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Mechanisms of Chromospheric and Coronal Heating

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With 260 Figures

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Cover picture: In this scenario by Chitre and Davila (see the article on p. 402 of this book) acoustic waves shake coronal magnetic loops and get resonantly absorbed in the loop.

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Preface

The plans for the Heidelberg Conference *Mechanisms of Chromospheric and Coronal Heating*, held from June 5 to 8, 1990, materialized during several discussions between Eric Priest, Robert Rosner, Peter Ulmschneider, and later Jeff Linsky at meetings in Titisee and Tenerife in 1987 and 1988, in which we all realized that, despite the extensive work in the field, our understanding of the physics of stellar chromospheres and coronae, the sources of stellar radio, UV and X-ray emission, and stellar winds remains in a dismal state.

The principal reason for this is that the fundamental physical process – the mechanical heating mechanism, which is the cause of these important stellar layers – is still largely unknown, 50 years after W. Grotrian and B. Edlén discovered that the solar corona is hot by identifying the source of the 6374 Å line as Fe X, and 45 years after L. Biermann proposed the first coronal heating theory. We appreciated that the identification of the heating mechanism is a formidable observational problem because it involves very small spatial scales, possibly down to (for current sheets) thicknesses in the meter range, and far beyond even the most sophisticated present instrumentation.

This observational difficulty is complemented by severe problems on the theoretical side. The many very complicated heating theories, most of which derive from terrestrial plasma and MHD applications, cannot be adequately simulated at present even with the most advanced supercomputers. Moreover, it is not well understood whether these (primarily) fusion-physics-related applications are in fact suitable for stellar environments. Yet worse, there has been an apparent lack of contact between the many researchers in the field of stellar atmospheric heating, who often laboured exclusively on their own favoured heating mechanism and disregarded the work of their colleagues or of the observers. (This sort of behaviour is of course not only characteristic of stellar astronomers!)

These realizations led to the idea of organizing a meeting devoted entirely to the topic of atmospheric heating, where for the first time a comprehensive inventory of our knowledge of heating mechanisms could be made, and where disparate workers could learn about the wide scope of the field and about the new observations. The present book is the result of this effort. We leave it to the reader to judge how well we have succeeded. But even if this book fails our expectations, it nevertheless reveals the exciting new plans to use large-scale numerical simulations and fascinating new instrumentation to attack the formidable heating problem.

Our most sincere thanks go to the other members of the Scientific Organizing Committee, to Lawrence Cram, Joe Hollweg, Jeff Linsky, Dan Spicer, Giuseppe

Vaiana, Yuzef Zhugzhda, and Cornelis Zwaan for help in the selection of the speakers. We also very warmly thank the Local Organizing Committee for the smooth organization, particularly Bodo and Elke Baschek, Hans-Peter Gail, Darren Kelly, Peter Korevaar, Helgard and Katharina Ulmschneider, and Rainer Wehrse. The support by the Max-Planck-Institut through Hans Elsässer, which offered to house the conference, is gratefully acknowledged. These thanks also extend to the Institut für Theoretische Astrophysik, where Werner Tscharnuter gave us all the support we needed. We are especially grateful to the Deutsche Forschungsgemeinschaft, to the State of Baden-Württemberg, and particularly to Dr. Theodor Mayer, Firma Bessey, for generous provision of funds.

Heidelberg, *Peter Ulmschneider, Eric Priest, Robert Rosner*
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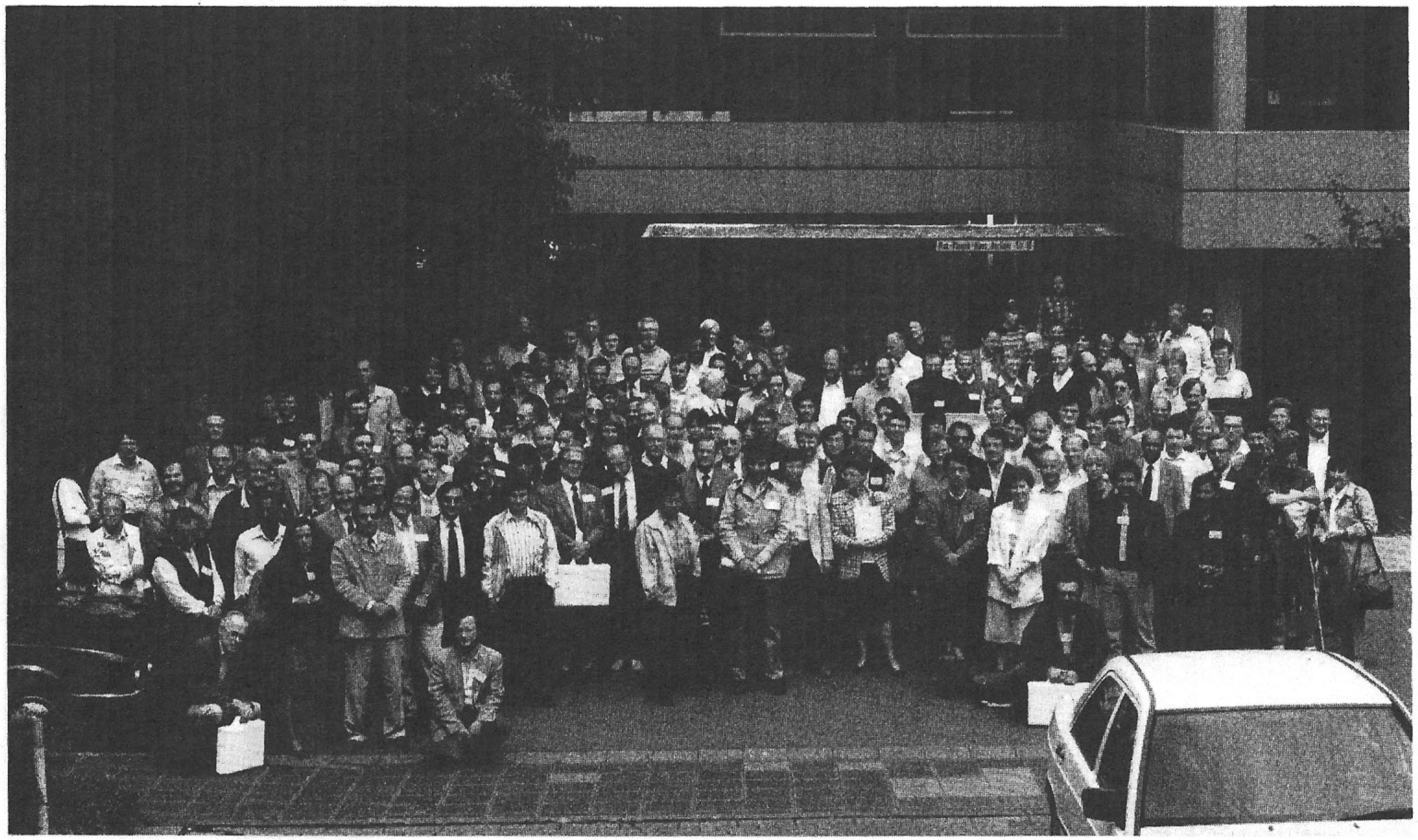

International Heidelberg Conference *Mechanisms of Chromospheric and Coronal Heating,* June 5–8, 1990, in front of the Max-Planck-Haus, Berlinerstr. 10

Introduction

Over the past few years it has become clear that the heating phenomenon in chromospheres and coronae very likely cannot be explained by a single process alone, but is rather due to a *multitude of mechanisms*. Some of these mechanisms operate globally, others only in particular physical situations or in very special magnetic field geometries. At the present time, it is not possible to decide which mechanisms are the important ones. This is due to the relatively primitive theoretical development of many mechanisms, and to the paucity of definitive observational tests which are capable of deciding between alternative mechanisms, or of testing specific predictions of particular mechanisms. This book is devoted to an exposition of the observational and theoretical work on stellar atmospheric heating which is pursued today, as propounded by the scientists conducting this research. As a consequence, the reader will not find here an exhaustive compendium of all possible such heating processes, but rather only discussions of those mechanisms which have survived the challenges of past observational tests (the interested reader will find a more extensive review, based on the published literature up to mid-1989, in Narain and Ulmschneider, *Space Science Reviews*, to appear 1990).

A reader entirely unfamiliar with the subject of this book might be excused if he or she obtains the impression that virtually nothing is known for certain in the field of chromospheric and coronal heating. For this reason, it might be useful to make some comments about the past evolution of the field.

To begin with, the past decade has seen a dramatic change in our view of what the heating problem is all about. At the end of the 1970s, solar observations had already shown that magnetic fields must play a significant role in (at least) coronal heating, but it was not yet clear that the solar problem was extendable to other stars. With the flight of HEAO-1, and especially the *Einstein* Observatory and the *International Ultraviolet Explorer*, it became clear by the beginning of the 1980s that mechanical heating of the outer layers of stars is a general phenomenon. Indeed, these observations, together with data from solar observations by OSO-8, finally definitively excluded the damping of classic acoustic waves as a viable *coronal* heating process. This produced a profound change in the cast of theorists working on the heating problem: There was a continued influx of plasma physicists trained in fusion research, who focussed their attention on the heating problem as yet another instance of plasma heating. The magnetic field was now seen as *the* key player, whereas before magnetic fields were viewed by most (not all!) researchers as a (possibly annoying) secondary complication.

This change in perspective, and in the style of carrying out the research, is very much in evidence here: Most (if not all) of the coronal heating processes discussed here are related to magnetic fields in one way or another (but see below); and the level of sophistication with which the heating problems are discussed has far more the flavor of physics discussions rather than of astronomy. A measure of the impact made by the idea that magnetic fields play the central role in coronal heating is that theorists interested in the chromospheric heating problem must today defend themselves if they do *not* place magnetic fields at the center of their theories – this despite the fact that observations of both the Sun and other late-type stars give abundant evidence that (at least) the "quiet" chromosphere is heated by mechanisms having little to do with magnetic fields. In particular the acoustic wave heating has been rediscovered in the last few years and appears now a very likely method for heating the nonmagnetic regions of stars.

In any case, the level of sophistication that heating theories now aim for is a clear reflection of the level of detail which observations – especially observations of the Sun – can now give us; and the prospect of yet more exacting observational constraints which the instruments on SOHO and SOLAR-A, as well as on the more remote projects such as the Orbiting Solar Laboratory

(OSL), will give us, is clearly inspiring much new, detailed work. Similarly, the enormous increase in available data on stellar coronae which ROSAT is now giving us is bound to lead to new constraints on heating processes: If nothing else, the resulting large stellar data base will contain statistically useful information about the extremes of coronal behaviour, information which eluded us previously because of the relatively small sample sizes. Thus, while we are unlikely to see, for example, nanoflares directly resolved within the next decade, we most likely will be able to constrain the flux of Alfvén waves in the solar atmosphere, and thus at minimum to finally provide a direct observational test of the mechanism underlying the acceleration of the solar wind.

In order to provide somewhat more guidance to the reader, we provide below an essentially annotated table of contents, which gives an account of the organization of this book, and of the basis on which this organization was carried out.

1. The observations

Observations are the prime source of our knowledge of the existence of heating processes in stellar atmospheres, and ultimately must also be the means by which we distinguish among the various proposed mechanisms by testing their specific predictions. Because of the great differences in spatial, temporal, and spectral resolution, we have classified the observations in a somewhat arbitrary manner in two broad categories: *solar observations* and *stellar observations*, corresponding to the first two chapters of this book.

The first chapter, **Solar Observations** is organized as follows. In Ch. 1.1 we compile the observations of oscillations and waves, which are the signatures of the wave-like (alternating current: AC) energy input in the outer solar atmosphere. Ch. 1.2 describes the observations of the photospheric dynamics which, through the slow (direct current: DC) footpoint motion, leads to a buildup of magnetic energy. Ch. 1.3 summarizes the chromospheric observations, with controversial opinions on the nature and heating of the chromospheric bright points and with a discussion of proposed new instruments. Ch. 1.4 discusses the chromosphere-corona transition layer observations, including the spicule and microflare phenomena, and outlines the difficulties which we still have in understanding this region, which is characterized by very rapid change in temperature over small distances. Ch. 1.5 gives an overview of the coronal and solar wind observations and modeling; it also discusses the first results of the new NIXT experiment by Leon Golub, the normal incidence X-ray telescope which gave us the breathtaking photo shown as our frontispiece.

In the second chapter, **Stellar Observations**, we first review the heating-related chromospheric and coronal observations which are derived mainly from the UV. Ch. 2.2 summarizes the observations and the modeling of cool giants, together with the infrared observations. The intimate relation between the chromospheric and coronal activity and the magnetic field is discussed in Ch. 2.3. Ch. 2.4 summarizes the coronal heating constraints, and particularly discusses the X-ray observations. It shows that the heating question must also be considered in the investigation of early-type stars and of accretion disks.

2. The heating mechanisms

Based on the mechanical energy input, the various chromospheric and coronal heating processes can be broadly classified as *wave mechanisms* and *electrodynamic mechanisms*, corresponding to the last two chapters of this book. The wave mechanisms comprise acoustic waves, fast and slow magnetoacoustic waves, and Alfvén waves. The magnetohydrodynamic (MHD) waves can be both body and surface waves. Waves in late-type stars are excited by fast turbulent motions near the top of the convection zone, by small-scale instabilities, or by mode-coupling with other waves. The electrodynamic mechanisms include current dissipation, both in loops and in arcade systems resulting from large-scale magnetic flux emergence, and locally in micro/nanoflares. Here the energy is introduced into the magnetic field by slow convective motions of the photospheric foot points, or by buoyancy.

The third chapter, on **Wave Heating Mechanisms**, is subdivided as follows. In Ch. 3.1 we discuss planar acoustic waves, as well as acoustic waves in tubes (as may be relevant for the spicule problem). Ionization pumping and radiative amplification are important effects for acoustic waves. The acoustic and MHD wave energy generation by turbulent motions in the convection zone is summarized in Ch. 3.2 both from the general perspective as well as from the more specific perspective of 2D granular convection simulations. Ch. 3.3 discusses fast and slow MHD waves and longitudinal MHD tube waves. The generation, propagation, and damping of Alfvén waves are discussed in Ch. 3.4; particular emphasis is placed in the damping processes, including phase-mixing, resonant absorption and propagation in stochastic magnetic fields. Ch. 3.5 is dedicated to magnetoacoustic and Alfvén surface waves.

In the fourth and last chapter, **Electrodynamic Heating Mechanisms**, we first devote an extensive section (Ch. 4.1) to the formation of current sheets, both in large-scale arcade systems and in loops. The relation of heating and helicity is summarized in Ch. 4.2; and in Ch. 4.3 are discussed two- and three-dimensional magnetic reconnection and the heating by large-scale magnetic flux emergence. Finally, the micro and nanoflare heating mechanisms are discussed in Ch. 4.4.