

## COMBUSTION WAVES AND FRONTS IN FLOWS

Combustion is a fascinating phenomenon coupling complex chemistry to transport mechanisms and nonlinear fluid dynamics. This book provides an up-to-date and comprehensive presentation of the nonlinear dynamics of combustion waves and other non-equilibrium energetic systems. The major advances in this field have resulted from analytical studies of simplified models performed in close relation with carefully controlled laboratory experiments. The key to understanding the complex phenomena is a systematic reduction of the complexity of the basic equations.

Focusing on this fundamental approach, the book is split into three parts. Part I provides physical insights for physics-oriented readers, Part II presents detailed technical analysis using perturbation methods for theoreticians and Part III recalls the necessary background knowledge in physics, chemistry and fluid dynamics. This structure makes the content accessible to newcomers to the physics of unstable fronts in flows, whilst also offering advanced material for scientists who wish to improve their knowledge.

PAUL CLAVIN is Professor Emeritus at Aix-Marseille Université and is an honorary member of the Institut Universitaire de France (Chair of Mécanique Physique 1993–2004). In 1995 he founded a renowned research institute, the Institut de Recherche sur les Phénomènes Hors Équilibre (IRPHE), and has received major awards from the Société Française de Physique (Plumey 1988), French Academy of Sciences (Grand Prix 1995) and the Combustion Institute (Zeldovich Gold Medal, San Francisco, August 2014).

GEOFF SEARBY is retired Director of Research at the Institut de Recherche sur les Phénomènes Hors Équilibre (IRPHE). He is a renowned specialist of the physics of thermo-acoustic instabilities in combustion chambers and rocket motors, and his experiments have made major contributions to the understanding of the dynamics of flame fronts. In 2004 he obtained a major award from the French Academy of Sciences.

Cambridge University Press & Assessment

978-1-107-09868-8 — Combustion Waves and Fronts in Flows

Flames, Shocks, Detonations, Ablation Fronts and Explosion of Stars

Paul Clavin , Geoff Searby

Frontmatter

[More Information](#)

# COMBUSTION WAVES AND FRONTS IN FLOWS

Flames, shocks, detonations, ablation  
fronts and explosion of stars

PAUL CLAVIN

*Aix Marseille Université, France*

GEOFF SEARBY

*Formerly of the Centre National de la Recherche  
Scientifique (CNRS), Marseille, France*



CAMBRIDGE  
UNIVERSITY PRESS

Cambridge University Press & Assessment  
 978-1-107-09868-8 — Combustion Waves and Fronts in Flows  
 Flames, Shocks, Detonations, Ablation Fronts and Explosion of Stars  
 Paul Clavin, Geoff Searby  
 Frontmatter  
[More Information](#)



CAMBRIDGE  
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom  
 One Liberty Plaza, 20th Floor, New York, NY 10006, USA  
 477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
 314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India  
 103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,  
 a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of  
 education, learning and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9781107098688](http://www.cambridge.org/9781107098688)

© Cambridge University Press & Assessment 2016

This publication is in copyright. Subject to statutory exception and to the provisions  
 of relevant collective licensing agreements, no reproduction of any part may take  
 place without the written permission of Cambridge University Press & Assessment.

First published 2016

*A catalogue record for this publication is available from the British Library*

*Library of Congress Cataloging-in-Publication data*

Names: Clavin, Paul, author. | Searby, Geoff, 1945– author.

Title: Combustion waves and fronts in flows : flames, shocks, detonations,  
 ablation fronts and explosion of stars / Paul Clavin (Aix Marseille  
 Université, France), Geoff Searby (Formerly Centre National de la  
 Recherche Scientifique (CNRS), Marseille, France).

Description: Cambridge, United Kingdom ; New York, NY : Cambridge University  
 Press, 2016. | ©2016 | Includes bibliographical references and index.

Identifiers: LCCN 2016011752 | ISBN 9781107098688 (hardback ; alk. paper) |  
 ISBN 1107098688 (hardback ; alk. paper)

Subjects: LCSH: Combustion. | Waves. | Chemical reactions. | Dynamics. |  
 Nonlinear theories. | Fluid mechanics.

Classification: LCC QD516 .C57 2016 | DDC 541/.361–dc23 LC record available at  
<http://lcn.loc.gov/2016011752>

ISBN 978-1-107-09868-8 Hardback

Cambridge University Press & Assessment has no responsibility for the persistence  
 or accuracy of URLs for external or third-party internet websites referred to in this  
 publication and does not guarantee that any content on such websites is, or will  
 remain, accurate or appropriate.

Contents

|  |                |
|--|----------------|
| <i>Preface</i>   | <i>page ix</i> |
| Introduction   | 1              |
| Brief Historical Introduction                            | 1              |
| Energy and Modern Society                                | 6              |
| Combustion and Related Phenomena                         | 8              |
| Scope of the Book  | 8              |
| <b>Part One   Physical Insights</b>                      | <b>11</b>      |
| 1 General Considerations                                 | 13             |
| 1.1 Introductory Remarks                                 | 14             |
| 1.2 Combustion Waves on Earth                            | 15             |
| 1.3 Fronts and Thermal Waves in Extreme Conditions       | 30             |
| 1.4 Appendix: Physical Constants and Conversion of Units | 43             |
| 2 Laminar Premixed Flames                                | 45             |
| 2.1 Main Characteristics                                 | 48             |
| 2.2 Hydrodynamic Instability                             | 56             |
| 2.3 Flame Stretch and Markstein Numbers                  | 69             |
| 2.4 Thermo-Diffusive Phenomena                           | 77             |
| 2.5 Thermo-Acoustic Instabilities                        | 101            |
| 2.6 Curved Fronts  | 121            |
| 2.7 Nonlinear Dynamics of Unstable Flame Fronts          | 135            |
| 2.8 Additional Laboratory Experiments                    | 146            |
| 2.9 Appendix   | 156            |
| 3 Turbulent Premixed Flames                              | 174            |
| 3.1 Basic Considerations                                 | 176            |
| 3.2 Turbulent Wrinkled Flames                            | 188            |
| 3.3 Turbulent Combustion Noise                           | 197            |
| 3.4 Appendix   | 203            |

|      |  |            |
|------|--|------------|
| 4    | Gaseous Shocks and Detonations                     | 210        |
| 4.1  | Introductory Remarks                               | 213        |
| 4.2  | Planar Supersonic Waves                            | 214        |
| 4.3  | Initiation of Detonation                           | 231        |
| 4.4  | Dynamics of Shock Fronts                           | 261        |
| 4.5  | Instabilities of Detonation Fronts                 | 279        |
| 4.6  | Appendix   | 300        |
| 5    | Chemical Kinetics of Combustion                    | 305        |
| 5.1  | Introduction                                       | 306        |
| 5.2  | Basics Concepts in Chemical Kinetics               | 307        |
| 5.3  | Combustion of Hydrogen                             | 311        |
| 5.4  | Combustion of Lean Methane Mixtures                | 317        |
| 6    | Laser-Driven Ablation Front in ICF                 | 323        |
| 6.1  | Approximations and Constitutive Equations          | 324        |
| 6.2  | Dynamics of the Ablation Front                     | 329        |
| 7    | Explosion of Massive Stars                         | 339        |
| 7.1  | Constitutive Equations of Stars                    | 341        |
| 7.2  | Stellar Equilibrium                                | 346        |
| 7.3  | Instability and Gravitational Collapse             | 352        |
| 7.4  | Appendix   | 370        |
|      | <b>Part Two Detailed Analytical Studies</b>        | <b>375</b> |
| 8    | Planar Flames                                      | 377        |
| 8.1  | General Formulation                                | 379        |
| 8.2  | Thermal Propagation                                | 381        |
| 8.3  | Reaction–Diffusion Waves                           | 393        |
| 8.4  | Chain Branching and Flame Propagation              | 403        |
| 8.5  | Flame Quenching                                    | 411        |
| 9    | Flame Kernels and Flame Balls                      | 429        |
| 9.1  | Flame Kernels Near the Flammability Limits         | 431        |
| 9.2  | Stability Analysis of Spherical Flame Kernels      | 440        |
| 9.3  | Flame Expansion at Lewis Number Smaller Than Unity | 447        |
| 10   | Wrinkled Flames                                    | 460        |
| 10.1 | Hydrodynamics                                      | 463        |
| 10.2 | Thermo-Diffusive Instabilities of Planar Flames    | 473        |
| 10.3 | Hydrodynamics and Diffusion Coupling               | 481        |
| 10.4 | Appendix   | 500        |

Cambridge University Press & Assessment  
978-1-107-09868-8 — Combustion Waves and Fronts in Flows  
Flames, Shocks, Detonations, Ablation Fronts and Explosion of Stars  
Paul Clavin , Geoff Searby  
Frontmatter  
[More Information](#)

|   |     |
|---|-----|
| <i>Contents</i>   | vii |
| 11 Ablative Rayleigh–Taylor Instability                     | 504 |
| 11.1 Linear Analyses of Simplified Models                   | 506 |
| 11.2 Asymptotic Analysis of the Quasi-Isobaric Model        | 511 |
| 11.3 Nonlinear Dynamics in the Limit of a Large Power Index | 522 |
| 12 Shock Waves and Detonations                              | 527 |
| 12.1 Linear Dynamics of Wrinkled Shocks                     | 529 |
| 12.2 Dynamics of Detonation Fronts                          | 543 |
| <b>Part Three   Complements</b>                             | 565 |
| 13 Statistical Physics                                      | 567 |
| 13.1 Statistical Thermodynamics                             | 569 |
| 13.2 Ideal Gases  | 580 |
| 13.3 Physical Kinetics                                      | 591 |
| 14 Chemistry  | 606 |
| 14.1 Elementary Combustion Chemistry                        | 607 |
| 14.2 Chemical Equilibrium                                   | 620 |
| 14.3 Elements of Thermonuclear Fusion                       | 633 |
| 15 Flows  | 637 |
| 15.1 Macroscopic Conservation Equations                     | 640 |
| 15.2 Approximations   | 654 |
| 15.3 One-Dimensional Compressible Flows                     | 663 |
| <i>References</i>   | 685 |
| <i>Index</i>  | 704 |

## Preface

Combustion is a fascinating phenomenon coupling complex chemistry to transport mechanisms and nonlinear fluid dynamics. The combustion of reactive mixtures, frozen far from chemical equilibrium, is an irreversible process in which the approach to equilibrium proceeds through the propagation of nonlinear waves in the form of sharp fronts exhibiting complex geometrical forms. These waves were discovered in the nineteenth century, but the understanding of their structure and dynamics is quite recent. In gaseous mixtures, the rate of chemical heat release is small compared with the rate of elastic collisions, so that combustion is described by the macroscopic equations for the conservation of mass, species, momentum and energy, assuming local equilibrium (except for the inner structure of shock waves). The full system of equations is complicated and is not useful to describe each of the elementary phenomena, separate from the others. Even the coupling of two phenomena, as for example a quasi-isobaric flame and acoustic waves, is represented by simplified equations. The major advances have resulted from analytical studies of simplified models performed in close relation to carefully controlled laboratory experiments. A systematic reduction of the complexity of the basic equations, validated by the confrontation with experiments, is the key to understanding. It is also the most difficult step. The analytical and numerical solutions of simplified equations of relevant models can be completed in a second step by direct numerical simulations of a more detailed system of equations.

The book is written along this line and attention is focused on fundamental aspects. It is meant to be a survey of the nonlinear dynamics of combustion waves, which now constitute a mature scientific field. A similar approach is used to improve the understanding of other types of waves such as ablation fronts in inertial confinement fusion. The approach is also tentatively extended to the explosion of stars at the end of their lifetime, the famous supernovae. A large variety of phenomena is presented. The purpose is to provide a wide view of the physical problems involved in different domains that can benefit from cross-fertilisation. The most important scientific results are reported, ranging from the pioneering works of the last century to the advanced research of the last decade.

The book is aimed at both newcomers to the physics of unstable fronts in flows and scientists who wish to improve their knowledge. It is self-contained and can also be used as a textbook by students. The background in physics, chemistry and fluid mechanics is given in the last part as complements. Physical insights into the phenomena occupy half

Cambridge University Press & Assessment  
978-1-107-09868-8 — Combustion Waves and Fronts in Flows  
Flames, Shocks, Detonations, Ablation Fronts and Explosion of Stars  
Paul Clavin , Geoff Searby  
Frontmatter  
[More Information](#)

---

of the book and are presented first. Detailed analytical studies are developed in the second part and no prerequisites in applied mathematics are required concerning the perturbation methods that are used (multiple-scale and asymptotic analyses).

This book would never have been written without 40 years of activity in our research group, interacting closely with our friends and colleagues, Louis Boyer, Bruno Denet, Alain Pocheau, Joel Quinard and Emmanuel Villermaux. We are also grateful to our close friends and outstanding theoretical physicists for fruitful collaboration and enlightening discussions of great help to improve our understanding of nonlinear problems related to combustion, particularly Guy Joulin, Amable Liñan, Yves Pomeau, Grisha Sivashinsky and Forman A. Williams.