Preface

Context

Astronomy covers numerous aspects of physics and mathematics across many orders of magnitude in size, from the quantum mechanical laws that determine nuclear fusion reactions in the centre of a star, to the dynamics of galaxy clusters over cosmological distances. Astronomy studies the smallest and largest known structures in the universe and the physical laws that govern them. Over the last century, a general description of stellar structure and evolution has been developed. However, the inclusion of physics such as rotation, binarity, pulsation and magnetic fields causes stellar structure and evolution to become more complicated.

Using traditional observational techniques such as photometry and spectroscopy, one barely scratches beneath the visible surface of a star, because these methods are only sensitive to the stellar atmosphere. Until the advent of asteroseismology, astronomy lacked the techniques to validate or invalidate theoretical predictions of the interior conditions of a star through observation and experimentation. This is famously encapsulated by the text *The Internal Constitution of the Stars* published in 1926 by Sir Arthur Stanley Eddington, who asked the following questions:

> "*At first sight it would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region in the universe. 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 behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?*"

Asteroseismology is the tool that Eddington sought, which provides direct insight into the interior of a star by studying its oscillations. The pulsations within an oscillating star are governed by the physics of stellar structure, so from observations and analysis of these pulsations the interior properties of a star can be measured. Many different types of pulsator have been discovered, including our nearest stellar neighbour—the Sun. Its proximity has allowed the Sun to be extensively studied since the discovery of its oscillations in the 1960s. Asteroseismology has rapidly expanded in recent years because of improvements in

instrumentation and has been applied to many types of stars across a wide range in stellar mass and for different stages of stellar evolution.

Motivation

This monograph is centred on a group of variable stars called δ Sct stars, which are the most common type of pulsator among the intermediate-mass A and F stars, and have been studied since their discovery in the early twentieth century. Historically, using several hours of ground-based observations, these variable stars were straightforward to classify because they have similar effective temperatures and pulsate with periods of order hours and minutes.

Prior to the twenty-first century, only a handful of δ Sct stars had been extensively studied using ground-based campaigns, which provided intermittent observations with duty cycles typically less than 50 per cent. These investigations were limited by the data coverage and precision of the instrumentation used, but revealed that we lack a complete physical description of these pulsators, primarily because of the diversity of observed pulsations in these stars. A few δ Sct stars were found to exhibit a phenomenon called amplitude modulation—in the time domain this appears as a change in the maxima and minima of the light excursions over time, and in the Fourier domain this appears as variable pulsation mode amplitudes.

Naturally, this causes problems for intermittent observations over a few days if the pulsation mode amplitudes of a variable star change on timescales of order years to decades. From only a few in-depth studies, it was not clear what determines this effect in δ Sct stars, as not all stars exhibited such behaviour. This provides strong motivation to study amplitude modulation in δ Sct stars further. The space-based telescopes CoRoT and *Kepler*, which were launched in 2006 and 2009, respectively, have led to a photometry revolution. The *Kepler* Space Telescope provided a large increase in high-quality observations of hundreds of thousands of stars, including many δ Sct stars, which form the basis of this research text.

Overview

This monograph addresses Eddington's questions by using asteroseismology to expand our understanding of δ Sct stars and studies the incidence of amplitude modulation in approximately 1000 δ Sct stars observed by the *Kepler* Space Telescope. In the original edition of this thesis, the peer-reviewed journal papers by the author were included as they were published, but in this monograph they have been discussed as part of the literature. As a second edition, much of the content is the same, although it has been updated and expanded upon since the original work was published. The general theme of this text is the journey through the discoveries that were made throughout the work.

The pulsations in δ Sct stars are excited by a heat engine driving mechanism caused by increased opacity in their surface layers and have pulsation periods of order a few hours. Observations from the *Kepler* Space Telescope have revealed a diverse range of pulsational behaviour in these stars, which has been investigated using an ensemble of 983 δ Sct stars that were observed continuously for four years at an unprecedented level of photometric precision. A search for amplitude modulation in these stars showed that the majority exhibit amplitude modulation in at least a single pulsation mode. Thus, timescales of years and longer are significant in these stars both observationally and theoretically. The various causes of amplitude modulation include beating, non-linear mode coupling and stellar evolution, each having a characteristic pattern that must be recognised and disentangled to truly understand the physical processes occurring within a star. The observational studies of individual stars in this monograph provide strong evidence that non-linear processes are clearly at work in the many δ Sct stars and provide valuable constraints for future asteroseismic modelling.

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