Steven W. Stahler and Francesco Palla

The Formation of Stars

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The Rosette Nebula in Monoceros. Massive young stars in the central cluster have cleared a hole in the cloud. Ionizing radiation from these stars causes surrounding gas to glow brightly.

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to our families

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Preface

While there has long been theoretical speculation concerning the early life of stars, the subject first became an empirical one in the middle of the last century. Starting in the 1940s, the T Tauri class of objects, residing within dark clouds, was recognized and subsequently examined in considerable detail. This interest stemmed from the gradual realization that these peculiar variables represent a primitive phase of solar-type stars. It also became apparent that the observed objects must have condensed out of the dark clouds in which they are presently still found. By the mid 1950s, theorists began constructing numerical models for the pre-main-sequence evolutionary phase. The following decade saw advances in understanding the basic physics of cloud collapse.

The pace of discovery accelerated rapidly in the 1970s, largely as a result of new instrumentation. The advent of infrared astronomy allowed observers to peer behind the thick veil of obscuring dust and view even younger objects. Millimeter dishes, X-ray telescopes, and sensitive array detectors in the optical and near-infrared all had major impacts. Meanwhile, theoretical research kept apace, with studies of everything from chemical reaction networks in cloud environments to the interiors of the youngest stars. By the 1980s, star formation became one of the most vigorous areas of astronomical research.

There has been no sign of abatement in this activity. Indeed, parallel developments in other areas have underscored the central importance of the problem of star formation. Since the mid 1990s, observers have detected large numbers of giant planets encircling nearby stars. The properties of these systems range widely and call out for a more general understanding of the planet formation process. These bodies arise from dusty, circumstellar disks, which themselves appear during cloud collapse. Thus, a full account of planetary origins cannot ignore the early evolution of the central, stellar object.

Equally relevant are contemporary advances in cosmology. Numerical simulations of the last few decades follow the condensation of gas inside clumps of dark matter spread throughout the expanding Universe. This gas ultimately converts itself into stars. We can even track observationally the record of this transformation in both nearby and ancient, far-off galaxies. The pattern of star formation in a galaxy is a fundamental characteristic, one that correlates with, and in some measure determines, its observed structure. What had traditionally been viewed as a local phenomenon is now appreciated as a truly global one.

In the midst of such ongoing interest and progress, there is evidently a need to summarize the state of our knowledge and the pressing, unsolved questions. A number of excellent textbooks already cover the physics and chemistry of the interstellar medium, out of which stars are born. Equally well represented is the theory of stellar structure and evolution. Planetary science and galaxy formation have long been part of the standard curriculum. Still lacking, however, is a comprehensive treatment of the area touching all of these, the formation of stars themselves.

Any work attempting to encapsulate a rapidly evolving field must face the issue of timeliness. Won't any "facts" we present become outdated very quickly? The answer very much depends on the type of information conveyed. In the decade since we began this collaborative effort, it is certainly true that there have been many exciting discoveries. There is a core of

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understanding, however, that has remained substantially intact. To put the matter succintly and somewhat glibly: Pictures and numbers indeed change rapidly; ideas do not.

This, then, is primarily a book about the ideas of star formation. Developing and illustrating these ideas has often required detailed exposition. This necessity, along with the sheer breadth of the field, has resulted in a much thicker volume than we originally anticipated. We ask the reader to be patient, trusting that the journey is worth some time and effort.

Two major hurdles confronted us at the very outset of the project. First was the daunting task of collecting a vast amount of research results on many diverse topics. As one collects, one also evaluates. Facts we had assumed were "well known" within the community often turned out, upon scrutiny, to be either wrong or to require significant qualification. Note also that we were not able to amass information through the time-honored method of constructing or borrowing from lecture notes in a star formation course. We stress that it was the very lack of such a course at our own and other institutions that provided an initial motivation for writing this work.

A second, and related, difficulty we faced was organizing all of this material in a logically compelling manner. Our solution here has been to group similar chapters into Parts. The ordering of these six Parts then dictates the overall flow of the narrative. We thus start from a general description of stars and their birth environments (Part I), before proceeding to a more detailed look at physical processes occurring within interstellar clouds (Part II). Part III spans the critical transition from clouds to stars. We describe the possible equilibrium configurations of clouds, and how these structures are disrupted through collapse. We also examine the primitive stars built up within the smallest collapsing entities. The profound thermal and mechanical effect of young stars on their surroundings is the subject of Part IV. In Part V, we see how stars, once divested of their cloud gas, evolve to maturity. Finally, the two chapters of Part VI return to a larger-scale view. Chapter 19 describes star formation activity in local galaxies and beyond, while Chapter 20 summarizes briefly our progress toward understanding key issues in the field.

We have aimed this book nominally at the level of graduate students in physics and astronomy. The complete text contains far more material than can be digested in a single semester. As a guide to the instructor, we list here the chapters and sections we consider most essential. We also suggest the time that could be devoted to each Part, assuming a 15-week course with 3 lecture hours per week.

Part	Weeks	Chapter/Sections
I	2	1; 2; 3; 4.1–4.3, 4.5
II	2	5.1–5.3; 6.1–6.2; 7; 8.1–8.2
III	4	9.1, 9.4–9.5; 10.1–10.2, 10.4; 11.1–11.3, 11.5; 12.1–12.3
IV	2	13.1–13.2; 14.1–14.2; 15.1–15.2,15.5
V	4	16.1–16.4; 17.1–17.3,17.5; 18.1–18.2, 18.4–18.5
VI	1	19.1–19.3; 20

Our book should also serve as a reference for professional researchers. This latter group will observe that we have *not* simply compiled all of the currently popular models in each topic. We have instead selected interpretations that fit best into the broad story of star formation, as we understand it. Some aspects of this story will undoubtedly change in the coming years. We nevertheless feel that anyone trying to master the subject is best served by a unified, coherent presentation. Whoever wishes to follow more closely the underlying debates or to acquire historical perspective on any topic will want to consult key research and review articles, many of which are cited as Suggested Reading at the end of each chapter.

As preparation, the prospective reader should have a solid background in physics at the undergraduate level. We do not assume similar training in astronomy. Many basic astronomy results, as well as much of its terminology, are presented within the text. Indeed, the study of star formation itself provides a good introduction to astrophysical concepts, simply because of the great variety of topics embraced by the field. In this context, the student should be comfortable with both theoretical arguments and observational results. Note that we have not shied away from describing observations for which no adequate model exists. To our minds, these results are among the most interesting, as they represent areas where fundamental progress can be made.

Over the years, we have received generous help and advice from many individuals. It is a pleasure to acknowledge them. We are indebted to Amanda McCoy for her tireless effort in producing hundreds of figures. Kevin Bundy read the entire manuscript and offered invaluable commentary on both the scientific content and the manner of its presentation. Eric Feigelson used a preliminary version of the book in a one-semester course; we are grateful to Eric and his students at Penn State for their comments and corrections. Others who reviewed selected chapters include Gibor Basri, Peter Bodenheimer, Jan Brand, Charles Curry, Daniele Galli, Dave Hollenbach, Richard Larson, Gary Melnick, Karl Menten, Mario Pérez, Steve Shore, and Hans Zinnecker. We have also benefited from discussions with Philippe André, Leo Blitz, Paola Caselli, Riccardo Cesaroni, Tom Dame, George Herbig, Ray Jayawardhana, Chung-Pei Ma, Thierry Montmerle, Antonella Natta, Sean Matt, Maria Sofia Randich, Leonardo Testi, Ed Thommes, Malcolm Walmsley, and Andrew Youdin.