

ASTRONOMICAL MASERS

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by

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To my wife, Shlomit, for her understanding and companionship,
and to my sons, Ofer, Haggai, and Ben.

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PREFACE

In the last two decades, the study of astronomical masers has made dramatic advances. Once a rather narrow field of interesting physics but limited applications, maser studies have now emerged as a powerful probe of small scale structure, dynamics and physical conditions in many astronomical environments. These advances have been driven by complementary contributions from observers and theorists, the former greatly aided by continuing progress in very long baseline interferometric (VLBI) techniques. With the completion of the VLBA network, and with the prospect of space VLBI observations in the next decade, progress in maser studies can only accelerate in the foreseeable future. These factors no doubt influenced the decision of Reidel (now Kluwer Academic Publishers) to commission this textbook on astronomical masers.

This book is primarily intended for graduate students embarking upon research in astronomy, and this consideration greatly influenced the selection of material and the order of presentation. The most difficult problem posed by these choices is circularity: certain issues cannot be discussed before some concepts have been clarified, and these cannot be introduced without first establishing the proper context. The order of the chapters reflects my attempts to solve this problem. Also, the coverage of many of the basic concepts involved in the analysis of molecular lines in general and masers in particular is scattered throughout the literature. Chapter 2 attempts to address this problem by providing a comprehensive coverage of the fundamentals of line formation in interstellar clouds. I have had the opportunity to use this chapter twice in the teaching of graduate courses and to incorporate student comments and suggestions. In addition, P. Lockett, who was completing his Ph.D. thesis with me during the writing of this text, provided many useful suggestions (as he did on a number of other chapters). After a study of Chapter 2, a student should be ready to tackle research problems involving line formation.

To the greatest extent possible, the emphasis of the presentation is on practical applications rather than formal developments. However, discussion of some formal material is unavoidable in an area where unique physical effects are an essential part of the phenomena studied. Topics of a more formal nature are assembled into separate sections, marked with a dagger sign[†]. These sections can be skipped by readers mainly interested in practical applications. To help the flow of the presentation, some technical developments are left to the problems, which are an integral part of the text and contain many essential results. Problems should be considered part of the presentation and should be read even if a solution is not attempted. Most problems are phrased in the style "show that..." and contain their own solutions.

Texts on active research topics always risk being overtaken by rapid developments and new discoveries. This book is no exception. The manuscript was completed in December, 1990, and it reflects the status of the field at that time. As can be expected, in the relatively short time since that completion date a number of significant developments have already occurred. Two stand out in particular. The

first is the discovery by A. W. Clegg and J. M. Cordes (*Ap. J.* **374**, 150, 1991) of fluctuations with time scales of minutes to an hour in maser emission from Galactic HII/OH regions (these sources are discussed in sections 8.3 and 9.3). This discovery raises fundamental questions about the generation of astronomical maser radiation and, if verified, may provide a new probe of very detailed properties of the source environments (M. Elitzur, *Ap. J. Lett.* **370**, L45, 1991). The second development is the discovery by K. M. Menten (*Ap. J. Lett.* **380**, L75, 1991) of a new, strong methanol maser transition at 6.6 GHz. Except for the H₂O maser at 22 GHz, this line provides the strongest maser emission observed to date. An opening sentence of Chapter 12 states that methanol "shows the promise that it will soon join the three 'classical' masers OH, H₂O and SiO as equally important". Obviously, the basic approach to the classification of the various maser molecules taken in this book became dated before the book even went to press.

In preparing this text, I have greatly benefited from the generous help and assistance of numerous people. G. Kiers of Kluwer Academic Publishers brought competence and professionalism to the technical overseeing of this project. T. Troland was always there with advice on the inner workings of the English language. Many colleagues provided invaluable scientific help, in particular W. A. Baan, M. M. Litvak, K. M. Menten, C. M. Walmsley and T. L. Wilson. Special thanks to D. Downes and J. M. Moran for their careful reading of the entire manuscript and the perceptive comments and suggestions they provided.

Above all, I am deeply indebted to my collaborators D. J. Hollenbach and C. F. McKee. The many discussions and arguments we have had (quite heated at times) were instrumental in clarifying many of the intricacies and subtleties of maser theory. The different perspectives each one of us brought to our common deliberations invariably resulted in deeper understanding. I hope the insight gained in those sessions is reflected in the presentation offered here.

Last, and most important, I thank my wife, Shlomit. Without her patience and understanding I could not have completed this undertaking.

Moshe Elitzur

Lexington, KY
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