

# **Magnetohydrodynamic Relaxation in Astrophysical Plasmas**

**A Thesis**

**submitted for the Award of Ph.D. degree of**

**MOHANLAL SUKHADIA UNIVERSITY**

**in the**

**Faculty of Science**

**By**

**Sanjay Kumar**



**Under the supervision of**

**Dr. Ramitendranath Bhattacharyya**

**Associate Professor**

**Udaipur Solar Observatory**

**Physical Research Laboratory**

**Udaipur, India**

**DEPARTMENT OF PHYSICS**

**FACULTY OF SCIENCE**

**MOHANLAL SUKHADIA UNIVERSITY**

**UDAIPUR (RAJ)**

**Year of submission: 2016**



## ***DECLARATION***

I, **Mr. Sanjay Kumar**, S/o Mr. Fakir Chand, resident of C-2, USO staff quarters, Badi road, Udaipur-313001, hereby declare that the research work incorporated in the present thesis entitled, "**Magnetohydrodynamic Relaxation in Astrophysical Plasmas**" is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I have properly acknowledged the material collected from secondary sources wherever required. I solely own the responsibility for the originality of the entire content.

**Date:**

**Sanjay Kumar**  
**(Author)**



## ***CERTIFICATE***

I feel great pleasure in certifying that the thesis entitled, “**Magnetohydrodynamic Relaxation in Astrophysical Plasmas**” embodies a record of the results of investigations carried out by **Mr. Sanjay Kumar** under my guidance. He has completed the following requirements as per Ph.D regulations of the University.

- (a) Course work as per the university rules.
- (b) Residential requirements of the university.
- (c) Regularly submitted six monthly progress reports.
- (d) Presented his work in the departmental committee.
- (e) Published minimum of one research papers in a referred research journal.

I recommend the submission of thesis.

**Date:**

**Dr. Ramitendranath Bhattacharyya**  
**(Thesis Supervisor)**  
Associate Professor, USO,  
Physical Research Laboratory,  
Udaipur - 313 001.

Countersigned by

Head of the Department



*To*

*My Family*



## Acknowledgements

*I would like to start by expressing my sincere and deep gratitude to my supervisor Dr. Ramitendranath Bhattacharyya for his invaluable guidance, encouragement and support throughout my PhD tenure. I immensely benefited from his insight and expertise in the subject. Discussions with him were a great pleasure as he always gave importance to my views and was patient with me. I thank him for the patience and confidence that he showed in me. Apart from being my thesis supervisor, I also felt that he is my true teacher who introduced me to the joy of doing science, especially physics. Moreover, he treated me as a younger brother which enables me to share my personal problems with him and he always helped me to overcome them.*

*I further extend my special thanks to Prof. Piotr K. Smolarkiewicz for helping me in various ways whenever I got stuck with the numerical models. I also acknowledge his constant support to enhance the presentation as well as the academic content of the work presented in the thesis.*

*I also express my gratitude to the academic committee of PRL for reviewing my progress in research periodically. I am grateful to my thesis experts Prof. Jitesh Bhatt and Dr. Bhuwan Joshi for thoroughly reviewing my thesis. I thank the faculty members of USO, Prof. Ashok Ambastha, Prof. Nandita Srivastava, Prof. Shibu K. Mathew, Dr. Brajesh Kumar and Dr. Raja Bayanna for their generous helps and encouragements throughout my research endeavor. I also convey my sincere thanks to Prof. P. Venkatakrishnan for his continuous encouragement to do good work. A very special thanks to all other staff members of USO, Mr. Raju Koshy, Ms. Ramya Bireddy, Mr. Rakesh Jaroli, Mr. Naresh Jain, Mr. Mukesh M. Saradava and all the trainees for their help and support in various ways during my stay at USO.*

*My special thanks goes to all the staff members of the computer center of PRL for providing uninterrupted computing facility which helps me to complete computations in time. The computations presented in the thesis are performed using the High Performance Computing (HPC) cluster and the 100 TF cluster*

*Vikram-100 at Physical Research Laboratory, India. I also wish to acknowledge the visualisation software VAPOR ([www.vapor.ucar.edu](http://www.vapor.ucar.edu)) for generating relevant graphics.*

*I must express my sincere gratitude to my seniors at USO; Dr. Anand D. Joshi, Dr. Vema Reddy Panditi, Dr. Suruchi Goel, Dr. Wageesh Mishra, Dr. Dinesh Kumar, Dr. Upendra Kushwaha, Dr. Sajal Dhara, and Dr. Avijeet Prasad for helping me at various stages of the thesis work. I also thank all the seniors at PRL for being supportive whenever I visited PRL. I would like to thank all my batch-mates; Alok Ranjan, Arun Pandey, Guru Kadam, Girish Kumar, Manu George, Ikshu Gautam, Sharadha Band, Tanmoy Mondal, Gaurava Jaiswal, Abhaya, Chithrabhanu, Kuldeep Suthar, and my junior Rahul Yadav for making my stay at PRL/USO comfortable and enjoyable. I extend my thank to my college and university friends Prashant, Dinesh Mahala, Pawan, Mahipal, Akhil, Pooja, Neha, Swati, Anmol and many others who have been always supportive.*

*I would like to take this opportunity to thank all the family members at USO colony Mrs. Usha Venkatakrishnan, Mrs. Saraswati, Mrs. Mahima, and Mrs. Bharti for inviting me for lunches and dinners on various occasions. I especially thank to Mrs. Uhsa Venkatakrishnan for arranging get-together and making the environment of colony homely.*

*Finally, I owe my deepest gratitude to my parents who have given me the freedom necessary to concentrate on my research. I convey my gratitude for their constant support, encouragement and unconditional love. I am also thankful to other family members, in particular, grandparents, uncles, aunties, siblings and cousins for their wholehearted love. It was extremely pleasurable to spend time with my nephews, Vineet, Viren and Akshat whenever I visited home. I must say, that being away from home, I have missed many opportunities to be with my family members. But, they have always been by my side all the time.*

Sanjay Kumar

## ABSTRACT

The astrophysical plasmas in general, and the solar corona in particular, are described by the non-diffusive limit of magnetohydrodynamics. The reason for the achievement of this limit is the large length scales and high temperatures inherent to such plasmas, making magnetic Reynolds number ( $R_M = vL/\lambda$ , in usual notations) extremely high. These high  $R_M$  plasmas satisfy the Alfvén theorem of flux-freezing, resulting in tying magnetic field lines with fluid parcels during an evolution. In such plasmas, small scales in magnetic field, or equivalently current sheets develop spontaneously in accordance with the Parker's magnetostatic theorem. These current sheets are the locations where the plasma becomes locally diffusive because of a local reduction in  $R_M$ . The consequent magnetic reconnections convert the magnetic energy into heat and kinetic energy of mass outflow along with a topological rearrangement of magnetic field lines. With reconnections, the current sheets decay and magnetic field lines frozen with the mass outflows push onto other magnetic field lines and, under favorable conditions may lead to secondary current sheets and second generation reconnections. These reconnections are expected to repeat in time until the plasma relaxes to a terminal state characterized by an allowable minimum of the magnetic energy. Consequently, a scenario is proposed where the magnetohydrodynamic relaxation, maintained by the repeated magnetic reconnections, provides an autonomous mechanism which governs the creation and dynamics of coherent structures in relaxing astrophysical plasmas.

With the above scenario of magnetohydrodynamic relaxation in astrophysical plasmas, in the thesis, we first numerically explore the physics of spontaneous formation of current sheets and assess the important of magnetic field lines topology in the generation. For the purpose, we employ a novel approach of describing the plasma evolution in terms of magnetic flux surfaces instead of the vector magnetic field. The approach provides a direct visualization of the current sheet formation which is helpful in understanding the governing dynamics. The presented computations confirm spontaneous development of current

sheets through favorable contortions of magnetic flux surfaces where two oppositely directed parts of either the same or different field line(s) come to close proximity while the plasma undergoes a topology-preserving viscous relaxation from an initial non-equilibrium state with interlaced magnetic field lines. Importantly, these current sheet are distributed throughout the computational volume with no preference for favorable sites like magnetic nulls or field reversal layers. However for magnetic field with less interlaced magnetic field lines, the simulations show the development of current sheets only at the favorable sites. These current sheets originate as two sets of anti-parallel complimentary magnetic field lines press onto each other.

Further, we explore the ceaseless regeneration of current sheets. For the purpose, we advect vector magnetic field since the flux surface description is valid till onset of magnetic reconnections. Notably with a fixed grid resolution, the magnetic reconnections described in the thesis are related to under-resolved scales—generated by an unbounded increase of magnetic field gradient. The performed computations are then in the spirit of implicit large eddy simulations which regularize the under-resolved scales through simulated reconnections which are concurrent and collocated with developing current sheets. The spontaneous generation of current sheets is ensured by congruency of the computations with the magnetostatic theorem. An important finding of the thesis is the establishment of the comparative scaling of peak current density with spatial resolution for current sheets developing near and away from different magnetic nulls. The results document the current sheets near two dimensional magnetic nulls to have larger strength while exhibiting a stronger scaling than the current sheets close to three dimensional magnetic nulls or away from any magnetic null. The comparative scaling points to a scenario where the energetics of the secondary reconnections is determined by the magnetic topology near a developing current sheet.

Finally, we explore magnetohydrodynamic relaxation with magnetic field line geometry similar to the solar corona. In particular, through numerical simulations we identify the relaxation as an autonomous mechanism for creating a magnetic flux-rope from initial bipolar magnetic field lines and, subsequently,

for triggering and maintaining its ascend via reconnections that occur below the rope. The revealed morphology of the evolution process including onset and ascend of the rope, reconnection locations and the associated topology of the magnetic field lines agrees with observations, and thus substantiates physical realizability of the advocated mechanism. The computations support the scenario where repeated reconnections can generate observed magnetic structures in any high  $R_M$  plasma.

**Keywords :** Magnetohydrodynamics, MHD relaxation, Current sheets, Magnetic reconnections, EULAG

## LIST OF PUBLICATIONS

1. *Formation of magnetic discontinuities through viscous relaxation*, **Sanjay Kumar**, R. Bhattacharyya, and P. K. Smolarkiewicz, Physics of Plasmas, **21**, 052904 (2014).
2. *On the role of topological complexity in spontaneous development of current sheets*, **Sanjay Kumar**, R. Bhattacharyya, and P. K. Smolarkiewicz, Physics of Plasmas, **22**, 082903 (2015).
3. *Continuous development of current sheets near and away from magnetic nulls*, **Sanjay Kumar** and R. Bhattacharyya, Physics of Plasmas, **23**, 044501 (2016).
4. *On the Role of Repetitive Magnetic Reconnections in Evolution of Magnetic Flux-Ropes in Solar Corona*, **Sanjay Kumar**, R. Bhattacharyya, Bhuwan Joshi, and P. K. Smolarkiewicz, The Astrophysical Journal (*accepted*).

# Contents

<b>Acknowledgements</b>	i
<b>Abstract</b>	iii
<b>List of Publications</b>	vi
<b>List of Figures</b>	xi
<b>1 Introduction</b>	1
1.1 Formation of small scales in magnetic field . . . . .	3
1.2 Reconnections in astrophysical systems . . . . .	4
1.3 Reconnections in the interplanetary medium . . . . .	6
1.4 Objectives and organization of the thesis . . . . .	8
<b>2 Magnetohydrodynamic Relaxation</b>	11
2.1 Introduction . . . . .	11
2.2 Magnetohydrodynamics . . . . .	11
2.3 Magnetohydrodynamic relaxation . . . . .	15
2.3.1 The Woltjer invariants and relaxed state . . . . .	18
2.3.2 Presence of finite resistivity . . . . .	21
2.3.3 Taylor's hypothesis . . . . .	22
2.3.4 Requirement of small scales for relaxation . . . . .	23
2.3.5 Taylor's theory for open systems . . . . .	24
2.4 Summary . . . . .	26

<b>3 Astrophysical Plasmas: Current Sheet Formation and Magnetic Reconnection</b>	<b>27</b>
3.1 Introduction . . . . .	27
3.2 Magnetostatic theorem . . . . .	27
3.3 The Optical Analogy . . . . .	31
3.4 Magnetic Reconnection . . . . .	34
3.5 Summary . . . . .	37
<b>4 Solar Corona as a Prototype Example</b>	<b>39</b>
4.1 Introduction . . . . .	39
4.2 Solar corona . . . . .	40
4.3 Current sheet and magnetic reconnection in the corona . . . . .	44
4.3.1 Potential sites for current sheet formation . . . . .	45
4.4 Observational signatures of magnetic reconnection . . . . .	46
4.4.1 Prominence/Filament . . . . .	46
4.4.2 Solar Flares . . . . .	48
4.4.3 Coronal Mass Ejection . . . . .	50
4.5 Summary . . . . .	52
<b>5 Numerical Models</b>	<b>53</b>
5.1 Introduction . . . . .	53
5.2 Advection solver MPDATA . . . . .	54
5.2.1 Derivation of MPDATA . . . . .	55
5.2.2 Extension to generalized transport equation . . . . .	59
5.2.3 Nonoscillatory MPDATA . . . . .	61
5.3 EULAG-MHD . . . . .	62
5.3.1 Governing equations of EULAG-MHD . . . . .	62
5.3.2 Numerics . . . . .	63
5.4 EULAG-EP . . . . .	67
5.5 Implicit large eddy simulation . . . . .	70
5.6 Summary . . . . .	71

<b>6 Initial Value Problems: Current Sheet Formations</b>	<b>73</b>
6.1 Introduction . . . . .	73
6.2 Numerical experiment I . . . . .	78
6.2.1 Initial value problem . . . . .	78
6.2.2 Results . . . . .	86
6.3 Numerical experiment II . . . . .	99
6.3.1 Initial value problem . . . . .	99
6.3.2 Results . . . . .	107
6.3.2.1 Case (I) $\epsilon_0 = 0.1$ . . . . .	111
6.3.2.2 Case (II) $\epsilon_0 = 0.3$ . . . . .	113
6.3.2.3 Case (III) $\epsilon_0 = 0.5$ . . . . .	115
6.3.2.4 Case (IV) $\epsilon_0 = 0.7$ . . . . .	117
6.4 Summary . . . . .	122
<b>7 Initial Value Problems: Magnetic Reconnections</b>	<b>127</b>
7.1 Introduction . . . . .	127
7.2 Numerical experiment I . . . . .	130
7.2.1 Results . . . . .	130
7.3 Numerical experiment 2 . . . . .	137
7.3.1 Initial value problem . . . . .	137
7.3.2 Results . . . . .	139
7.3.2.1 Auxiliary simulation I . . . . .	150
7.3.2.2 Auxiliary simulation II . . . . .	153
7.4 Summary . . . . .	156
<b>8 Summary and Future Works</b>	<b>159</b>
8.1 Summary of the thesis . . . . .	159
8.2 Future works . . . . .	164
8.2.1 Continuation of the present work . . . . .	164
8.2.2 Development of Hall-MHD based numerical model . . . . .	164
<b>Appendix A</b>	<b>168</b>

<b>Appendix B</b>	<b>171</b>
<b>Appendix C</b>	<b>173</b>
<b>Bibliography</b>	<b>175</b>
<b>Publications attached with the thesis</b>	<b>183</b>

# List of Figures

1.1	Typical solar coronal loops observed by the Transition Region And Coronal Explorer. . . . .	2
1.2	Magnetic flux-rope observed by the Atmospheric Imaging Assembly in 131Å. . . . .	5
1.3	Schematic of the occurrence of magnetic reconnection in the earth's magnetosphere. . . . .	7
2.1	Schematic of field line configuration for spheromak. . . . .	17
2.2	Two interconnected magnetic flux tubes. . . . .	20
3.1	Schematic of non-interlaced, and interlaced field lines generated by footpoints motion. . . . .	28
3.2	Schematic of field lines streaming on a flux surface with local maximum in magnetic field and drawing of a stack of such flux surfaces.	33
3.3	An illustration of field lines geometry near a current sheet. . . . .	34
4.1	Plots of density and temperature profiles in the solar corona. . . .	40
4.2	An image of the corona in X-ray, illustrating coronal active regions.	41
4.3	Maps of photospheric magnetic field, indicating the positive and negative polarity of the field. . . . .	42
4.4	Change in plasma- $\beta$ with height in the solar atmosphere. . . . .	43
4.5	Plots of field lines near <i>X</i> -type and <i>O</i> -type magnetic nulls. . . . .	45
4.6	Field lines in the vicinity of a 3D null and QSLs. . . . .	46
4.7	A famous gigantic prominence observed in $H_{\alpha}$ on 1946 June 4 from the High Altitude Observatory. . . . .	47

---

4.8	Images of confined and eruptive flares. . . . .	48
4.9	A schematic representation of unified flare model proposed by Shibata (Shibata 1996). . . . .	50
4.10	A classical three part CME viewed by LASCO on SOHO. . . . .	51
6.1	Variation of magnetic energy, magnetic helicity and $ \mathbf{J} \times \mathbf{B} _{max}$ with an increase in $s_0$ . . . . .	80
6.2	Illustration of magnetic nulls for initial field $\mathbf{B}$ for $s_0 = 3$ and corresponding force-free field. . . . .	82
6.3	Field lines topology in the vicinity of a 3D and $X$ -type nulls of the $\mathbf{B}$ . . . . .	83
6.4	Depiction of the Euler surfaces corresponding to untwisted component fields $\mathbf{B}_1$ , $\mathbf{B}_2$ and $\mathbf{B}_3$ of the initial field $\mathbf{B}$ . . . . .	85
6.5	Time evolution of normalized magnetic and kinetic energies for $s_0 = 2$ and $s_0 = 3$ . . . . .	87
6.6	History of the normalized a: $\langle  \mathbf{J}  \rangle$ , b: $ \mathbf{J}_{max} $ , c: $\langle  \mathbf{J}_1  \rangle$ , d: $\langle  \mathbf{J}_2  \rangle$ , e: $\langle  \mathbf{J}_3  \rangle$ and f: grid averaged Lorentz force, for $s_0 = 3$ . . . . .	89
6.7	Time profiles of the normalized a: $\langle \mathbf{J}_1 \cdot \mathbf{J}_2 \rangle$ , b: $\langle \mathbf{J}_1 \cdot \mathbf{J}_3 \rangle$ and c: $\langle \mathbf{J}_2 \cdot \mathbf{J}_3 \rangle$ for $s_0 = 3$ . . . . .	90
6.8	The history of energy budget for kinetic and magnetic energies for $s_0 = 3$ . . . . .	91
6.9	Time sequence of direct volume rendering of total current density $ \mathbf{J} $ for $s_0 = 3$ . . . . .	92
6.10	Time evolution of magnetic nulls, overlaid with isosurface of total current density having a magnitude of 30% of its maximum value ( $J-30$ ). . . . .	94
6.11	Evolution of Euler surfaces $\phi_1$ -constant, overlaid with $J_1 - 60$ surface. . . . .	95
6.12	The Euler surface $\phi_1$ at two time instants overlaid with isosurfaces of component field $ \mathbf{B}_1 $ . . . . .	97
6.13	Evolution of Euler surfaces $\psi_2$ -constant, overlaid with $J_2 - 60$ . . . . .	98
6.14	Time sequence of Euler surfaces $\phi_2$ -constant, overlaid with $J_2 - 60$ . . . . .	99

---

6.15 Illustration of Euler surfaces corresponding to untwisted component fields $\mathbf{B}_1$ and $\mathbf{B}_1$ of the initial field $\mathbf{B}$ . . . . .	101
6.16 Plots of magnetic field lines of the initial field $\mathbf{B}$ for $\epsilon_0 = 0.1, 0.3, 0.5$ and 0.7. . . . .	104
6.17 Field lines of $\mathbf{B}$ for $\epsilon_0 = 0.1, 0.3, 0.5$ and 0.7 plotted in close proximity of the $y = \pi$ plane and with $z \in \{0, \pi\}$ . . . . .	105
6.18 The figure demonstrates the magnetic nulls by isosurfaces of $\chi(x, y, z)$ , with parameter $H_0 = 0.01$ and $d_0 = 0.05$ , for $\epsilon_0 = 0.5$ . . . . .	106
6.19 Time evolution of normalized kinetic and magnetic energies for $\epsilon_0 = 0.1$ . . . . .	107
6.20 Deviations of normalized kinetic (dashed) and magnetic (solid) energy rates from their analytical values during computations with $\epsilon_0 = 0.1, 0.3, 0.5$ , and 0.7. . . . .	108
6.21 Time evolution of normalized $\langle  \mathbf{J}  \rangle$ and $J_{\max}$ for $\epsilon_0 = 0.1, 0.3$ , 0.5, and 0.7. . . . .	109
6.22 Time evolution of $\langle  \mathbf{J}_2  \rangle$ , $\langle \mathbf{J}_1 \cdot \mathbf{J}_2 \rangle$ , and $\langle  \mathbf{J}_1  \rangle$ for $\epsilon_0 = 0.1, 0.3$ , 0.5, and 0.7. . . . .	110
6.23 Plot of $J_{\max}$ against grid resolution for $\epsilon_0 = 0.1$ and $\epsilon_0 = 0.5$ . . . . .	111
6.24 Evolution of the isosurface $J - 50$ , having an isovalue which is 50% of the maximum $ \mathbf{J} $ for $\epsilon_0 = 0.1$ . . . . .	112
6.25 History of two complementary sets of oppositely directed field lines of the $\mathbf{B}$ along with $J - 50$ surfaces for $\epsilon_0 = 0.1$ . . . . .	113
6.26 Time sequence of the isosurface $J - 50$ overlaid with magnetic nulls, for $\epsilon_0 = 0.3$ . . . . .	114
6.27 Evolution of the surface $J - 50$ overlaid with magnetic nulls, for $\epsilon_0 = 0.5$ . . . . .	115
6.28 Appearance of $J_1 - 40$ surfaces at $t = 112s$ for $\epsilon_0 = 0.5$ , plotted in the half computational domain with $z \in \{0, \pi\}$ . . . . .	116
6.29 Evolution of Euler surface $\psi_1$ -constant overlaid with the $J_1 - 40$ surface, for $\epsilon_0 = 0.5$ . . . . .	117

---

6.30 Time profile of Euler surfaces $\phi_1$ -constant overlaid with the surface $J_1 = 40$ for $\epsilon_0 = 0.5$ , plotted in a selected portion of the computational domain. . . . .	118
6.31 Development of the surface $J = 50$ overlaid with magnetic nulls, for $\epsilon_0 = 0.7$ . . . . .	119
6.32 A snapshot of the $J = 50$ surfaces at $t = 112s$ , for $\epsilon_0 = 0.7$ , plotted in the half computational domain with $z \in \{0, \pi\}$ . . . . .	120
6.33 Appearances of $J_1 = 40$ surface at $t = 112s$ for $\epsilon_0 = 0.7$ , depicted in the half computational domain with $z \in \{0, \pi\}$ . . . . .	120
6.34 Evolution of Euler surfaces $\psi_1$ -constant overplotted with the surface $J_1 = 40$ for $\epsilon_0 = 0.7$ , shown in the computational domain with $x \in \{\frac{2\pi}{3}, \frac{4\pi}{3}\}$ . . . . .	121
6.35 Evolution of Euler surfaces $\phi_2$ -constant overlaid with the surface $J_2 = 40$ for $\epsilon_0 = 0.7$ . . . . .	122
6.36 Two sets of MFLs $\mathbf{B}$ overlaid with the $J = 50$ surfaces at $t = 0s$ and $t = 112s$ , for $\epsilon_0 = 0.5$ . . . . .	123
7.1 The evolution of kinetic energy, normalized to initial total (kinetic+magnetic) energy. . . . .	131
7.2 Plot of magnetic nulls and isosurfaces of $ \mathbf{J} $ having a magnitude of 40% of the $ \mathbf{J} _{\max}$ at $t = 8s$ . In addition, field lines in the locality of a CS is plotted. . . . .	131
7.3 Evolution of field lines in neighborhoods of $X$ -type nulls situated at $(x, y, z) = (\pi, \pi, 2.64\pi)$ , $(\pi, \pi, 3\pi)$ , and $(\pi, \pi, 3.36\pi)$ . . . . .	132
7.4 History of MFLs in the vicinity of an $X$ -type null situated at $(x, y, z) = (\pi, \pi, 3\pi/2)$ , overplotted with isosurface of $ \mathbf{J} $ at 40% of $ \mathbf{J} _{\max}$ in the vicinity. . . . .	133
7.5 Time sequence of field lines in the immediate neighborhood of a representative 3D magnetic null situated at $(x, y, z) = (\pi/2, \pi/2, 3\pi)$ in their important phases of evolution. . . . .	134

---

7.6 Isosurfaces of $ \mathbf{J} $ having a magnitude of 40% of the $ \mathbf{J} _{\max}$ at $t = 130s$ . . . . .	135
7.7 Scaling of $ \mathbf{J} _{\max}$ with resolution, for the CSs near 2D nulls at $t = 83s$ , 3D nulls at $t = 90s$ , and away from these nulls at $t = 8s$ . . . . .	135
7.8 History of magnetic energy and magnetic helicity. . . . .	136
7.9 Variation of $ \mathbf{J} \times \mathbf{B} _{\max}$ with an increase in $s_0$ . . . . .	139
7.10 Field lines of the initial field $\mathbf{B}$ for $s_0 = 6$ and their projections of the $z = 0$ plane. . . . .	140
7.11 As in Fig. 7.10 but for field lines of $\mathbf{B}_{lf}$ and their projections on the $z = 0$ plane. . . . .	141
7.12 The evolution of kinetic energy, normalized to initial total (kinetic+magnetic) energy. . . . .	142
7.13 Time sequences of magnetic field lines in their important phases of evolution. . . . .	143
7.14 Snapshot of field lines at $t = 10s$ , plotted in the neighborhood of the detached structure. . . . .	144
7.15 Evolution of magnetic field lines, overlaid with contours of magnetic pressure drawn on a $y$ -constant plane, concurrent with the first phase. . . . .	145
7.16 The plot of current density (in vicinity of R as marked in Fig. 7.15) against grid resolution. . . . .	146
7.17 Time sequence of field lines at instances $t = 6s$ and $t = 8s$ , projected on a $y$ -constant plane. . . . .	146
7.18 Evolution of field lines (projected on a $y$ -constant plane) coincides with quasi-steady state of the relaxation. . . . .	148
7.19 Plots of field lines during the third phase of evolution. . . . .	149
7.20 Time sequences of two sets of field lines (overlaid with contours of magnetic pressure) for the three-dimensional simulation with initial field $\mathbf{B}^*$ . . . . .	151
7.21 Time sequences of evolution with more densely plotted field lines of the $\mathbf{B}^*$ . . . . .	152

- 7.22 Field lines for the three-dimensional simulation with initial field  $\mathbf{B}^*$  at instances  $t = 10.4s$  and  $t = 36s$ . The plots are overlaid with isosurfaces of current density with isovalues 15% and 20% of its maximum and contours of  $|\mathbf{B}^*|$  on a  $y$ -constant plane. . . . . 153
- 7.23 Evolution of two sets of field lines, overplotted with contours of magnetic pressure, for the three-dimensional simulation with initial field  $\mathbf{B}^{**}$ . . . . . 154
- 7.24 Evolution of field lines for with initial field  $\mathbf{B}^{**}$ , overplotted with with isosurfaces of current density with isovalues 15% and 20% of its maximum and contours of  $|\mathbf{B}^*|$  on a  $y$ -constant plane. . . . . 155

# Bibliography

- Alfvén, H.: 1942, *Nature* **150**, 405
- Amari, T. and Aly, J. J.: 1990, *Astron. Astrophys.* **231**, 213
- Amari, T. and Aly, J. J.: 1992, *Astron. Astrophys.* **265**, 791
- Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., and Linker, J.: 2003, *Astrophys. J.* **585**, 1073
- Amari, T., Luciani, J. F., Mikic, Z., and Linker, J.: 1999, *Astrophys. J.* **518**, L57
- Aschwanden, M. J.: 2005, *Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd edition)*, Springer
- Aulanier, G., Pariat, E., and Démoulin, P.: 2005, *Astron. Astrophys.* **444**, 961
- Aulanier, G., Török, T., Démoulin, P., and DeLuca, E. E.: 2010, *Astrophys. J.* **708**, 314
- Beaudoin, P., Charbonneau, P., Racine, E., and Smolarkiewicz, P. K.: 2013, *Solar Phys.* **282**, 335
- Bellan, P. M.: 2008, *Fundamentals of Plasma Physics*, Cambridge University Press
- Berger, M. A.: 1997, *J. Geophys. Res.* **102**, 2637
- Berger, M. A. and Field, G. B.: 1984, *Journal of Fluid Mechanics* **147**, 133
- Bhattacharjee, A.: 2004, *Ann. Rev. Astron. Astrophys.* **42**, 365
- Bhattacharyya, R. and Janaki, M. S.: 2004, *Physics of Plasmas* **11**, 5615
- Bhattacharyya, R., Janaki, M. S., and Dasgupta, B.: 2000, *Physics of Plasmas* **7**, 4801
- Bhattacharyya, R., Janaki, M. S., and Dasgupta, B.: 2003, *Plasma Physics and Controlled Fusion* **45**, 63
- Bhattacharyya, R., Low, B. C., and Smolarkiewicz, P. K.: 2010, *Physics of Plasmas* **17(11)**, 112901
- Book, D. L., Boris, J. P., and Hain, K.: 1975, *Journal of Computational Physics* **18**, 248
- Boris, J. P. and Book, D. L.: 1973, *Journal of Computational Physics* **11**, 38

- Boris, J. P. and Book, D. L.: 1976, *Journal of Computational Physics* **20**, 397
- Born, M. and Wolf, E.: 1975, *Principles of optics. Electromagnetic theory of propagation, interference and diffraction of light*, Cambridge University Press
- Brown, J. C.: 1971, *Solar Phys.* **18**, 489
- Carcedo, L., Brown, D. S., Hood, A. W., Neukirch, T., and Wiegmann, T.: 2003, *Solar Phys.* **218**, 29
- Carmichael, H.: 1964, *NASA Special Publication* **50**, 451
- Chandrasekhar, S. and Kendall, P. C.: 1957, *Astrophys. J.* **126**, 457
- Chen, P. F.: 2011, *Living Reviews in Solar Physics* 8
- Cheng, X., Zhang, J., Liu, Y., and Ding, M. D.: 2011, *Astrophys. J.* **732**, L25
- Chifor, C., Tripathi, D., Mason, H. E., and Dennis, B. R.: 2007, *Astron. Astrophys.* **472**, 967
- Chiuderi, C., Giachetti, R., and van Hoven, G.: 1977, *Solar Phys.* **54**, 107
- Cho, K.-S., Lee, J., Bong, S.-C., Kim, Y.-H., Joshi, B., and Park, Y.-D.: 2009, *Astrophys. J.* **703**, 1
- Choe, G. S. and Lee, L. C.: 1996, *Astrophys. J.* **472**, 372
- Choudhuri, A. R.: 1998, *The Physics of Fluids and Plasmas: An Introduction for Astrophysicists*, Cambridge University Press
- Choudhuri, A. R.: 2010, *Astrophysics for Physicists*, Cambridge University Press
- Clyne, J. and Rast, M.: 2005, in R. F. Erbacher, J. C. Roberts, M. T. Gröhn, and K. Börner (eds.), *Visualization and Data Analysis 2005*, Vol. 5669, pp 284–294
- Craig, I. J. D. and Effenberger, F.: 2014, *Astrophys. J.* **795**, 129
- Craig, I. J. D. and Litvinenko, Y. E.: 2005, *Physics of Plasmas* **12**(3), 032301
- Craig, I. J. D. and Pontin, D. I.: 2014, *Astrophys. J.* **788**, 177
- Daglis, I. A., Thorne, R. M., Baumjohann, W., and Orsini, S.: 1999, *Reviews of Geophysics* **37**, 407
- Dahlburg, R. B., Antiochos, S. K., and Zang, T. A.: 1991, *Astrophys. J.* **383**, 420
- Dasgupta, B., Janaki, M. S., Bhattacharyya, R., Dasgupta, P., Watanabe, T., and Sato, T.: 2002, *Phys. Rev. E* **65**(4), 046405
- del Toro Iniesta, J. C.: 2003, *Introduction to Spectropolarimetry*, Cambridge University Press
- Démoulin, P.: 2006, *Advances in Space Research* **37**, 1269
- Demoulin, P., Priest, E. R., and Anzer, U.: 1989, *Astron. Astrophys.* **221**, 326

- DeVore, C. R. and Antiochos, S. K.: 2000, *Astrophys. J.* **539**, 954
- Domaradzki, J. A. and Radhakrishnan, S.: 2005, *Fluid Dynamics Research* **36**, 385
- Domaradzki, J. A., Xiao, Z., and Smolarkiewicz, P. K.: 2003, *Physics of Fluids* **15**, 3890
- Drenkhahn, G. and Spruit, H. C.: 2002, *Astron. Astrophys.* **391**, 1141
- Dungey, J. W.: 1961, *J. Geophys. Res.* **66**, 1043
- Eisenstat, S. C.: 1983, *SIAM Journal on Numerical Analysis* **20**, 358
- Eisenstat, S. C., Elman, H. C., and Martin, H. S.: 1983, *SIAM Journal on Numerical Analysis* **20**, 345357
- Fan, Y.: 2001, *Astrophys. J.* **554**, L111
- Fan, Y.: 2010, *Astrophys. J.* **719**, 728
- Fan, Y.: 2011, *Astrophys. J.* **740**, 68
- Fan, Y. and Gibson, S. E.: 2003, *Astrophys. J.* **589**, L105
- Fan, Y. and Gibson, S. E.: 2004, *Astrophys. J.* **609**, 1123
- Fletcher, L., Dennis, B. R., Hudson, H. S., Krucker, S., Phillips, K., Veronig, A., Battaglia, M., Bone, L., Caspi, A., Chen, Q., Gallagher, P., Grigis, P. T., Ji, H., Liu, W., Milligan, R. O., and Temmer, M.: 2011, *Space Sci. Rev.* **159**, 19
- Foukal, P. V.: 1976, *Astrophys. J.* **210**, 575
- Galsgaard, K. and Nordlund, Å.: 1997, *J. Geophys. Res.* **102**, 231
- Gary, G. A.: 2001, *Solar Phys.* **203**, 71
- Gershberg, R. E.: 1983, in P. B. Byrne and M. Rodono (eds.), *IAU Colloq. 71: Activity in Red-Dwarf Stars*, Vol. 102 of *Astrophysics and Space Science Library*, pp 487–495
- Ghizaru, M., Charbonneau, P., and Smolarkiewicz, P. K.: 2010, *Astrophys. J.* **715**, L133
- Giannios, D.: 2010, *Mon. Not. Roy. Astron. Soc.* **408**, L46
- Gibson, S. E. and Fan, Y.: 2006, *Journal of Geophysical Research (Space Physics)* **111**, A12103
- Goedbloed, J. P. and Hagebeuk, H. J. L.: 1972, *Physics of Fluids* **15**, 1090
- Goldston, R. J. and Rutherford, P. H.: 1995, *Introduction to Plasma Physics*, Institute of Physics Publishing
- Golub, L., Bookbinder, J., Deluca, E., Karovska, M., Warren, H., Schrijver, C. J., Shine, R., Tarbell, T., Title, A., Wolfson, J., Handy, B., and Kankelborg, C.: 1999, *Physics of Plasmas* **6**, 2205

- Golub, L. and Pasachoff, J. M.: 1997, *The Solar Corona*, Cambridge University Press
- Gopalswamy, N., Yashiro, S., Vourlidas, A., Lara, A., Stenborg, G., Kaiser, M. L., and Howard, R. A.: 2004, in *American Astronomical Society Meeting Abstracts #204*, Vol. 36 of *Bulletin of the American Astronomical Society*, p. 738
- Griebel, M., Dornseifer, T., and Neunhoeffer, T.: 1998, *Numerical simulation in fluid dynamics: a practical introduction*, the Society for Industrial and Applied Mathematics
- Grinstein, F. F., Margolin, L. G., and Rider, W. J. (eds.): 2007, *Implicit Large Eddy Simulation: Computing Turbulent Fluid Dynamics*, Combridge University Press
- Hasegawa, A.: 1985, *Advances in Physics* **34**, 1
- Heyvaerts, J. and Priest, E. R.: 1984, *Astron. Astrophys.* **137**, 63
- Hirayama, T.: 1974, *Solar Phys.* **34**, 323
- Howard, T. A. and Tappin, S. J.: 2009, *Space Sci. Rev.* **147**, 31
- Illing, R. M. E. and Hundhausen, A. J.: 1985, *J. Geophys. Res.* **90**, 275
- Janse, A. M. and Low, B. C.: 2009, *Astrophys. J.* **690**, 1089
- Joshi, B., Veronig, A. M., Lee, J., Bong, S.-C., Tiwari, S. K., and Cho, K.-S.: 2011, *Astrophys. J.* **743**, 195
- Klimchuk, J. A.: 2006, *Solar Phys.* **234**, 41
- Kohl, J. L., Noci, G., Antonucci, E., Tondello, G., Huber, M. C. E., Gardner, L. D., Nicolosi, P., Strachan, L., Fineschi, S., Raymond, J. C., Romoli, M., Spadaro, D., Panasyuk, A., Siegmund, O. H. W., Benna, C., Ciaravella, A., Cranmer, S. R., Giordano, S., Karovska, M., Martin, R., Michels, J., Modigliani, A., Naletto, G., Pernechele, C., Poletto, G., and Smith, P. L.: 1997, *Solar Phys.* **175**, 613
- Kopp, R. A. and Pneuman, G. W.: 1976, *Solar Phys.* **50**, 85
- Krucker, S., Battaglia, M., Cargill, P. J., Fletcher, L., Hudson, H. S., MacKinnon, A. L., Masuda, S., Sui, L., Tomczak, M., Veronig, A. L., Vlahos, L., and White, S. M.: 2008, *Astron. Astrophys. Rev.* **16**, 155
- Kumar, D. and Bhattacharyya, R.: 2011, *Physics of Plasmas* **18**(8), 084506
- Kumar, D., Bhattacharyya, R., and Smolarkiewicz, P. K.: 2013, *Physics of Plasmas* **20**(11), 112903
- Kumar, D., Bhattacharyya, R., and Smolarkiewicz, P. K.: 2015a, *Physics of Plasmas* **22**(1), 012902
- Kumar, P., Yurchyshyn, V., Wang, H., and Cho, K.-S.: 2015b, *Astrophys. J.* **809**, 83
- Kumar, S. and Bhattacharyya, R.: 2016, *Physics of Plasmas* **23**(4), 044501

- Kumar, S., Bhattacharyya, R., Joshi, B., and Smolarkiewicz, P. K.: 2016, *Astrophys. J.* p. (in press)
- Kumar, S., Bhattacharyya, R., and Smolarkiewicz, P. K.: 2014, *Physics of Plasmas* **21**(5), 052904
- Kumar, S., Bhattacharyya, R., and Smolarkiewicz, P. K.: 2015c, *Physics of Plasmas* **22**(8), 082903
- Kuperus, M., Ionson, J. A., and Spicer, D. S.: 1981, *Ann. Rev. Astron. Astrophys.* **19**, 7
- Kusano, K., Maeshiro, T., Miike, H., Yokoyama, T., and Sakurai, T.: 2004, *J. Plasma Fusion Res. SERIES* **6**, 115
- Kusano, K., Suzuki, Y., Kubo, H., Miyoshi, T., and Nishikawa, K.: 1994, *Astrophys. J.* **433**, 361
- Kushwaha, U., Joshi, B., Cho, K.-S., Veronig, A., Tiwari, S. K., and Mathew, S. K.: 2014, *Astrophys. J.* **791**, 23
- Kushwaha, U., Joshi, B., Veronig, A. M., and Moon, Y.-J.: 2015, *Astrophys. J.* **807**, 101
- Lang, K. R.: 2006, *Sun, Earth and Sky*, Springer
- Lau, Y.-T. and Finn, J. M.: 1990, *Astrophys. J.* **350**, 672
- Leka, K. D., Canfield, R. C., McClymont, A. N., and van Driel-Gesztelyi, L.: 1996, *Astrophys. J.* **462**, 547
- Lin, R. P., Krucker, S., Hurford, G. J., Smith, D. M., Hudson, H. S., Holman, G. D., Schwartz, R. A., Dennis, B. R., Share, G. H., Murphy, R. J., Emslie, A. G., Johns-Krull, C., and Vilmer, N.: 2003, *Astrophys. J.* **595**, L69
- Longcope, D. W. and Parnell, C. E.: 2009, *Solar Phys.* **254**, 51
- Low, B. C.: 1996, *Solar Phys.* **167**, 217
- Low, B. C.: 2001, *J. Geophys. Res.* **106**, 25141
- Low, B. C.: 2006, *Astrophys. J.* **649**, 1064
- Low, B. C.: 2011, *Physics of Plasmas* **18**(5), 052901
- Low, B. C.: 2015, *Science China Physics, Mechanics, and Astronomy* **58**(1), 5626
- Mackay, D. H., Gaizauskas, V., and Yeates, A. R.: 2008, *Solar Phys.* **248**, 51
- Margolin, L. G., Rider, W. J., and Grinstein, F. F.: 2006, *Journal of Turbulence* **7**, N15
- Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., and Ogawara, Y.: 1994, *Nature* **371**, 495
- Mellor, C., Gerrard, C. L., Galsgaard, K., Hood, A. W., and Priest, E. R.: 2005, *Solar Phys.* **227**, 39

- Milligan, R. O., Gallagher, P. T., Mathioudakis, M., and Keenan, F. P.: 2006, *Astrophys. J.* **642**, L169
- Morales, L. F., Dasso, S., Gómez, D. O., and Mininni, P. D.: 2006, *Advances in Space Research* **37**, 1287
- Mullan, D. J.: 1986, *NASA Special Publication* 492
- Müller, D., Marsden, R. G., St. Cyr, O. C., and Gilbert, H. R.: 2013, *Solar Phys.* **285**, 25
- Nandy, D., Hahn, M., Canfield, R. C., and Longcope, D. W.: 2003, *Astrophys. J.* **597**, L73
- Nandy, D., Hahn, M., Canfield, R. C., and Longcope, D. W.: 2004, in A. V. Stepanov, E. E. Benevolenskaya, and A. G. Kosovichev (eds.), *Multi-Wavelength Investigations of Solar Activity*, Vol. 223 of *IAU Symposium*, pp 473–474
- Ohyama, M. and Shibata, K.: 1998, *Astrophys. J.* **499**, 934
- Ohyama, M., Shibata, K., Yokoyama, T., and Shimojo, M.: 1997, *Advances in Space Research* **19**, 1849
- Ortolani, S. and Schnack, D. D.: 1993, *Magnetohydrodynamics of Plasma Relaxation*, World Scientific Publishing Co. Pte. Ltd.
- Pallavicini, R., Serio, S., and Vaiana, G. S.: 1977, *Astrophys. J.* **216**, 108
- Parenti, S.: 2014, *Living Reviews in Solar Physics* 11
- Parker, E. N.: 1957, *J. Geophys. Res.* **62**, 509
- Parker, E. N.: 1972, *Astrophys. J.* **174**, 499
- Parker, E. N.: 1988, *Astrophys. J.* **330**, 474
- Parker, E. N.: 1989a, *Geophysical and Astrophysical Fluid Dynamics* **45**, 159
- Parker, E. N.: 1989b, *Geophysical and Astrophysical Fluid Dynamics* **45**, 169
- Parker, E. N.: 1989c, *Geophysical and Astrophysical Fluid Dynamics* **46**, 105
- Parker, E. N.: 1990, *Geophysical and Astrophysical Fluid Dynamics* **50**, 229
- Parker, E. N.: 1994, *Spontaneous current sheets in magnetic fields : with applications to stellar x-rays. International Series in Astronomy and Astrophysics, Vol. 1. New York : Oxford University Press, 1994.* 1
- Parker, E. N.: 2005, in D. E. Innes, A. Lagg, and S. A. Solanki (eds.), *Chromospheric and Coronal Magnetic Fields*, Vol. 596 of *ESA Special Publication*, p. 1.1
- Parker, E. N.: 2012, *Plasma Physics and Controlled Fusion* **54(12)**, 124028
- Pesnell, W.: 2010, in *38th COSPAR Scientific Assembly*, Vol. 38 of *COSPAR Meeting*, p. 2
- Petschek, H. E.: 1964, *NASA Special Publication* **50**, 425

- Poletto, G., Pallavicini, R., and Kopp, R. A.: 1988, *Astron. Astrophys.* **201**, 93
- Pontin, D. I.: 2012, *Philosophical Transactions of the Royal Society of London Series A* **370**, 3169
- Pontin, D. I. and Huang, Y.-M.: 2012, *Astrophys. J.* **756**, 7
- Priest, E.: 2014, *Magnetohydrodynamics of the Sun*, Cambridge University Press
- Priest, E. and Forbes, T.: 2006, *Magnetic Reconnection: MHD Theory and Applications*, Cambridge University Press
- Priest, E. R. and Démoulin, P.: 1995, *J. Geophys. Res.* **100**, 23443
- Priest, E. R. and Forbes, T. G.: 1986, *J. Geophys. Res.* **91**, 5579
- Priest, E. R., Heyvaerts, J. F., and Title, A. M.: 2002, *Astrophys. J.* **576**, 533
- Priest, E. R., Hood, A. W., and Anzer, U.: 1989, *Astrophys. J.* **344**, 1010
- Priest, E. R. and Titov, V. S.: 1996, *Proceedings of the Royal Society of London Series A* **354**, 2951
- Prusa, J. M. and Smolarkiewicz, P. K.: 2003, *Journal of Computational Physics* **190**, 601
- Prusa, J. M., Smolarkiewicz, P. K., and Wyszogrodzki, A. A.: 2008, *Computers Fluids* **37**, 11931207
- Pulkkinen, T.: 2007, *Living Reviews in Solar Physics* 4
- Raeder, J.: 2006, *Annales Geophysicae* **24**, 381
- Reynolds, R. J., Haffner, L. M., and Tufte, S. L.: 1999, *Astrophys. J.* **525**, L21
- Rider, W. J.: 2006, *International Journal for Numerical Methods in Fluids* **50**, 1145
- Romanova, M. M. and Lovelace, R. V. E.: 1992, *Astron. Astrophys.* **262**, 26
- Ruderman, M. S. and Roberts, B.: 2002, *Astrophys. J.* **577**, 475
- Rust, D. M. and Kumar, A.: 1996, *Astrophys. J.* **464**, L199
- Saroff, J., Almagri, A., Anderson, J., Brower, D., Craig, D., Deng, B., den Hartog, D., Ding, W., Fiksel, G., Forest, C., Mirnov, V., Prager, S., and Svidzinski, V.: 2005, in K. T. Chyzy, K. Otmianowska-Mazur, M. Soida, and R.-J. Dettmar (eds.), *The Magnetized Plasma in Galaxy Evolution*, pp 48–55
- Schmieder, B., van Driel-Gesztelyi, L., Aulanier, G., Démoulin, P., Thompson, B., De Forest, C., Wiik, J. E., Saint Cyr, C., and Vial, J. C.: 2002, *Advances in Space Research* **29**, 1451
- Shibata, K.: 1996, *Advances in Space Research* 17
- Shibata, K.: 1997, in A. Wilson (ed.), *Fifth SOHO Workshop: The Corona and Solar Wind Near Minimum Activity*, Vol. 404 of *ESA Special Publication*, p. 103

- Shibata, K. and Magara, T.: 2011, *Living Reviews in Solar Physics* 8
- Shibata, K., Masuda, S., Shimojo, M., Hara, H., Yokoyama, T., Tsuneta, S., Kosugi, T., and Ogawara, Y.: 1995, *Astrophys. J.* **451**, L83
- Smolarkiewicz, P. and Szmelter, J.: 2011, *Acta Geophysica* **59**, 1109
- Smolarkiewicz, P. K.: 1983, *Monthly Weather Review* **111**, 479
- Smolarkiewicz, P. K.: 1984, *Journal of Computational Physics* **54**, 325
- Smolarkiewicz, P. K.: 1991, *Monthly Weather Review* **119**, 2505
- Smolarkiewicz, P. K.: 2006, *International Journal for Numerical Methods in Fluids* **50**, 1123
- Smolarkiewicz, P. K. and Charbonneau, P.: 2013, *Journal of Computational Physics* **236**, 608
- Smolarkiewicz, P. K. and Clark, T. L.: 1986, *Journal of Computational Physics* **67**, 396
- Smolarkiewicz, P. K. and Grabowski, W. W.: 1990, *Journal of Computational Physics* **86**, 355
- Smolarkiewicz, P. K., Grubišić, V., and Margolin, L. G.: 1997, *Monthly Weather Review* **125**, 647
- Smolarkiewicz, P. K. and Margolin, L. G.: 1993, *Monthly Weather Review* **121**, 1847
- Smolarkiewicz, P. K. and Margolin, L. G.: 1997, *Atmosphere Ocean* **35**, 127
- Smolarkiewicz, P. K. and Margolin, L. G.: 1998, *Journal of Computational Physics* **140**, 459
- Smolarkiewicz, P. K. and Prusa, J. M.: 2002, *International Journal for Numerical Methods in Fluids* **39**, 799
- Smolarkiewicz, P. K. and Pudykiewicz, J. A.: 1992, *Journal of Atmospheric Sciences* **49**, 2082
- Smolarkiewicz, P. K. and Szmelter, J.: 2009, *Journal of Computational Physics* **228**, 33
- Spitzer, L.: 1962, *Physics of Fully Ionized Gases*
- Stern, D.: 1967, *J. Geophys. Res.* **72**, 3995
- Stern, D. P.: 1970, *American Journal of Physics* **38**, 494
- Stern, D. P.: 1976, *Reviews of Geophysics and Space Physics* **14**, 199
- Stevenson, J. E. H., Parnell, C. E., Priest, E. R., and Haynes, A. L.: 2015, *Astron. Astrophys.* **573**, A44
- Sturrock, P. A.: 1966, *Nature* **211**, 695
- Sweet, P. A.: 1958, in B. Lehnert (ed.), *Electromagnetic Phenomena in Cosmical Physics*, Vol. 6 of *IAU Symposium*, p. 499

- Syrovatskii, S. I. and Shmeleva, O. P.: 1972, *Sov. Astronom.* **16**, 273
- Taylor, J. B.: 1974, *Physical Review Letters* **33**, 1139
- Taylor, J. B.: 1986, *Reviews of Modern Physics* **58**, 741
- Taylor, J. B.: 2000, *Physics of Plasmas* **7**, 1623
- Temmer, M., Veronig, A. M., Kontar, E. P., Krucker, S., and Vršnak, B.: 2010, *Astrophys. J.* **712**, 1410
- Temmer, M., Veronig, A. M., Vršnak, B., Rybák, J., Gömöry, P., Stoiser, S., and Marićić, D.: 2008, *Astrophys. J.* **673**, L95
- Tsuneta, S.: 1996, *Astrophys. J.* **456**, L63
- van Ballegooijen, A. A. and Cranmer, S. R.: 2010, *Astrophys. J.* **711**, 164
- van Ballegooijen, A. A. and Martens, P. C. H.: 1989, *Astrophys. J.* **343**, 971
- Verbunt, F.: 1982, *Space Sci. Rev.* **32**, 379
- Vourlidas, A., Buzasi, D., Howard, R. A., and Esfandiari, E.: 2002, in A. Wilson (ed.), *Solar Variability: From Core to Outer Frontiers*, Vol. 506 of *ESA Special Publication*, pp 91–94
- Vourlidas, A. and Howard, R. A.: 2006, *Astrophys. J.* **642**, 1216
- Wheatland, M. S.: 1999, *Astrophys. J.* **518**, 948
- Wiegmann, T. and Sakurai, T.: 2012, *Living Reviews in Solar Physics* 9
- Wiegmann, T. and Solanki, S. K.: 2004, *Solar Phys.* **225**, 227
- Wilmot-Smith, A. L.: 2015, *Philosophical Transactions of the Royal Society of London Series A* **373**, 20140265
- Woltjer, L.: 1958, *Proceedings of the National Academy of Science* **44**, 489
- Xia, C., Keppens, R., and Guo, Y.: 2014, *Astrophys. J.* **780**, 130
- Zweibel, E. G. and Yamada, M.: 2009, *Ann. Rev. Astron. Astrophys.* **47**, 291

## Publications attached with the thesis

1. *On the role of topological complexity in spontaneous development of current sheets*, **Sanjay Kumar**, R. Bhattacharyya, and P. K. Smolarkiewicz, *Physics of Plasmas*, **22**, 082903 (2015).
2. *Continuous development of current sheets near and away from magnetic nulls*, **Sanjay Kumar** and R. Bhattacharyya, *Physics of Plasmas*, **23**, 044501 (2016).