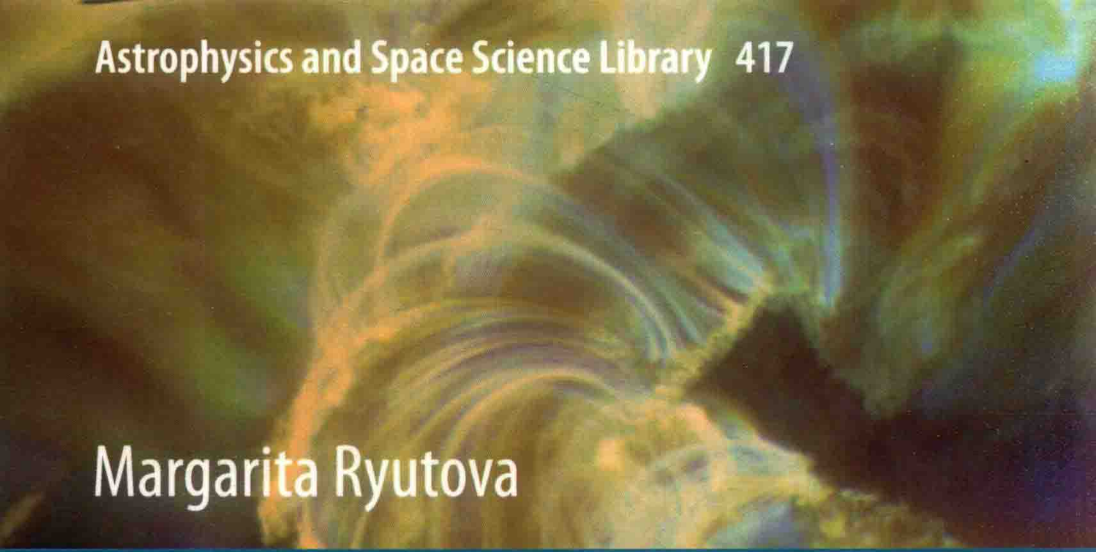

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Physics of Magnetic Flux Tubes

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

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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 Alkock, 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

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