

Astrophysics and Space Science Library 417

Margarita Ryutova

Physics of Magnetic Flux Tubes

AS
SL

 Springer

Margarita Ryutova

Physics of Magnetic Flux Tubes

Margarita Ryutova
Lawrence Livermore National Laboratory
Institute of Geophysics and Planetary
Physics
Livermore, CA
USA

ISSN 0067-0057 ISSN 2214-7985 (electronic)
Astrophysics and Space Science Library
ISBN 978-3-662-45242-4 ISBN 978-3-662-45243-1 (eBook)
DOI 10.1007/978-3-662-45243-1

Library of Congress Control Number: 2014958576

Springer Heidelberg New York Dordrecht London
© Springer-Verlag Berlin Heidelberg 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Cover illustration: The image is a 3-wavelength composite of solenoidal slinky at the coronal temperatures 2 MK (Fe XV 211 Å), 1.5 MK (Fe XII 193 Å) and 0.6 MK (Fe IX/X 171 Å) taken by the SDO/AIA on August 31, 2012.

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media
(www.springer.com)

Astrophysics and Space Science Library

Volume 417

Editorial Board

Chairman

W.B. Burton, *National Radio Astronomy Observatory, Charlottesville, VA, USA*
(bburton@nrao.edu); *University of Leiden, The Netherlands*
(burton@strw.leidenuniv.nl)

F. Bertola, *University of Padua, Italy*

C.J. Cesarsky, *Commission for Atomic Energy, Saclay, France*

P. Ehrenfreund, *Leiden University, The Netherlands*

O. Engvold, *University of Oslo, Norway*

A. Heck, *Strasbourg Astronomical Observatory, France*

E.P.J. Van Den Heuvel, *University of Amsterdam, The Netherlands*

V.M. Kaspi, *McGill University, Montreal, Canada*

J.M.E. Kuijpers, *University of Nijmegen, The Netherlands*

H. Van Der Laan, *University of Utrecht, The Netherlands*

P.G. Murdin, *Institute of Astronomy, Cambridge, UK*

B.V. Somov, *Astronomical Institute, Moscow State University, Russia*

R.A. Sunyaev, *Space Research Institute, Moscow, Russia*

More information about this series at <http://www.springer.com/series/5664>

To Dmitri, Alex and Dmitri, Jr.

Preface

The advanced space and ground-based observations show amazing details in the sun's behavior providing us with invaluable information on the sun as a star and as our own energy source. The behavior of the sun is determined by a tremendous variety of physical phenomena acting on a wide range of spatial and temporal scales. Every aspect requires its own specific subject studies, and a lot of work is still needed to understand the inner workings of this fascinating things.

This book addresses one group of the phenomena: those involving finely structured magnetic fields. It has been more than five decades since the small-scale intense magnetic flux tubes were found to cover the huge "magnetic free" surface of the sun outside sunspots and active regions. For the time being, the fact that all the magnetic field of the sun from its visible surface, throughout corona, and further to the interplanetary space has a fine filamentary structure, is well established. This ubiquity of the magnetic flux tubes and their obvious role in a variety of processes affecting the dynamics of the solar atmosphere and of the outflowing plasma calls for detailed study of their properties. And yet, no book on *Physics of Magnetic Flux Tubes* and their role in the dynamics of various magnetized objects has been available.

This book is intended to fill this gap at least partly, offering the first comprehensive account of the *Physics of Magnetic Flux Tubes*. The book provides side-by-side presentation of observations and analytical theory complemented by quantitative analysis. Many problems that are usually treated separately are presented in the book as a coupled phenomena and are treated on the unified basis. In some cases the author takes a risk to point at the effects that have not yet been looked for, or may be used for the predictability of events, and makes suggestions on what the observer should expect and what to search for in huge banks of observational data.

A major feature of the book is the application and observational test of the analytical theories that have not been previously considered in the context of the solar physics. Examples are: negative energy waves that may lead to formation of solitons propagating along flux tubes; explosive instability in the multiwave interactions; energetically open circuit leading to understanding of the observed variety of coronal structure formation, and others. These concepts are discussed

vis-à-vis pertinent observational data. Extremely important is assessment of collective phenomena in the ensembles of magnetic flux tubes randomly distributed in space and over their physical parameters making the rarefied ensembles in the quiet sun, more crowded families in plages, and dense conglomerates in sunspots and active regions.

The book contains also examples where, conversely, the new theory developments were prompted and enabled by the observations. One can mention the observations of continuous fragmentation of flux tubes accompanied by generation of mass flows, which turned out to be consistent with magnetoacoustic streaming—an effect analogous to Faraday's acoustic streaming. Likewise, the flux tube reconnections and post-reconnection processes that occur in high plasma beta environment have clearly demonstrated the need for significant extensions of the existing theory that focused on low beta coronal reconnections.

The reader will also find descriptions of such intriguing and not fully understood phenomena as the bullwhip effect—an explosively growing amplitude of flux tube oscillation; a greenhouse-like effect, where the temperature under the prominences grows much higher than the expected coronal temperatures; and the effects of a spatiotemporal echoes in the series of recurrent flares and microflares.

The work was done in Lawrence Livermore National Laboratory. The Lab's hospitality is greatly acknowledged. I am particularly grateful to Robert Becker, Kem Cook, Jim Sharp, Charles Alcock, John Bradely, and David Dearborn.

I would like to thank my former colleagues from Landau's theoretical department, Kapitza's Institute for Physical Problems in Moscow, where I received my graduate degrees and worked for years on quantum vortices in superfluid Helium and Type II superconductors. My special thanks go to my teachers Isaak Khalatnikov (my Diploma adviser), Lev Pitaevskii, and Alexei Abrikosov, my Ph.D. advisers.

My interest in solar physics dates back to the 1970s, when I once came across an early paper by Howard and Stenflo about small-scale magnetic flux tubes on the sun. I was captivated by this beautiful subject. I am grateful to Jan Stenflo and Robert Howard not only for their excellent paper, which triggered my lifetime interest, but for all the meetings and discussions that I have had with them later.

I would like to thank Henk Spruit, Gene Parker, Bernie Roberts, and Gene Avrett, who happened to be my first foreign correspondents in the field of solar physics. After about a decade and a half of working on magnetic flux tubes (still back in the Soviet Union), I realized that my results were not known in the West. I then chose these outstanding physicists and sent them some of my offprints. All responded. Henk Spruit immediately made me an invited speaker at the IAU Symposium. Gene Parker was also quick, but I found out about it only seven months later when I was summoned by the authorities and presented a huge tattered box full of papers for identification and explanation what it all meant. It meant that Gene Parker sent me all his papers without any note. Berny Roberts together with Eric Priest invited me to the University of St Andrews for several weeks to work together. I visited Gene Avrett in Harvard Smithsonian Center for Astrophysics several times and had wonderful communications with him and other researchers in

the CFA, especially with Shadia Habbal and Wolfgang Kalkofen, whom I also thank a lot.

I am pleased to thank all my collaborators, particularly Toshi Tajima, Barry LaBonte, Jun-ichi Sakai, Shadia Habbal, Richard Woo, Tom Berger, Mandy Hagenaar, and Zoe Frank. I am especially grateful to Dick Shine. Many beautiful results obtained from observations and described in this book would not have been here without his insight and help.

I would like to thank Alan Title, Philip Scherrer, and Ted Tarbell for not only being my collaborators, but also as trusting people who gave me a job at Stanford Lockheed Institute for Space Research. No CV, no references, and no questions were asked.

Finally, I am extremely grateful to my husband Dmitri (Mitya) Ryutov for his patience and encouragement expressed sometimes in my native Georgian.

Livermore, CA

Margarita Ryutova

Acronyms

AAS	American Astronomical Society
AIA	Atmospheric Imaging Assembly (on board of SDO)
APS	American Physical Society
BBSO	Big Bear Solar Observatory
CDS	Coronal Diagnostics Spectrometer (on board of SOHO)
DOT	Dutch Open Telescope
EIS	Extreme ultraviolet Imaging Spectrom (on board of Hinode)
EIT	Extreme ultraviolet Imaging Telescope (on board of SOHO)
EOS	Earth Observing System
EPOD	Earth Science Picture of Day
ESO	European Southern Observatory
EUV	Extreme Ultraviolet
GOES	Geostationary Operational Environmental Satellite
HAO	High Altitude Observatory
HEP	High Energy Proton (flux)
HMI	Helioseismic and Magnetic Imager (on board of SDO)
IOP	Institute of Physics
ISP	Institute for Solar Physics
JPL	Jet Propulsion Laboratory
KdV	Korteweg-de Vries equation
KH	Kelvin–Helmholtz (instability)
LASCO	Large Angle and Spectrometric Coronagraph Experiment (on board of SOHO)
MDI	The Michelson Doppler Imager (on board of SOHO)
MMFs	Moving Magnetic Features
NEWs	Negative Energy Waves
NST	New Solar Telescope
OCIW	Observatory of the Carnegie Institute of Washington
RT	Rayleigh–Taylor (instability)
SOHO	The Solar and Heliospheric Observatory

SDO	Solar Dynamics Observatory
SOT	Solar Optical Telescope (on board of Hinode)
SST	Swedish 1-m Solar Telescope (SST) on La Palma
SUMER	Solar Ultraviolet Measurements of Emitted Radiation (on board of SOHO)
SVST	Swedish Vacuum Solar Telescope on La Palma
SXT	Soft X-ray Telescope (on board of Yohkoh)
TRACE	Transition Region and Coronal Explorer
UV	Ultraviolet

Contents

1	The Sun's Magnetic Fields	1
1.1	The Sun as a Star	1
1.1.1	Legacy of Ancients	1
1.1.2	Hidden Interior	3
1.1.3	Magnetic Dipole	4
1.2	Magnetic Surface	6
1.2.1	Quiet Sun	7
1.2.2	Sunspots and Active Regions	8
1.2.3	Plages	10
1.2.4	High Latitudes and Polar Regions	11
1.3	Mass Flows	12
1.4	Magnetic Skeleton	18
	References	20
2	A Quick Look on Small Scale Flux Tubes	21
2.1	Early Years	21
2.1.1	First Direct Observational Signs of Magnetic Flux Tubes	22
2.1.2	The Sunspot Dilemma	23
2.2	Elements of Theory for de Facto Flux Tubes	25
2.3	Numerical Visualization and Observations	28
2.4	Filamentary Structures in Laboratory and Universe	32
	References	37
3	Intrinsic Properties of Flux Tubes—Wave Phenomena	39
3.1	Equations of Motion or How Are Tube Waves Excited	39
3.1.1	Equation of Motion for a Single Flux Tube	41
3.1.2	Macroscopic Motions of an Ensemble of Flux Tubes	42
3.2	Absorption of Acoustic Waves—Landau Resonance	45
3.3	Effects of Noncollinearity of Flux Tubes	48

3.4	Exact Theory of Linear Oscillations of Magnetic Flux Tube . . .	49
3.5	Radiation of Secondary Waves by Oscillating Flux Tubes	51
3.6	Scattering of Acoustic Waves and Maximum Energy Input . . .	53
3.7	Axisymmetric Oscillations of Flux Tube	54
3.7.1	Types of $m = 0$ Mode	54
3.7.2	Equation of Motion for Sausage Oscillations	56
3.7.3	Dispersion Relation	58
3.7.4	Sausage and Fast Oscillations in Homogeneous Flux Tube	60
3.7.5	Effects of Radial Inhomogeneities on Sausage Oscillations	61
	References	66
4	Effects of Flux Tube Inhomogeneities and Weak Nonlinearity . . .	69
4.1	Radially Inhomogeneous Flux Tube—Internal Resonances . . .	69
4.1.1	Anomalous Resonance in Kink Oscillations	69
4.1.2	Alfvén Resonance	72
4.2	Boundary Value Problem	75
4.2.1	Phase-Mixing in Flux Tubes	75
4.2.2	Phase-Mixed Torsional Waves	76
4.2.3	Phase-Mixed Kink Oscillations	78
4.3	Longitudinal Resonances	80
4.3.1	Loss of Radial Equilibrium	81
4.3.2	Bullwhip Effect	83
4.4	Standing Resonances and the Temperature Jump	87
4.4.1	Growth of the Oscillation Amplitude—First Resonance	88
4.4.2	Spectral Density and Strong Enhancement of the Oscillation Amplitude	90
4.5	Weakly Nonlinear Waves in Flux Tubes	91
4.5.1	Nonlinear Kink Oscillations—KdV-Bürgers Equation	91
4.5.2	Possibility of Solitary Sausage Wave	96
	References	97
5	Flux Tube Dynamics in the Presence of Mass Flows	99
5.1	Kelvin-Helmholtz Instability and Negative-Energy Waves . . .	99
5.2	Shear Flow Instabilities in Magnetic Flux Tubes	103
5.2.1	Specifics of Kelvin-Helmholtz Instability Along Flux Tubes	103
5.2.2	Flux Tubes and Negative-Energy Waves (NEWs)	104
5.3	Basic Equations of Flux Tube Oscillations with Shear Flows	106

5.4	Dissipative Instabilities of Negative-Energy Kink Oscillations	107
5.5	Radiative Instability of Flux Tube Oscillations in the Presence of Flows	110
5.5.1	Sausage Oscillations	111
5.5.2	Kink Oscillations	112
5.6	Parity of Negative and Positive Energy Waves	113
5.7	Explosive Instability of Negative-Energy Waves	115
5.8	Subcritical Mass Flows—Absence of Instabilities	116
5.8.1	Can the Alfvén Waves Heat the Corona?	117
5.8.2	Effect of Mass Flows on the Efficiency of Heating by Alfvén Waves	118
5.9	Phase Mixed Alfvén Waves at Sub-alfvénic Mass Flows	120
5.9.1	Damping Rate and Height of Energy Release	120
5.9.2	Observable Morphological Effects.	122
5.10	The Asymptotic Behavior of the Total Energy Flux	124
5.11	The Wave Extinction in the Presence of Downflows	126
	References.	134
6	Collective Phenomena in Rarefied Ensembles of Flux Tubes	137
6.1	Response of Flux Tubes to Propagation of Sound Waves.	137
6.1.1	Energy Exchange Between the Acoustic Waves and Ensembles of Flux Tubes	138
6.1.2	Near-Resonance Condition	140
6.2	Nonlinear Estimates of the Maximum Energy Input	141
6.3	Axisymmetric Oscillation in Flux Tube Ensembles	145
6.3.1	Equations of Motion	145
6.3.2	Dispersion Relation—Resonance and Frequency Shift	147
6.4	The Interaction of Unsteady Wave Packets with an Ensemble of Flux Tubes	151
6.5	Spreading of the Energy Absorption Region—“Clouds of Energy”	154
6.5.1	Large Wave Packets	155
6.5.2	Short Wave Packets—Energy Absorption and Release	157
6.6	The Energy Transfer from Unsteady Wave Packets to the Medium	161
	References.	165

7	Effects of Magnetic Flux Tubes in Helioseismology	167
7.1	The Time-Distance Tomography	167
7.1.1	Key Points of Time-Distance Analysis with Magnetic Fields	168
7.1.2	The Travel Times	169
7.2	The Effects of Horizontal Flows	171
7.3	Effects of Horizontal Magnetic Field	172
7.4	Effects of Background Inhomogeneities	174
7.4.1	Weak Inhomogeneities	174
7.4.2	Variations of Flow Velocities	175
7.5	Practical Use of the Forward-Backward Information	176
7.5.1	Symmetry Properties	176
7.5.2	Reconstruction of Subsurface Flow and Magnetic Fields from Observations	177
7.6	Magnetic Corrections in a Vertically Stratified Atmosphere	180
7.7	Estimate of the Energy Flux from Time-Distance Analysis	182
7.7.1	Heat and Magnetic Energy Fluxes	183
7.7.2	Contribution of Eddy Fluxes	185
7.7.3	Reconstruction of Energy Fluxes from Observational Data	186
7.8	Raman Spectroscopy of Solar Oscillations	186
7.8.1	Stokes and Anti-stokes Satellites	187
7.8.2	Using Raman Spectroscopy in Observations	190
	References	192
8	Wave Phenomena in Dense Conglomerate of Flux Tubes	193
8.1	Propagation of MHD Waves in an Ensemble of Closely Packed Flux Tubes	193
8.1.1	Basic Equations and Dispersion Relation	194
8.1.2	Special Cases	199
8.2	Dissipative Processes	200
8.2.1	Weakly Inhomogeneous Medium	201
8.2.2	Medium with Moderate and Strong Inhomogeneities	203
8.2.3	Dissipation by Thermal Conduction	204
8.2.4	Dissipation by Viscosity	206
8.2.5	Total Dissipation Rate	207
8.3	Anomalous Damping at Small Wavevectors	209
8.4	Absorption of P-Modes by Sunspots and Active Regions—Observations	211
8.5	The Interpolation Formula and Comparison with Observations	215
	References	220

9	Nonlinear Wave Phenomena in Dense Conglomerate of Flux Tubes	221
9.1	Nonlinear Equations in Strongly Inhomogeneous Medium	221
9.2	Formation of Shocks Across Small-Scale Inhomogeneities	225
9.2.1	Validation of the Overturning Condition	227
9.3	Effect of Inhomogeneities on the Dispersion Properties of the System	228
9.3.1	Basic Equations	228
9.3.2	Dispersion Relation	230
9.3.3	KdV—Bürgers' Equation with Strong Inhomogeneities	232
9.4	Numerical Analysis	233
9.4.1	The Model	233
9.4.2	Formation of Shock Waves	234
9.4.3	Energy Dissipation	236
	References	239
10	Magnetosonic Streaming	241
10.1	Secondary Flows—Boundary Layer Effects	241
10.1.1	Acoustic Streaming—History and Nature of Faraday's Effect	241
10.1.2	Secondary Flows in Magnetohydrodynamics	243
10.2	Magnetosonic Streaming Due to the Action of Ponderomotive Force	244
10.3	Process of Filamentation and Diffusive Vanishing of Magnetic Flux Tubes	249
10.3.1	Diffusive Broadening of Flux Tube	250
10.3.2	Quantitative Estimates—Lifetimes and Spatial Scales of Flux Tubes	252
10.4	Generation of Mass Flows Due to the Absorption Mechanisms	254
10.5	Numerical Analysis	257
10.5.1	Basic Equations and Numerical Method	258
10.5.2	Numerical Results	259
10.6	Intrinsic Nature of Flux Tube Fragmentation	263
	References	265
11	Moving Magnetic Features (MMFs)	267
11.1	Types of MMFs and Their Observed Properties	267
11.2	Impossibility of the Origin of MMF's in Conservative Systems	269
11.2.1	The Mechanism	271
11.3	Nonlinear Kink and Its Evolution in the Presence of Shear Flows	272

11.4	Soliton and Shocklike Formations Along the Flux Tube—Numerical Studies	275
11.5	Observations and Comparison with Theory	279
11.6	Quantitative Analysis	283
11.7	Unification of Known Types of Moving Magnetic Features	287
11.8	Impact of MMFs on the Overlying Atmosphere	290
11.9	Anticorrelation Between Population of MMF's and Coronal Loop Formation	294
	References.	298
12	Reconnection of Flux Tubes—Specifics of High Plasma β	299
12.1	Basics of Magnetic Reconnection	299
12.2	Photospheric Reconnections—No Immediate Gain in Energy.	304
12.2.1	Specifics of Photospheric Reconnections	305
12.2.2	Flux Tubes Carrying Different Amount of Magnetic Flux	308
12.2.3	Number of Events—Importance of Noncollinearity of Flux Tubes.	311
12.3	Dynamics of Post-reconnection Products	312
12.3.1	Self-similarity of Solution	313
12.3.2	Energy Analysis	315
12.3.3	Transsonic Motion	316
12.4	Dynamics of U-shaped Flux Tubes	317
12.5	Dynamics of \cap -shaped Flux Tube	319
	References.	323
13	Post-reconnection Processes—Shocks, Jets, and Microflares	325
13.1	Key Regularities Observed in the Photosphere/Transition Region	325
13.2	Post-reconnection Shocks and Hydromagnetic Cumulation of Energy	328
13.2.1	Head-On Convergence of Shock Fronts	329
13.2.2	Energy Distribution Between Heat, Jet, and Their Combinations.	331
13.3	Observation of Photospheric Reconnections and Their Impact on Overlying Atmosphere.	334
13.3.1	Microflares, Jets, and Their Combinations	336
13.3.2	Effects of Converging Supergranular Flows	339
13.4	Key Elements of Energy Production and Observation of Shocks	341