EXTRATERRESTRIAL SEISMOLOGY

Seismology, the study of waves traveling through a medium, is a highly effective tool for investigating the internal structure of the Earth. Similar techniques have also successfully been used to study other planetary bodies (planetary seismology), the Sun (helioseismology), and other stars (asteroseismology). Despite obvious differences between stars and planetary bodies, these disciplines share many similarities and together form a coherent field of scientific research.

This unique book takes a transdisciplinary approach to seismology and seismic imaging, reviewing the most recent developments in these extraterrestrial contexts. With contributions from leading scientists, this timely volume systematically outlines the techniques used in observation, data processing, and modeling for asteroseismology, helioseismology, and planetary seismology, drawing comparisons with seismic methods used in geophysics. Important recent discoveries in each discipline are presented along with the interdisciplinary work that underpins them.

With an emphasis on transcending the traditional boundaries of astronomy, solar, planetary, and Earth sciences, this novel book is an invaluable resource and reference for undergraduates, postgraduates, and academics.

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Preface

Stars and planetary bodies have a special place in our study of the universe. Identifying new planets and stars has a long history in astronomy, and studying their complex surface phenomena continues to be an important scientific endeavor in planetary science and astrophysics. With the advent of modern observational techniques and approaches to data analysis, it is now possible to probe their internal structure at increasingly high resolution and to monitor subtle changes in the deep interiors.

Indeed, having more accurate and detailed information about the stellar and planetary interiors helps us understand the evolution of stars and planetary bodies. Such information is invaluable for studying the links between subsurface structures and surface processes, too. Seismology is therefore central to our quests for understanding their interiors *and* surfaces. It provides a set of powerful and versatile tools capable of revealing the hidden phenomena inside the Earth, the Moon, and the Sun, amongst other stars, asteroids, planets, and their satellites.

Why extraterrestrial seismology?

In seismic studies, it is critically important to be able to relate any measurable or scientifically significant effects associated with seismic waves to the spatially varying physical properties in the subsurface. Research into the modeling of seismic sources and wave propagation in different stellar and planetary media has allowed scientists to build this foundation for imaging the interiors of stars and planetary bodies. Advances in the acquisition, processing, and modeling of seismic data as a whole have drastically improved the quality of the seismic images and information we have about the subsurface.

Encompassing both the theoretical studies of seismic phenomena and technical applications of seismic imaging developed over the past few decades, seismology is both a pure and an applied science. The pure and applied nature of seismology underpins many major breakthroughs across modern solid-earth planetary, and astrophysical sciences: the discovery of the Earth's and lunar cores, the presence of complex time-dependent differential rotation patterns of the solar interior, and the characterization of the inner radiative cores of red giants, to name but a few.

The development of seismic methods for studying this vast range of astrophysical bodies other than our own planet has naturally taken different paths. The approaches vary according to the physics pertinent to the targeted bodies, responding to and overcoming specific limitations in data acquisition as well as data quality and availability. Given the existence of gaseous and rocky planetary bodies of different sizes in the Solar System, it is perhaps not surprising that both the study of the seismic phenomena and the application of seismic imaging vary considerably within planetary seismology.

Solar seismology, or helioseismology, is different from planetary seismology in the sense that helioseismic analyses are based on the detection and analysis of changes in the electromagnetic radiation that the Sun emits. With the availability of ultra-high-resolution images of the visible solar surface, opportunities and challenges associated with the joint analysis of surface observations and seismic data in the solar context are as plentiful as they are unique.

Stellar seismology, or asteroseismology, builds on our understanding of the internal structure of the Sun and techniques developed by helioseismologists. However, the spatial resolution of the stellar phenomena that can be investigated in reality is vastly different from the solar ones, given the much greater distances between these stars and the Earth. Interestingly, the limited spatial resolution of seismic models of distant stars is compensated by the availability of seismic data from a large number of stars at different stages of their life cycles, resulting in the development of the statistical study of "ensemble" asteroseismology.

In other words, the development of stellar, solar, and planetary seismology is intricately linked to the nature of seismic sources, composition, and physical conditions of the stellar and planetary bodies. The distance between the Earth and the targeted body also affects the volume and quality of the seismic data available and hence the way to analyze and interpret them. Given these diverse flavors of planetary, solar, and stellar seismology, what is our rationale for grouping them under the umbrella of extraterrestrial seismology?

Despite the obvious physical differences between the targeted bodies, the methodologies used in the data processing and modeling share many similarities across the seismology spectrum. Challenges in the detection of seismic wave propagation and complex seismic resonance patterns are present in all seismic investigations. So are those related to the processing and inversion of seismic data with constraints from theoretical models and surface observations.

In order to acquire seismic data of the highest possible quality and with the optimal spatial coverage, extraterrestrial seismic studies require not only the development of state-of-the-art networks of ground-based telescopes but also pushing the frontiers of space science. From the development of nanosatellites to the launches of major multinational space missions, and from the incorporation of next-generation optical detector systems to the deployment of robotic seismologists to other planetary bodies, it is clear that scientists and engineers working in extraterrestrial seismology play a key part in driving the development of a wide range of subdisciplines in space science.

The very idea of extraterrestrial seismology does not imply that this collection of seismic disciplines bears few similarities with its terrestrial counterpart. In fact, earth seismologists also have to overcome difficulties and make technical advances in the acquisition, processing, and modeling of seismic data. Like extraterrestrial seismology, novel ways of analyzing seismic data are being developed for studying the Earth, with monitoring based on ambient seismic noise and high-resolution seismic imaging of ocean currents being two recent examples. Even space science has become part of the recipe in terrestrial seismology, with satellite data being used to monitor strong ground motions and to study deformations caused by earthquakes.

However, seismic investigations of other planetary and stellar bodies are still relatively young compared with terrestrial seismology, which has long been an established part of earth science. Generally speaking, planetary, solar, and stellar seismology are not featured regularly as a subject area in astrophysics or planetary science at undergraduate levels. In contrast, seismology has long been taught and prominently featured in undergraduate programs in geology and earth sciences. Furthermore, extraterrestrial seismic investigations do not (yet) have the immediate societal impact that many terrestrial seismic studies have in terms of natural hazards and commercial exploration of natural resources.

A cross-disciplinary subject space for research and education

We therefore believe that there is a strong case for creating a coherent "subject space" for research and education by drawing planetary seismology, helioseismology, and asteroseismology together. Sharing similarities in terms of methodologies, such as acquisition, processing, and modeling of seismic data, allows critical comparisons across disciplines that have been shaped by their own scientific priorities and traditions. This commonality in methodologies serves as an excellent context or even as a catalyst for both interdisciplinary research and education.

However, unfamiliar terminologies, conventions, and scientific contexts can present formidable barriers impeding possible cross-disciplinary exchanges between researchers, educators, and students, who may have different academic training and backgrounds. Moreover, as terrestrial, planetary, solar, and stellar seismologists are likely to be affiliated to different university departments and research institutes with different disciplinary focuses, the formation of a coherent research and education area of extraterrestrial seismology has hitherto been particularly challenging.

This volume is an important part of our efforts to create a new and accessible subject space for promoting cross-disciplinary research and education based on extraterrestrial seismology. This subject space has three cross-disciplinary dimensions:

1. The first part of the book highlights their commonalities and differences in research methodologies (Parts I to III). The aim is to encourage an understanding of *research methodologies in multidisciplinary contexts* by drawing attention to these key aspects of the research methods used across planetary, solar, and stellar seismology. These sections also serve as overviews to those who are new to the respective research approaches.

2. The part on scientific discoveries across planetary science and astronomy is aimed at highlighting *transdisciplinary findings* based on the use of extraterrestrial seismic methods. This part discusses how subsurface phenomena have been discovered and studied (Part IV), showcasing the immense contribution of extraterrestrial seismology to our study of the physical universe.
3. *Interdisciplinary research* involving other branches of planetary and astrophysical sciences (Part V) and studies incorporating terrestrial seismic methods (Part VI) are featured in the final parts of the book.

It is our wish to demonstrate the three cross-disciplinary aspects of this new exciting subject space, in order to facilitate exchanges of scientific ideas in explicit, helpful, and systematic ways. With an emphasis on the cross-disciplinary aspects, we do not intend to impose an overarching “discipline” of extraterrestrial seismology per se. In fact, we believe that thespectrum of seismology with inherently different conventions and scientific priorities should enrich this subject space for research and education.

The book comprises 26 chapters written by leading stellar, solar, planetary, and terrestrial seismologists currently based in 12 countries. In addition, following this preface, there are two short introductory articles with some personal thoughts on the development of planetary seismology (Mosser) and stellar-solar seismology (Christensen-Dalsgaard). The chapters are grouped under six parts, which are designed to provide a systematic survey of the multidisciplinary research methodologies, transdisciplinary findings, and interdisciplinary research.

The first part, entitled “Observation and space missions,” is about the acquisition of extraterrestrial seismic data. The chapters together showcase how state-of-the-art space science and ground-based observations lie at the heart of the data acquisition. The chapter on asteroseismology (Appourchaux and Grundahl) and the one on helioseismology (Pallé, Appourchaux, Christensen-Dalsgaard, and García) together show similarities and differences between observational techniques used for studying stars. In contrast to the remote sensing techniques used in stellar and solar seismology, Lognonné and Pike discuss the design and deployment of seismometers on the Moon, Mars, and other planetary bodies.

Part II is on the relationship between “data and physical parameters,” and the theme of the chapters in this part is to explore the crucial link between observations and information about the interiors of stellar and planetary bodies. These are explored in the stellar context (Kawaler) and are compared and contrasted between the Sun and solar-like stars (Chaplin and Howe). For the study of more local solar structure, Braun discusses in his chapter how helioseismic data can be analyzed. Nakamura reviews the links between data and models based on the landmark Apollo lunar experiments and the Viking experiments on Mars.

Building on the first two parts, Part III explores another multidisciplinary aspect of research methodologies – seismic data modeling. This is examined systematically in Aerts’ chapter on asteroseismic modeling, Rajaguru’s chapter in helioseismology with more mathematical details, and a comprehensive review that covers both lunar and martian seismology (Weber, Knapmeyer, Panning, and Schmerr).

Part IV comprises five chapters reviewing recent transdisciplinary discoveries in a diverse range of planetary and stellar contexts. They together underline the transdisciplinary power of applying seismic techniques to the study of a wide range of astrophysical bodies. The chapter by García and Stello shows how our knowledge of red giants has been dramatically enhanced by asteroseismology. Basu and Thompson review our understanding of the solar internal structure and dynamics based on the application of helioseismology. The local solar phenomena found relatively close to the Sun's visible surface are discussed in Sekii and Hiromoto's chapter. There are two chapters on planetary seismology, with a chapter on gaseous planets focusing on Jupiter's seismology (Gaulme, Mosser, Schmider, and Guillot) and one on our current understanding of the internal structure of the Moon (Knapmeyer and Weber).

The final parts of the book are on interdisciplinary research methodologies. Part V consists of eight chapters, showing exciting interdisciplinary developments in planetary and astrophysical sciences. Chaty's chapter on the new field of diskoseismology explains how matter accumulation under gravity can be exploited in seismic analyses. Kitiashvili reviews the use of numerical simulation in studying complex convection patterns in the solar interior and its links with solar seismology. Linking planetary seismology for both terrestrial and gaseous planets, a chapter by Lognonné and Kawamura introduces the field of impact seismology.

The next four chapters in Part V focus on solar and stellar phenomena and their links to seismology. The transport of angular momentum in stars during their evolution is explored in Brun and Mathis's chapter. By drawing on research progress in astrophysics, Christensen-Dalsgaard presents his suggestions for future research directions in stellar and solar seismology. The relationships between magnetic activity cycles and rotation patterns in stars are discussed in Mathur, Ballot, and García's chapter. Kosovichev's contribution investigates an important link between the solar interior and solar atmosphere: solar flares and helioseismic phenomena. Last but not least, the part ends with the contrasting branch of seismology: the seismic study of small bodies such as asteroids (Walker, Huebner, Bigger, Chocron, and Kirchdoerfer).

Part VI, the final one, is on interdisciplinary research linking terrestrial seismic methods and extraterrestrial seismology. The three chapters showcase the close relationships in research methodologies. The chapter on how models can be obtained by data inversion in solar and terrestrial contexts (Nolet) is complemented by Hanasoge's review on the use of cross-correlation in analyzing solar and terrestrial seismic data. The similarities and differences between seismic tomography based on studying seismic waveforms are compared and contrasted in the final chapter (Cobden, Fichter and Tong).

Interseismology: The book and beyond

Apart from creating this cross-disciplinary subject space, we endeavor to enhance the accessibility of the content to a wider readership beyond the science communities of both extraterrestrial and terrestrial seismology. This volume is not a textbook or a conventional edited research volume. Nor is it a collection of review articles written in journal styles. Instead, all the book chapters are relatively short overview articles featuring the chapter authors' perspectives on well-defined topics, contributing to the overall cross-disciplinary aims of the volume.

Most of the book chapters are written with minimum use of mathematical equations in this otherwise highly quantitative research area and do not assume specialist knowledge in the respective subjects. Equations are used to illustrate key scientific concepts and methods only, and the equations should therefore be useful to specialists and researchers who are interested in the mathematical description of the methodologies. Most chapters can therefore be readily used in undergraduate programs and courses in astrophysics, and planetary and earth sciences. Chapters on transdisciplinary findings (Part IV) are also suitable for use in non-seismology courses in physical sciences, including those at introductory levels.

Although there is some cross-referencing between book chapters, all chapters are essentially self-contained and can be read independently and in any order. This is particularly important for encouraging comparisons with different combinations of research methodologies and in different branches of extraterrestrial seismology. This format also allows the book to be used in university courses with different disciplinary (or even interdisciplinary) focuses and in flexible ways.

Inevitably there are overlapping topics and concepts that are relevant to a number of chapters. These commonly encountered concepts, such as "normal modes" and "tomographic inversion," are introduced by chapter authors in a way and to the level that are appropriate to the respective chapters. Comparing how these common concepts in seismology are introduced in different chapters may indeed be part of enhancing multidisciplinary understanding of the research methodologies.

Linked content is available on the publisher's dedicated webpage for the book. As part of our efforts to create the cross-disciplinary subject space, there is an associated project with multimedia research content and educational material about extraterrestrial seismology and its links to terrestrial seismology. Here is the web address for the Interseismology Project:

interseismology.org

It is a place for researchers and educators, including the chapter authors, to promote interdisciplinary dialogues and understanding in seismology. The website offers a dedicated platform to reach out to other branches of seismology and the wider physical sciences community about their work in a coherent subject space.

We hope that this book, together with other resources in the Interseismology Project, will be useful to you as well as to our colleagues and students in the earth, planetary, and astrophysical science communities. We would like to thank all our chapter authors for their immense contribution to this book project with their invaluable insights in a fast-developing subject, as well as their efforts into reviewing other book chapters.We are enormously grateful to Dr Emma Kiddle, Rosina Piovani, Zoë Pruce, Bronte Rawlings, Emily Trebilcock, and Martin Tynan at Cambridge University Press for their extremely generous support, help, and advice throughout this book project. We would like to thank

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Abbreviations

ACRIM	active cavity radiometer
AMP	Asteroseismic Modeling Portal
ASE	Active Seismic Experiment
ASLEP	Apollo Lunar Surface Experiment Package
asteroFLAG	Astero Fitting at Low Angular degree Group
ATHENA	Advanced Telescope for High ENergy Astrophysics
BiSON	Birmingham Solar Oscillation Network
CCD	charge-coupled device
CFHT	Canada France Hawaii Telescope
CME	coronal mass ejection
CNES	Centre National d'Etudes Spatiales
CoRoT	Convection Rotation and planetary Transits
CV	cataclysmic variable
CZ	convection zone
EASEP	Early Apollo Surface Experiment Package
EIS	Extreme-ultraviolet Imaging Spectrometer
EOS	equation of state
ESA	European Space Agency
ESO	European Southern Observatory
EVRIS	Etude de la Variabilité, de la Rotation et des Intérieurs Stellaires
FD	finite difference
FFT	fast Fourier transform
FT	Fourier transform
FTS	Fourier transform spectrometry
GEMINI	Green function of the Earth by MINor Integration
GOES	Geostationary Operational Environmental Satellite
GOLF	Global Oscillations at Low Frequencies
GONG	Global Oscillation Network Group
GRB	gamma-ray burst
HARPS	High Accuracy Radial velocity Planetary Search
HFT	high-frequency teleseism

HMI	Helioseismic and Magnetic Imager
HMXRB	high-mass X-ray binary
HR	Hertzsprung–Russell
IRIS	International Research on the Interior of the Sun
IRTF	Infrared Telescope Facility
ISCO	innermost stable circular orbit
JUICE	JUpiter ICy moon Explorer
KASC	Kepler Asteroseismic Science Consortium
LES	large eddy simulation
LM	Lunar Module
LMXRB	low-mass X-ray binary
LOFT	Large Observatory For X-ray Timing
LOI	Luminosity Oscillations Imager
LP	long period
LRO	Lunar Reconnaissance Orbiter
LSG	Lunar Surface Gravimeter
LSPE	Lunar Seismic Profiling Experiment
MCMC	Markov chain Monte Carlo
MDI	Michelson Doppler Imager
MHD	magnetohydrodynamic
MOF	magneto-optical filter
MOST	Microvariability and Oscillations of Stars Telescope
NASA	National Aeronautics and Space Administration
OGLE	Optical Gravitational Lensing Experiment
OHP	Observatoire de Haute Provence
OLA	optimally localized averages
OPD	optical path difference
PDS	power density spectrum
PLATO	PLAnetary Transits and Oscillations of stars
PRISMA	Probing Rotation and Interiors of Stars: Microvariability and Activity
PRNU	pixel-to-pixel response non-uniformity
PSE	Passive Seismic Experiment
QPO	quasi-periodic oscillations
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RLS	regularized least squares
RXTE	Rossi X-ray Timing Explorer
SCLERA	Santa Catalina Laboratory for Experimental Relativity by Astrometry
SDO	Solar Dynamics Observatory
SEIS	Seismic Experiment for Interior Structure
SEM	spectral element method
SL9	Shoemaker–Levy 9 comet
SMBH	supermassive black hole

SOHO	Solar and Heliospheric Observatory
SOI	Solar Oscillation Investigation
SOLA	subtractive optimally localized averages
SP	short period
SPICE	Seismic wave Propagation and Imaging in Complex media: a European network
SSM	standard solar/stellar model
TESS	Transiting Exoplanet Survey Satellite
VBB	very broad band
VIRGO	Variability of Irradiance and Gravity Oscillations
WIRE	Wide Field Infrared Explorer
WPP	Wave Propagation Program
XRB	X-ray binary
YSO	young stellar object
ZAMS	zero-age main sequence