress in understanding other aspects of stars, including the physical conditions that prevail at the interface between discrete stellar regions where the energy generated in the core is transported to the surface via radiation or convection. The Sun – and sun-like stars – for instance, commonly have several regions, which include a region where fusion takes place deep inside the star; a radiative zone, where energy from the core is primarily transported through radiative diffusion; and a convective zone, which extends to just below the surface of a red-giant star and is characterised by energy transport through movement of plasma. It is very unlikely for the transition between the radiative and convective zones to be abrupt, and a sort of transition layer where convection is slowing down is thought to provide a more realistic description. This is based on our knowledge of the Earth’s atmosphere, among other things. But questions remain about how fast convection can slow down and how thick such a translation layer would be. Insight into this is growing and being used to update stellar models.

Enhancing our insight into stellar and planetary physics
To advance our understanding of the physics of the interiors of stars, the TOS group is aiming to use not only stellar surface properties such as temperature, chemical composition, and gravity, but also the knowledge of the internal structures of stars that we have gained thanks to asteroseismology. The combination of accurate and precise observations of these different parts of stars, together with continuously improving models, will enhance our knowledge and understanding of stellar physics.

To do this most effectively we make use of synergies between asteroseismology and other fields of research, such as the search for exoplanets. These synergies exist both in terms of

GEHEIMNISVOLLE SCHWINGUNGEN

DIE INNERE STRUKTUR VON STERNEN

SASKIA HEKKER

Das Leben auf der Erde ist eng mit der Sonne und unseren Nachbarsternen verbunden. Will man die Bedingungen verstehen, die Leben auf unserem Planeten ermöglichen, so muss man auch die unmittelbare kosmische Umgebung der Erde – unser Sonnensystem und die Milchstraße – betrachten. Die Sterne mögen geheimnisvoll wirken, aber das Wissen um ihre physikalischen Gesetzmäßigkeiten bringt Licht ins sprichwörtliche Dunkel.

Heute sind Wissenschaftler*innen in der Lage, nicht nur die Oberflächenbeschaffenheit von Sternen zu bestimmen, sondern auch ihre innere Struktur unmittelbar zu erforschen. Dank der Asteroseismologie – einer Wissenschaft, die aus den Schwingungen der Sterne Erkenntnisse über ihren inneren Aufbau ableitet – rückt ein umfassendes Verständnis der Physik und Evolution dieser Himmelskörper in greifbare Nähe.

In den letzten beiden Jahrzehnten hat die Asteroseismologie zu bahnbrechenden Entdeckungen geführt und kontinuierliche Fortschritte ermöglicht. Doch zahlreiche Fragen sind noch immer unbeantwortet. Die Arbeitsgruppe „Theory and Observations of Stars“ (TOS) bearbeitet diese Fragen mit dem Ziel, neue Erkenntnisse über die Physik, Struktur und Evolution der Sterne zu gewinnen. Diese Erkenntnisse wiederum sind Voraussetzung für ein besseres Verständnis unserer kosmischen Nachbarschaft – einschließlich Exoplanetensystemen und der Milchstraße – sowie der grundlegenden Gesetze der Physik. ●

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„Die Asteroseismologie bietet Zugang zu einer Art Weltraumlabor, in dem wir unser Wissen über Physik unter extremen Bedingungen testen können.“

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our observations and our scientific questions. For example, time series data acquired for asteroseismic investigations are similar to data needed to search for exoplanets. In order to detect exoplanets, we also need to closely monitor the stars to see if a planet is transiting – i.e. moving in front of the star – thereby dimming its brightness. Furthermore, it is only possible to determine the properties of a planet from the properties of its star – ‘know thy star, know thy planet’, as the saying goes. This is because planets do not emit light, which means that, in most cases, they can only be detected through changes in the parameters of their star. Typically, the asteroseismic properties of stars are the most accurate and precise, also providing immensely valuable information for age-dating planetary systems, and for determining planetary densities that reveal whether a planet is a gas giant – like Jupiter or Saturn – or a rocky planet like our Earth.

Illuminating the cosmic landscape

Asteroseismology also has a profound impact on what we know about our galaxy. One of the main missing links in galactic archaeology – the study of the formation and evolution of the Milky Way – is the age of stars, which are used to reconstruct how the galaxy has evolved over its 13-billion-year history. With the help of asteroseismology we can estimate the age of stars with unprecedented accuracy and precision. These age estimates play a crucial role in determining the history of our host galaxy.

Finally, by enabling us to systematically study entire ensembles of stars, or even stellar populations, asteroseismology allows us to probe matter at physical conditions, such as temperature and pressure, that do not exist and cannot be created here on Earth. Asteroseismology offers access to a space laboratory, of sorts, in which we can test our knowledge of physics in extreme circumstances. In this way, asteroseismology serves as a connector and a conduit, not only enhancing our understanding of stars, but also illuminating a broader cosmic landscape, and even shedding more light on the fundamental laws of physics. ●

Das Heidelberger Institut für Theoretische Studien (HITS)

Das Heidelberger Institut für Theoretische Studien (HITS) wurde 2010 von SAP-Mitgründer Klaus Tschira und der Klaus Tschira Stiftung als private, gemeinnützige Forschungseinrichtung ins Leben gerufen. Das HITS betreibt mit derzeit 13 Forschungsgruppen Grundlagenforschung in den Naturwissenschaften, der Mathematik und der Informatik, wobei große Datenmengen verarbeitet, strukturiert und analysiert werden. Die HITS-Stiftung, eine Tochter der Klaus Tschira Stiftung, stellt die Grundfinanzierung der HITS gGmbH auf Dauer sicher. Die Mittel dafür erhält sie von der Klaus Tschira Stiftung. Gesellschafter des HITS sind neben der HITS-Stiftung die Universität Heidelberg und das Karlsruher Institut für Technologie (KIT). Das HITS arbeitet außerdem mit weiteren Universitäten und Forschungsinstituten sowie mit industriellen Partnern zusammen. Die wichtigsten externen Mittelgeber sind das Bundesministerium für Bildung und Forschung (BMBF), die Deutsche Forschungsgemeinschaft (DFG) und die Europäische Union.

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