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Asteroseismology and Exoplanets: Listening to the Stars and Searching for New Worlds

IVth Azores International Advanced School in Space Sciences

Springer

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As armas e os barões assinalados,
Que da ocidental praia Lusitana,
Por mares nunca de antes navegados,
Passaram ainda além da Taprobana,
Em perigos e guerras esforçados,
Mais do que prometia a força humana,
E entre gente remota edificaram
Novo Reino, que tanto sublimaram;

— Luís de Camões, in *Os Lusíadas*

Foreword to Part I

Vibrations of an object depend on the overall characteristics, such as size, of the object and its more detailed internal properties. The sound of a violin is very different from that of a double bass, but at a more subtle level there are also differences between a violin built by Stradivarius and one bought in a cheap store. This principle is the basis for the use of waves and vibrations to probe the properties of objects, from machinery over seismic studies of the Earth to stars.

Stars may support a broad range of oscillations. Whether or not these are useful as diagnostics of the stars depends on their excitation to observable levels. Here I concentrate on the so-called solar-like oscillators where, as in the Sun, the modes are intrinsically stable and would damp out if not excited by some external source. That source is the vigorous near-surface convective motions, with speed approaching the local speed of sound, found in relatively cool stars with outer convection zones.

Solar oscillations were first detected in the early 1960s, but it was only in 1975 that their nature as normal modes of the Sun was definitely established. The modes initially identified had short horizontal wavelengths, but the presence of modes in the 5-min range of very large scale including radial (spherically symmetric) oscillations was established a few years later. The diagnostic potential of these observations for the study of the solar interior was immediately obvious, and indeed even the early observations led to interesting inferences on, for example, the depth of the solar convective envelope. Also, early results strongly indicated that models of the solar core were essentially correct, ruling out attempts to explain the low observed flux of electron neutrinos from the Sun in terms of modifications to solar modelling and supporting the idea of neutrino oscillations. As a result of these early successes, several projects were developed to carry out detailed observations of solar oscillations, culminating in the ground-based GONG network of observing stations and instruments on the *SOHO* satellite, both starting operations in the middle of the 1990s.

Analysis of the helioseismic observations has resulted in remarkably detailed inferences of structure and rotation in most of the solar interior. The latitudinal differential rotation observed at the solar surface has been found to extend throughout the convection zone, with a sharp transition to nearly solid-body rotation in the radiative interior. The resulting rotational shear is believed to play an important role in the generation of the solar magnetic activity. The sound speed in the solar interior was determined with very high accuracy, agreeing within a fraction of a per cent with existing models. Revised determinations of the solar surface composition have, however, caused changes in solar models, greatly increasing the discrepancy. The origin of this discrepancy is still to be found.

The solar excitation mechanism is expected to be active in all stars with substantial outer convection zones. However, the very small amplitudes of these modes make the observations challenging, and it was only in the late 1990s that definite detections of solar-like oscillations in other stars were made. Subsequent observing campaigns, in many cases using some of the largest telescopes in the World to observe bright stars, resulted in analysis of the oscillations in a few main-sequence and red-giant stars. However, a major breakthrough in the field of solar-like asteroseismology came with space-based photometry from the *CoRoT* and *Kepler* missions, launched in 2006 and 2009, respectively, with the combined goals to search for exoplanets and carry out asteroseismology. These missions have provided high-quality asteroseismic data for hundreds of main-sequence and subgiant stars, and tens of thousands of red giants.

Early results have focused on the determination of overall stellar parameters, such as mass, radius and age. This has been particularly important in the cases where asteroseismic characterisation was possible for hosts of exoplanets. A second important application of such asteroseismic surveys is the use in galactic archaeology, i.e., the investigation of the structure and evolution of the Milky Way Galaxy based on characterising the present distribution, ages and composition of stars. Here asteroseismology of red giants plays a crucial role in providing determinations of distances and ages of stars over a large part of the Galaxy.

From the point of view of stellar astrophysics the asteroseismic data provide detailed tests of the internal structure and in many cases rotation of the stars. An important example is the study of the rotation of subgiant and red-giant stars which has demonstrated the need for so far unidentified mechanisms of angular-momentum transport to explain the comparatively slow rotation of the stellar cores. Detailed analysis of the data in terms of stellar internal structure is just starting. Indeed, the already available data from *CoRoT* and *Kepler* will remain an invaluable resource for stellar astrophysics for a long time to come. More data will come from the NASA *TESS* mission scheduled for launch in 2017 and the ESA *PLATO* mission with expected launch in 2025.

The fields of helio- and asteroseismology remain extremely rich in the potential for further scientific investigations and breakthroughs, towards the goal of obtaining a proper physically based understanding of stellar structure and evolution. I hope that the school, and this volume, will inspire a new generation of young scientists to work with the marvellous data now available and expected, and tackle these issues. You will surely have fun!

Aarhus, Denmark Jørgen Christensen-Dalsgaard
January 2017

Foreword to Part II

Since the Copernican revolution, philosophers and astronomers have interpreted the nearly circular and coplanar orbits of the Sun's family of planets as clues to their origins. The Sun contains over 99% of the solar system's mass, but 98% of its angular momentum resides in the planets. In the eighteenth century, Kant and Laplace hypothesised that if the Sun had condensed from a contracting cloud of gas, any residual angular momentum must necessarily result in the formation of a flattened disc of nebular material. If planets condensed within such a nebular disc, near-circular orbits and coplanarity would be assured. Others were less convinced. In the following century, James Clerk Maxwell argued that Keplerian shear within the disc would inhibit condensation of planetary bodies. Early in the twentieth century, James Jeans proposed instead that planet formation was a rare process occurring in tidal streams resulting from close stellar encounters. Planets were either almost impossibly rare products of close stellar encounters or commonplace natural by-products of the star formation process itself.

The advent of infrared astronomy in the 1980s produced the first indirect evidence that protoplanetary systems might be common features of young stars in star-forming regions like Taurus-Auriga. The spectral energy distributions of T Tauri stars were found to have multiple components: the stellar spectrum itself, an ultraviolet component arising from accretion-driven heating of the outer stellar atmosphere, and an extended infrared tail emitted by circumstellar dust at temperatures from 1000 K down to a few tens of K. Links between emission-line behaviour and the infrared luminosity suggested active disc accretion might be present. These conclusions were vindicated spectacularly by early Hubble Telescope images showing protoplanetary discs clearly silhouetted against the background of the Orion Nebula.

The prospects of detecting mature planets remained bleak in the face of angular separations smaller than the seeing limitations on ground-based observations, and contrast ratios ranging from billions for reflected light to thousands for gas giants viewed at thermal-infrared wavelengths. In the end, the breakthrough came not from advances in direct imaging but from clever use of indirect dynamical effects. As long ago as 1952, Otto Struve had proposed that if Jupiter-mass planets existed in close orbits about their parent stars, it should be possible to detect the Doppler effect of the host star's reflex motion about the system's centre of mass. Moreover, some 10% of planets in few-day orbits would transit the face of the host star, yielding a periodic, temporary reduction in stellar flux of 1 or 2% for a Jupiter-like gas giant. The 1992 detection by Alex Wolczcan and Dale Frail of a family of planets around pulsar PSR J1300+1240 was achieved through modulation of the pulse period by reflex orbital motion. Three years later, Michel Mayor and Didier Queloz detected the 4.2-day, $56\,\mathrm{m\,s^{-1}}$ reflex motion of a normal Sun-like star, 51 Peg, around an unseen object with about half the mass of Jupiter.

Encouraged by this result, other teams carrying out high-precision radial-velocity searches announced further discoveries of Jupiter-mass planets in short-period orbits around F, G and K main-sequence stars. Their gas-giant nature was confirmed with the detection of transits in HD 209458b by David Charbonneau and Tim Brown. Their instrument was the prototype for a new type of planet search: wide-field transit surveys using small off-the-shelf camera lenses on robotic mounts, backed by science-grade CCDs. Over the ensuing decade, transit surveys such as TrES, WASP, HAT and XO eventually amassed hundreds of hot-Jupiter detections, while high-precision, long-duration radial-velocity surveys pushed towards ever longer orbital periods and lower planet masses. Space-based surveys such as *MOST*, *CoRoT* and *Kepler* revealed dozens, then hundreds, then thousands of transiting planets with radii too small to detect from the ground. The exquisite photometric performance and uninterrupted observations of these missions also made asteroseismic characterisation of exoplanet host stars possible for the first time. Radial-velocity surveys reached the threshold of 1 Earth mass at about the same time as *Kepler* detected the first transits of Earth-sized planets, in 2012.

We are now moving from an era of discovery into one of characterisation. Many stars possess compact systems of multiple coplanar planets in orbits closer than Mercury's orbit about the Sun. Others possess hot Jupiters and little else; others still have gas-giant planets in highly eccentric orbits. The orbital planes of a significant fraction of hot Jupiters are strongly inclined with respect to their stars' rotation axes. Some are even retrograde. Although it is now clear that Kant and Laplace were on the right track after all, we still have a long way to go in understanding the detailed physical processes that take place in protoplanetary discs, and the compositions and orbital properties of the planetary bodies that eventually emerge.

In only 20 years, exoplanetary science has grown into one of the most challenging and rewarding areas of research in observational and theoretical astrophysics. It is a rich mix of superbly engineered instrumentation, large-scale data handling, orbital dynamics, gas and dust chemistry, and stellar physics. The latter is vital: the properties of the host star are intimately connected to the composition of a planetary system, and its surface activity presents a challenge to our efforts to characterise small planets. The techniques presented at the school and in this volume are the foundations on which our explorations of worlds around other stars are based. I hope that it will prove useful and inspirational to all who read it. With the *TESS*, *CHEOPS* and *PLATO* missions on the near horizon, the adventure is only just beginning.

St Andrews, Scotland
January 2017

Andrew Collier Cameron

Preface

This volume is a collection of original review articles resulting from the lectures presented at the *IVth Azores International Advanced School in Space Sciences* on

ASTEROSEISMOLOGY AND EXOPLANETS:
LISTENING TO THE STARS AND SEARCHING FOR NEW WORLDS
17–27 July 2016, Horta, Faial, Azores Islands, Portugal
Website: http://www.iastro.pt/research/conferences/faial2016/

This Advanced School was jointly organised by the *Instituto de Astrofísica e Ciências do Espaço – Universidade do Porto*, the *Universidade dos Açores* and the *University of Birmingham*. Its main goal was to address the topics at the forefront of scientific research being conducted in the fields of stellar physics and exoplanetary science, being mainly aimed at PhD and MSc students in any field of Astrophysics. The School was an excellent opportunity for the young researchers to network with fellow students and lecturers, thereby promoting awareness of areas outside the main specialisation of the student, and potential cross-fertilisation of techniques and concepts.

The School covered two scientific topics that share many synergies and resources: Asteroseismology and Exoplanets. Therefore, the program was defined with a clear strategy of building opportunities for cooperation and sharing of methods that will benefit both communities. This cooperation has experienced great success in the context of past space missions such as *CoRoT* and *Kepler*. Upcoming photometry and astrometry from space, as well as complementary data from ground-based networks, will continue to foster this cooperation. Observations of bright stars and clusters in the ecliptic plane are being made by the repurposed K2 mission, and NASA's *TESS* and ESA's *CHEOPS* missions will soon start obtaining similar data over the entire sky, thus allowing the detection and precise characterisation of planets around nearby stars. ESA's *PLATO* mission will then build upon these successes by providing photometric light curves on a wealth of stars. Ground-based spectroscopy from state-of-the-art instruments will complement the satellite data for the brightest stars in the sky. This includes projects such as the Stellar Observations Network Group (SONG) and a whole new generation of high-precision spectrographs being developed for the ESO, like the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO).

Lectures at the School included both a teaching and hands-on component, respectively consisting of a series of theoretical courses and tutorials. These were presented by a group of young, dynamic lecturers, who have already established themselves as leaders in their respective fields of research. This volume is then the collection of these lectures, covering in detail several critical methods and descriptions that are central to the School's two main thematic lines. As such, this volume constitutes a valuable and timely review that should prove useful to a new generation of PhD students and young postdocs in the fields of Asteroseismology and Exoplanets. We would like to thank all lecturers for accepting the challenge to take part in this School and for submitting the manuscripts for inclusion in this volume.

We are very grateful for the hard work and dedication invested by all participants in the School, in particular by the students, who have contributed to a very pleasant and friendly atmosphere (the evenings spent at Peter's shall never be forgotten!). A special thanks goes to the Chair of the Local Organising Committee, João Miguel Ferreira (Universidade dos Açores), for his dedication and thorough planning, and to Elsa Silva for her invaluable support over the entire duration of the School.

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March 2017

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