

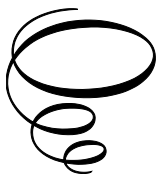
Particle Kinetics and Dynamics in Flaring Atmospheres Leading to Sunquakes

Particle Kinetics and Dynamics in Flaring Atmospheres Leading to Sunquakes

By

Valentina Zharkova and Serhii Zharkov

**Cambridge
Scholars
Publishing**



Particle Kinetics and Dynamics in Flaring Atmospheres Leading to Sunquakes

By Valentina Zharkova and Serhii Zharkov

This book first published 2025

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

Copyright © 2025 by Valentina Zharkova and Serhii Zharkov

All rights for this book reserved. No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the copyright owner.

ISBN: 978-1-0364-5856-0

ISBN (Ebook): 978-1-0364-5857-7

Contents

1	The observational constraints in solar flares and interplanetary space	1
1.1	Solar flares	1
1.1.1	Summary of HXR and SXR emission features	2
1.1.1.1	Lightcurves	2
1.1.1.2	Hard X-ray footpoint and coronal sources	5
1.1.1.3	Hard X-ray and gamma-ray source geometry	5
1.1.2	Magnetic Field Changes Associated with Flares	6
1.1.2.1	Overall topological magnetic field changes	8
1.1.2.2	Local magnetic field variations	9
1.1.2.3	Morphology of the active region NOAA 11283	10
1.1.3	Energy spectra of HXR emission	11
1.1.3.1	Key features of HXR spectra in flares	11
1.1.3.2	Differences in footpoint spectral indices	12
1.1.3.3	Electron numbers	13
1.2	Light curves and energy spectra of Gamma-rays	14
1.2.1	γ -ray lightcurves (GRLs)	14
1.2.2	Energy spectra and abundances of ions in flares	15
1.2.3	Ion numbers	16
1.3	Multi-wavelength emission in flares	17
1.3.1	Soft X-ray and UV emission	17
1.3.2	H α and white light emission	17
1.3.3	Flare emission linked to magnetic topology	18
1.3.4	Sunquakes induced by solar flares	20

1.4	Critical issues for the interpretation of flares	23
1.5	Reconnecting Current Sheets in the interplanetary magnetic field	27
1.5.1	Heliospheric current sheet	28
1.5.1.1	Sector boundary crossing (SBC)	28
1.5.1.2	Electron dynamics in a vicinity of the main sector boundary	31
1.5.1.3	Averaged ion velocities and plasma densities at SBC	33
1.5.2	Current sheets associated with Interplanetary Coronal Mass Ejections (ICME)	34
1.5.2.1	Existence of additional current sheets	34
1.5.2.2	Current sheets formed by ICME	34
1.5.2.3	Current sheets with magnetic islands	37
1.5.3	Pitch-angle distributions in solar wind	40
1.6	Summary of the outstanding problems in solar wind data	43
2	Particle acceleration in a 3D RCS - Test Particle approach	63
2.1	General introduction	63
2.2	Acceleration in 3D RCS with a single X-nullpoint	66
2.2.1	Basic Physics	66
2.2.1.1	Magnetic field topology	66
2.2.1.2	Super-Dreicer drifted electric field	69
2.2.1.3	Particle Motion Equations	72
2.2.2	Simulation Results	72
2.2.2.1	Accepted Parameters	72
2.2.2.2	Separation of particles with the opposite charges	74
2.2.2.3	Transit and bounced particles	77
2.2.2.4	Particle energy gains	79
2.2.2.5	The simulated energy gains	81
2.2.2.6	Particle drifts in RCSs of different thickness	83
2.3	Particle acceleration in multiple O- and X- nullpoints. Test particle approach.	87
2.3.1	Magnetic and electric field topologies	87
2.3.1.1	Magnetic field in islands	87
2.3.1.2	Reconnection electric field	88

2.3.2	Simulation results	90
2.3.2.1	Particle trajectories in magnetic islands	90
2.3.2.2	Preferential ejection of particles with the opposite charges	94
2.3.2.3	The effect of the initial position: transit and bounced particles	95
2.3.2.4	Energy gains	98
2.4	Test particle approach: advantages and limitations	104
2.4.1	Main features of accelerated particles in RCS with single X-nullpoint	104
2.4.2	Summary of the features of acceleration in RCS with magnetic islands	105
2.4.3	Limitations of test particle approach	108
2.4.3.1	The polarization electric field	109
2.4.3.2	Turbulent electric fields	109
3	Particle acceleration In a 3D reconnecting current sheet. Particle-in-cell approach	113
3.1	Introduction	113
3.2	Particle acceleration in RCS with a single X-nullpoint	114
3.2.1	Model Description	114
3.2.1.1	Magnetic & Electric field topology near a single X-nullpoint	115
3.2.1.2	Motion Equation	115
3.2.1.3	The plasma feedback	116
3.2.1.4	Accepted parameters	117
3.2.2	Simulation Results of a single X-nullpoint	118
3.2.2.1	Separation of particles of the opposite charges	118
3.2.2.2	Transit versus bounced particles of the same charge	119
3.2.2.3	The polarisation and turbulent electric fields in RCS with a single X-nullpoint	121
3.2.2.4	The energy distributions	122
3.2.2.5	Comparison of 2.5D and 3D simulation effects	125
3.2.3	Electron PADs in the vicinity of a single X-nullpoint	127

3.3	Particle acceleration in an RCS with magnetic islands	130
3.3.1	Background field topology	131
3.3.2	Simulation results	133
3.3.2.1	Particle separation in coalescent magnetic islands:	133
3.3.2.2	Polarisation electric field in coalescent magnetic islands	134
3.3.2.3	Differences in particle energy gains in coalescent magnetic islands	135
3.3.2.4	Squashed magnetic islands	136
3.3.2.5	3D effects	138
3.3.2.6	Energy spectra	138
3.3.3	Electron PADs in magnetic islands	140
3.3.3.1	Weak guiding field	142
3.3.3.2	Strong guiding field	143
3.3.4	Comparison with in-situ observations	145
3.3.4.1	Observations with the STEREO and WIND missions	145
3.3.4.2	New observations with Parker's Solar Probe	148
3.4	Kinetic turbulence generated in a 3D reconnecting current sheet	149
3.4.1	Simulation model and basic results	149
3.4.1.1	Simulation model	149
3.4.1.2	Suppression of kink instability by a strong guiding field	150
3.4.1.3	Simulation results of 3D reconnection with magnetic islands	151
3.4.1.4	Evaluation of generated turbulence	152
3.4.2	Generation of kinetic turbulence	154
3.4.2.1	Wavenumber spectra of electromagnetic fields	154
3.4.2.2	Phase space distributions	154
3.4.3	Frequency analysis of generated turbulence	156
3.4.3.1	Wavelet analysis	156
3.4.3.2	Frequency spectra of electromagnetic fields	156
3.5	Role of magnetic topology in particle energisation in RCS	158

3.5.1	Evaluation of energy gains in different magnetic configurations	159
3.5.2	Pitch-angle distributions in vicinity of RCS	160
3.5.3	Summary of the kinetic turbulence properties in RCS	162
3.5.4	General points	165
4	Electron beam precipitation - continuity equation approach	177
4.1	Introduction	177
4.2	Interaction of precipitating particles with the ambient plasma	179
4.2.1	Rutherford scattering of charged particles	179
4.2.2	Energy loss and momentum variations	183
4.2.2.1	Energy and momentum loss rates	184
4.2.2.2	Energy and pitch angle losses for a cold target approach	185
4.2.3	Collisional energy losses for precipitating electrons	187
4.2.3.1	Basic equations for particle energy and pitch angle variations	187
4.2.3.2	Energy losses in Coulomb collisions	189
4.2.3.3	Collisional stopping depth	191
4.2.3.4	The effect of pitch-angle scattering	191
4.2.3.5	Kinetics of a particle beam in pure converging magnetic field	193
4.2.3.6	Energy losses in the electric field induced by beam electrons	196
4.2.4	Electron energy losses in a self-induced electric field	196
4.2.4.1	Estimation of the Ohmic energy losses	196
4.2.4.2	Electric stopping depth	197
4.2.4.3	Comparison of heating rates by collisional and Ohmic losses	198
4.2.5	Estimations of the electron beam stability	201
4.3	Continuity equation approach for electrons with collisional losses	202
4.3.1	Continuity equation for pure Coulomb collisions	202
4.3.2	Solutions of the updated CE for differential density	205
4.3.3	Differential energy spectra	207
4.3.4	Mean electron spectra	208

4.3.5	Beam electron densities	210
4.3.6	Hard X-ray bremsstrahlung emission by beam electrons	211
4.3.6.1	General formulae	211
4.3.6.2	Comparison of HXR photon spectra for the original and updated CE	216
4.3.7	Heating functions	218
4.3.7.1	Heating by bombarding particles in the continuity equation approach	218
4.3.7.2	Heating by particle beams in the flux conservation approach	220
4.4	The continuity equation approach for electrons - pure electric field	222
4.4.1	Kinetic solutions for a pure electric field	222
4.4.1.1	Continuity equation solution for constant electric field	224
4.4.1.2	Simulated differential energy spectra	226
4.4.1.3	Continuity equation solution for variable electric field	227
4.4.1.4	Mean electron fluxes	233
4.4.1.5	Photon spectra	234
5	Proton beam kinetics: continuity equation and particle-wave interaction	237
5.1	Proton beam distribution function	237
5.1.1	Effect of Coulomb collisions on proton precipitation	237
5.1.2	Effect of a self-induced electric field on proton precipitation	240
5.1.3	Effect of magnetic field convergence on proton precipitation	241
5.1.4	Effect of wave-proton interaction	241
5.1.5	Collisions versus kinetic Alfvén waves: the effect on proton precipitation	244
5.1.6	Fokker-Planck equation for proton beam	247
5.1.6.1	General form of equation	247
5.1.6.2	Collisions, KAWs and magnetic field	247
5.2	Precipitation of proton beam: numerical simulations	249

5.2.1	Numerical calculation of proton beam distribution function	249
5.2.2	Accepted parameters	250
5.2.3	Proton beam distribution functions	253
5.3	General discussion of proton and electron precipitation	255
5.3.1	Beam spectra at precipitation	255
5.3.2	Energy and momentum transfer	255
6	Stationary and impulsive injection of electron beams	261
6.1	General comments on particle and energy transport	261
6.2	Problem formulation	263
6.2.1	The Fokker-Planck equation	263
6.2.2	Normalisation of a distribution function	265
6.2.3	The dimensionless equations	266
6.2.4	Integral characteristics of an electron beam	269
6.3	Method of simulations	270
6.4	Time-dependent Fokker-Planck equation	271
6.4.1	Initial and boundary conditions	272
6.4.2	Stationary injection of a power-law electron beam	273
6.4.2.1	The electric field induced by beam electrons	273
6.4.2.2	Fraction of precipitating and returning electrons	274
6.4.2.3	The effect of a self-induced electric field on distribution functions	277
6.4.2.4	The effects of electric field on electron density	284
6.4.3	Steady injection of power law electron beams with a lower energy part	285
6.4.3.1	Electron beam distribution functions	285
6.4.3.2	Relaxation to a steady state	286
6.4.3.3	The effect of electric field	293
6.4.4	Steady injection into the atmospheres with magnetic field convergence	294
6.4.4.1	Exponential approximation	295
6.4.4.2	Parabolic approximation	295
6.4.4.3	Hybrid approximation	296
6.4.4.4	Magnetic field model fitted to the observations	297

6.4.4.5	The effect of a converging magnetic field on beam distributions	298
6.4.5	Electron beam variations in converging magnetic field	299
6.4.5.1	Pitch-angle diffusion in converging magnetic field	299
6.4.5.2	Electron beam density variations	300
6.4.5.3	Mean electron fluxes	302
6.4.5.4	Plasma heating by a stationary beam in converging magnetic field	305
6.5	Impulsive injection	306
6.5.1	Mean electron flux for the beam impulse	308
6.5.2	Energy deposition by the beam impulse	310
6.6	Conclusions	313
7	Hydrodynamic response to particle injection	317
7.1	Formulation of the problem	317
7.1.1	Hydrodynamic equations in 1D atmosphere	318
7.1.2	Additional equations	319
7.1.3	The initial and boundary conditions	320
7.2	Simulated hydrodynamic responses to heating by particle beams	322
7.2.1	The heating functions by high energy particles	322
7.2.2	Simulated heating functions	323
7.2.3	Hydrodynamics caused by electron beams	325
7.2.3.1	Temperature variations	327
7.2.3.2	Density variations	329
7.2.3.3	Macro-velocity variations	330
7.2.4	Hydrodynamics formed by mixed electron and proton beams	331
7.2.5	The momenta delivered by beams and hydrodynamic shocks	334
7.2.5.1	The momentum delivered by a proton and/or electron beam	334
7.2.5.2	The momentum delivered by a hydrodynamic shock	335

7.2.6	Comparison of the ambient heating by electrons and protons for the flare of 28 October 2003	336
7.3	Case study of a hydrodynamics of the flare of 25 July 2004	340
7.3.1	Observations	340
7.3.1.1	Magnetic field variations	342
7.3.1.2	Morphology of flaring kernels in the main event	345
7.3.1.3	Correction of the HXR photon energy flux for Ohmic losses	346
7.3.2	Hydrodynamics of the ambient plasma	350
7.4	Case study of the 6 September 2017 flare	351
7.4.1	Active region and magnetic field evolution	351
7.4.2	γ - and hard X-ray bremsstrahlung emission observed by KONUS/WIND	354
7.4.3	Lyman- α emission	357
7.4.4	RHESSI HXR emission	358
7.4.5	Simulation of hydrodynamic responses	359
7.4.6	Probing hydrodynamic results with the EIS observations	365
7.4.7	Properties of hydrodynamic shocks	367
7.5	Conclusions	369
8	Hard X-ray bremsstrahlung emission and polarisation	371
8.1	Stokes parameters for HXR emission	372
8.1.1	Geometry of observations	374
8.1.2	Non-relativistic HXR cross-sections	377
8.1.3	Relativistic angle-dependent cross-sections	379
8.2	Simulation results	382
8.2.1	Time-dependent Hard X-ray photon spectra for a short impulse	382
8.2.2	HXR emission with non-relativistic cross-sections for steady injection	384
8.2.3	HXR emission with relativistic cross-sections for steady injection	391
8.2.3.1	Depth variations of HXR bremsstrahlung emission	391
8.2.3.2	Integrated HXR bremsstrahlung emission	399

8.2.4	HXR bremsstrahlung directivity and polarisation for a steady beam injection	400
8.2.4.1	Depth variations of the HXR bremsstrahlung polarisation	400
8.2.4.2	Depth variation of HXR bremsstrahlung directivity	402
8.2.4.3	Integrated HXR bremsstrahlung directivity and polarisation	404
8.3	Comparison with observations	405
8.3.1	HXR bremsstrahlung photon spectra	405
8.3.2	HXR bremsstrahlung directivity and polarisation	407
8.3.3	Relationships between electron and HXR photon spectra and electron numbers	409
8.3.3.1	Particle number	409
8.3.3.2	HXR spectral evolution at lower energies	412
9	Microwave emission and polarisation	415
9.1	General comments	415
9.2	Evaluation of models for electron precipitation	417
9.3	Gyrosynchrotron plasma emissivity and absorption coefficient	419
9.4	Gyrosynchrotron emission from a homogeneous source	422
9.4.1	Depth variations of MW emission	422
9.4.1.1	Effect of a magnetic field convergence	425
9.4.1.2	Effects of a self-induced electric field	426
9.4.1.3	Effect of a power-law index of beam electrons	429
9.4.1.4	Effect of the ambient plasma density	430
9.4.2	Gyrosynchrotron emission from a whole coronal magnetic tube	432
9.5	Comparison with observations	436
9.5.1	Flare of 23 July 2002	436
9.5.2	Flare 10 March 2001	438
9.5.2.1	Light curves of MW and HXR emissions	439
9.5.2.2	MW and HXR images	442
9.5.2.3	Deduced parameters	444
9.5.3	Simulated HXR and MW emission	445

9.5.3.1	HXR emission and directivity	445
9.5.3.2	MW emission	450
9.5.3.3	MW emission directivity	454
9.5.3.4	Hard X-ray emission	456
9.5.3.5	MW emission and polarization	457
9.6	Conclusion	461
10	Wave-particle interaction and space-charge structures in radio emission	467
10.1	Introduction	467
10.2	Kinetic simulation of particle-wave interaction in collisional atmosphere	474
10.2.1	Fokker-Planck and wave equations	474
10.2.2	Electron beam distribution functions	475
10.2.3	Method of solution and model parameters	475
10.2.4	Electric field effects on Langmuir turbulence	475
10.2.4.1	Selection of the initial beam distribution	475
10.2.4.2	Electron distribution during precipitation	476
10.2.4.3	Generation of Langmuir waves	478
10.3	Periodic space-charge waves in magnetised collisionless plasma	482
10.3.1	Equations of coupled oscillations	483
10.3.2	Periodic solutions	484
10.3.2.1	General solutions	484
10.3.2.2	Particular solutions	485
10.3.3	Analysis of periodic solutions	486
10.4	Application to the particle-wave interaction in solar flares	489
10.4.1	General estimations for flaring atmospheres	489
10.4.2	Links to the kinetic simulation results	490
10.4.3	Electromagnetic radiation from the periodic wave plasma	492
10.4.4	Observations of zebra patterns in flares	495
10.5	Conclusions	497
11	Hydrogen emission in flaring atmospheres heated by particle beams	501
11.1	Introduction	501
11.2	Non-thermal excitation and ionisation rates	504

11.2.1	Beam electron density	504
11.2.2	Non-thermal hydrogen excitation rates	506
11.2.3	Non-thermal hydrogen ionisation rates	507
11.2.4	Comparison of thermal and non-thermal excitation and ionisation rates	508
11.3	Hydrogen emission produced by impacts with beam electrons	509
11.3.1	Physical conditions	509
11.3.2	Non-Local Thermal Equilibrium (NLTE) model for hydrogen atoms	512
11.3.2.1	Statistical Equilibrium	512
11.3.2.2	Particle conservation	516
11.3.2.3	Radiative Transfer	516
11.3.2.4	Method of solutions and source functions	520
11.3.3	Intensities of emission in the lines and continua	521
11.3.3.1	Line emission	521
11.3.3.2	Continuum emission	521
11.3.3.3	Contribution Functions	523
11.3.4	Results of simulations	523
11.3.4.1	Analysis of optical depths in hydrogen lines	523
11.3.5	Line intensity profiles: core and wings	526
11.3.5.1	Balmer and Paschen lines: core and wing responses	526
11.3.5.2	Macrovelocity: Pseudo-continuous plasma macrovelocity distribution	532
11.3.5.3	Macrovelocity effects on line profiles	533
11.3.6	Simulations of Balmer and Paschen continua	539
11.3.6.1	Intensity enhancements	539
11.3.6.2	Formation regions of Balmer and Paschen continua	544
11.4	Comparison with observations	546
11.4.1	Comparison with H α line observations	546
11.4.1.1	Line profiles	546
11.4.1.2	Temporal variations	548
11.4.2	Comparison with the observations of Balmer continuum enhancement	550

11.4.3	Comparison with the observations of white light enhancements	551
11.4.4	Hydrogen $H\alpha$ line and white light (WL) emission in the 6 September 2017 flare	553
11.4.4.1	Images of $H\alpha$ -sources with red shifts	553
11.4.4.2	Stimulated versus observed $H\alpha$ line profiles	555
11.4.4.3	The observed versus simulated Paschen continuum (WL) emission	559
11.5	Lyman- α line and continuum emission	562
11.5.1	Lyman- α line profiles	562
11.5.2	Profiles of other Lyman lines	571
11.5.3	Thermal and non-thermal Lyman line profiles	573
11.5.4	Simulations of Lyman continuum emission	576
11.5.5	Comparison with the Ly- α line observations and models	579
11.5.6	Comparison with the observations of Lyman continuum enhancement	584
12	Sunquakes associated with solar flares	587
12.1	Detection of seismic signatures (sunquakes) in flares	587
12.1.1	Complex physics of processes leading to sunquakes	587
12.1.2	Helioseismic techniques for sunquake detection	590
12.1.2.1	The time-distance diagrams technique	590
12.1.2.2	The acoustic holography	591
12.1.2.3	The directional acoustic holography	592
12.2	Sunquakes detected with the SOHO/MDI data	596
12.2.1	The first sunquake of the 9th July 1996 flare	596
12.2.1.1	Summary of the observed sunquake properties	597
12.2.1.2	Discrepancies between the derived and model parameters	601
12.2.2	Observations with SOHO/MDI of other sunquakes	603
12.2.3	Sunquakes detected in the flare of 28 October 2003	604
12.2.3.1	The observed seismic sources	604
12.2.3.2	The momenta estimated from dopplergrams	609
12.2.3.3	Evaluation of possible agents delivering the momenta	610

12.2.3.4	Momenta delivered by hydrodynamic shocks	611
12.2.4	Detection of a shock moving into deeper interior	612
12.3	Detection of sunquakes with the GONG data	615
12.3.1	Data reduction and verification	615
12.3.1.1	Additional corrections for the GONG data	615
12.3.1.2	Comparison of the GONG and MDI results	617
12.3.2	Seismic sources observed by GONG in the flare of 14 December 2006	621
12.3.2.1	Flare Morphology and Evolution	621
12.3.2.2	Photospheric and chromospheric signatures for the flare of 14 December 2006	622
12.3.2.3	Photospheric velocities	624
12.3.2.4	Observations of sunquakes	624
12.3.2.5	General comments on seismic signatures in the 14 December 2006 flare	627
12.4	The sunquakes detected with the SDO/HMI data	630
12.4.1	Sunquakes recorded for 15 February 2011 flare	630
12.4.1.1	Active region features	631
12.4.1.2	Two seismic sources	632
12.4.1.3	The links to a magnetic rope ejection	634
12.4.2	Sunquake of the flare of 6 September 2011	642
12.4.2.1	Active region with X2.1 Flare	642
12.4.2.2	X-rays, H α and white light flare emission	642
12.4.2.3	Seismic signatures with directional acoustic holography	646
12.4.2.4	Time-distance diagram of the missed sunquake	648
12.4.3	Seismic signatures with a double bounce in the 6 September 2017 flare	649
12.4.3.1	General helioseismic detection results	649
12.4.3.2	Sunquakes detected with acoustic holography	649
12.4.3.3	Detection of seismic sources with time- distance diagram	652
12.4.3.4	Physical properties of the detected sunquakes	661
12.4.4	Generic signatures of flares with sunquakes	663

13 Acoustic waves generated in the interior by moving pin-point sources	665
13.1 Geometric properties of the generated acoustic waves: role of acoustic cut-off frequency	665
13.1.1 General comments on the ray theory of acoustic waves	665
13.1.2 Equation for scaled pressure perturbation and geometrical asymptotics	667
13.1.3 Initial conditions	671
13.1.3.1 General approach	671
13.1.3.2 Monochromatic spherical point source	672
13.1.4 Geometric properties of acoustic waves for a polytrope model	675
13.1.4.1 Individual ray solution	675
13.1.4.2 Caustics	680
13.1.4.3 Wavefield at the surface	682
13.2 Seismic wave theory applications to the solar interior	685
13.2.1 Stationary monochromatic source	687
13.2.2 Moving source	688
13.2.3 Supersonic source	690
13.2.4 Application to the seismic signatures in sunquakes	692
13.3 Simulated seismic signatures for a few solar flares	694
13.3.1 Hydrodynamic atmospheres simulated for two flares of the 6 September 2011 and 2017	695
13.3.2 Seismic hydrodynamic responses of the interior	698
13.3.2.1 Links of the hydrodynamic models of flaring atmospheres and interior	698
13.3.2.2 Phase velocity and skip distance of acoustic waves	700
13.3.3 Interpretation of the seismic signatures of the flare of 6 September 2011	702
13.3.4 Simulated acoustic waves versus observations in the flare 6 September 2017	705
13.4 Summary of particle kinetics and dynamics leading to sunquakes	708
13.4.1 Particle acceleration in the corona	708

- 13.4.2 Heating of flaring atmospheres by precipitating high-energy particle beams 713
- 13.4.3 Hydrodynamic responses of flaring atmospheres to high energy particles 715
- 13.4.4 Generation of seismic response by a supersonic pin-point source 717
- 13.5 General conclusion 717
 - 13.5.1 Analytical and numeric hydrodynamic seismic solutions 718
 - 13.5.2 Simulations of seismic signatures for flaring events . . . 718
- 13.6 Technical details: Monochromatic point source: eikonal solution for polytrope model 720
 - 13.6.1 Characteristics 720
 - 13.6.2 Caustics 723
 - 13.6.3 Reconstructing phase function φ 725

14 References 727

1

The observational constraints in solar flares and interplanetary space

Energetic particles play a significant role in energy transfer inside the Sun and from the Sun to interplanetary space and planetary atmospheres. Solar energetic particles (SEP) are often associated with solar flares, streaming into the solar atmospheres and towards the interplanetary space. There are also energetic particles of solar wind originally generated from the Sun, which can undergo additional acceleration in current sheets formed in the interplanetary space. The nature of their energisation and transport over the solar atmosphere or interplanetary space are important in understanding the processes governing the solar-terrestrial connection.

1.1 Solar flares

The complex processes of plasma heating in solar flares are associated with a primary release of magnetic energy via magnetic reconnection occurring in the corona [Priest and Forbes 2000a, Somov 2000] and subsequent acceleration of energetic particles [Vilmer et al. 2011, Zharkova et al. 2011a] precipitating along newly reconnected field lines [Holman et al. 2011, Kontar et al. 2011]. These processes happen within a very short timescale during flare onset and can be effectively diagnosed from the increase of intensities in flaring emission of hard X-rays (HXR), γ -ray (GR), soft X-rays (SXR), extreme ultra-violet (EUV), ultra-violet (UV) and optical emission [Matthews et al. 2015, and references therein].

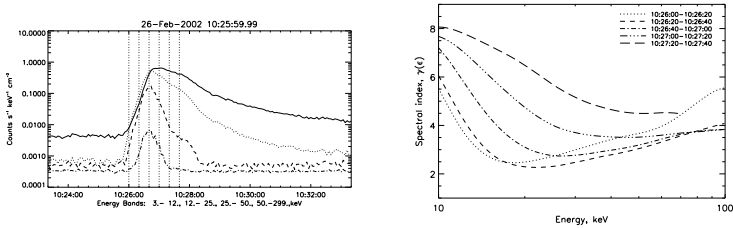


Fig. 1.1: Upper Panel: Temporal variation (4-second cadence) of the count rates in seven front RHESSI segments for the 2002, February26 solar flare (10:26 UT). The vertical lines show five 20-second accumulation intervals for spectral analysis. Lower Pane: Temporal variation of the energy-dependent photon spectral index $\gamma(\epsilon) = -d \log I(\epsilon)/d \log \epsilon$. Each line corresponds to one time interval. From Kontar and MacKinnon [2005].

Energetic electron beams precipitating into the flaring atmosphere [Brown 1971, Syrovatskii and Shmeleva 1972a;b] can account for HXR and MW emission [Holman et al. 2011, Kontar et al. 2011] while proton and ion beams [Vilmer et al. 2011] can account for observed γ -ray emission. The scenarios by which the magnetic field is reconfigured while triggering flaring events and converting the energy of magnetic field into radiation and macro-motions in flares are to a large extent defined by the initial magnetic field topologies of interacting loops and the trigger mechanisms that initiate the reconnection process in each flaring case [Priest and Forbes 2000a, Somov 2000].

1.1.1 Summary of HXR and SXR emission features

1.1.1.1 Lightcurves

Spatially-integrated hard X-ray lightcurves obtained by RHESSI or STIX payload shown as example in Fig.1.1, top plot, done for the flare of the 26 February, 2002, showing sharp increases (bursts) of hard X-ray intensity over a relatively short ($\sim 0.5 - 5$ seconds) timescale accompanied by a more slowly varying

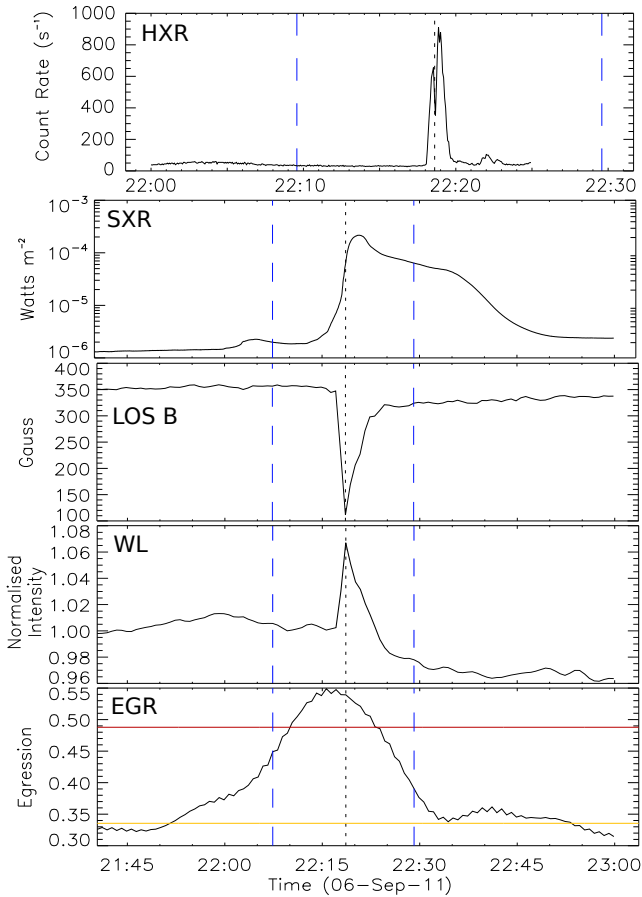


Fig. 1.2: Light curves for the flare of 6 September 2011 of RHESSI 100 – 300keV HXR (HXR), GOES (1.0 – 8.0Å) SXR (SXR), integrated HMI LOS magnetogram (LOS B), WL continuum (WL) and egression power (EGR). The HMI data products are integrated over the seismic signal. Black vertical dotted line denotes the sunquake onset time (22:18:37 UT) from time-distance diagrams (see chapter 12). Continuum emission shows a peak emission at 22:18:37 UT, coincident with quake onset and LOS magnetogram transient. Egression power, normalised with respect to quiet sun levels, peaks above a defined detection threshold (red horizontal line) of the local mean (yellow) plus 5σ within the flare temporal window (blue vertical lines). A courtesy of Macrae et al. [2018].

component with a timescale up to a few tens of minutes. The appearance of both sharp hard X-ray (HXR) bursts and steady increases in hard X-ray intensity suggest that electrons are accelerated on two fundamentally distinct timescales: a rapid acceleration to high, bremsstrahlung-emitting energies and a more stationary process that maintains the high-energy electron flux to produce steady hard X-ray emission for a substantial fraction of an hour or even longer.

At lower photon energies ϵ , where thermal bremsstrahlung dominates the total emission, the emission at higher photon energies is weighted more heavily by plasma at high temperatures T . As a result, the decrease in conductive cooling time with temperature ($\tau \sim T^{-5/2}$) leads to the emission at higher energies peaking sooner [Aschwanden 2007], and hence the lightcurve peaking progressively earlier with increase in photon energy. At higher energies, where non-thermal bremsstrahlung dominates, the relative timing of the emission at different energies depends on both the reduced “time-of-flight” for higher energy electrons before they impact upon the thick target of the lower atmosphere [which tends to advance high energy emissions relative to low energy ones – Aschwanden and Schwartz 1996, Brown et al. 1998] and on the decrease in collision frequency with energy [which tends to delay high energy emissions relative to low energy ones – Aschwanden et al. 1997]. Hard X-ray emission during flares typically shows a very steep spectrum at lower energies $\epsilon \sim 10$ keV, indicative of a thermal process. Although, the assumption of an isothermal source can be inconsistent with the observations of temporal variations of the hard X-ray spectrum in flares observed by RHESSI and now by STIX [Aschwanden 2007].

These spikes of HXR emission shown in Fig.1.2, top plot, for the flare of the 6 September 2011 are often followed by the increases of other high energy emission - soft X-ray (SXR), ultraviolet (UV) and extra UV (EUV) etc. SXR emission (see Fig.1.2, 2nd plot), transient variations of magnetic field (3rd plot) discussed in section 1.1.2, increase of white light emission (4th plot) and seismic egression power (bottom plot). SXR emission is assumed to be caused by the ambient plasma heating by particle beams produces emission in highly ionised elements, including e.g. Fe XXIV and Fe XXV ions [Porquet et al. 2001, Kawate et al. 2016c, Kuhar et al. 2016], and often shows a longer (hours) duration. Furthermore, there are observed blue-shifts in SXR and EUV emission with upward velocities of up to thousand $\text{km}\cdot\text{s}^{-1}$ [Antonucci et al. 1982,

Milligan et al. 2006a;b, Del Zanna 2008, Milligan and Dennis 2009, Polito et al. 2016]. In addition, observations of Lyman- α lines by the instruments with low spatial resolution show impulsive brightening of Lyman line emission and the appearance of either red or blue wing asymmetries at different times of flare developments [Druett and Zharkova 2018, Dominique et al. 2018]. This is also supported by brightening in Lyman continuum intensity, which becomes greatly enhanced in the head, resulting in strong flattening over the continuum wavelengths [Machado et al. 2018, Druett and Zharkova 2019].

1.1.1.2 Hard X-ray footpoint and coronal sources

The imaging capabilities of RHESSI, combined with its high spectral resolution, have allowed us to resolve in detail coronal sources [e.g., Masuda et al. 1994] and footpoints occurring in the same flare. See, for example, Figure 1.3 demonstrating the coronal and two footpoint sources in the flare of 23 July 2002 [Zharkova et al. 2005b]). This indicates a need to study the acceleration processes in flares that give rise to such different HXR sources.

The coronal source often appears before the main flare hard X-ray increase and the appearance of footpoints. In the impulsive phase, the coronal hard X-ray emission is, generally, well correlated in both time and spectrum with the footpoints [Emslie et al. 2003, Battaglia and Benz 2006]. These observations suggest strong coupling between the corona and chromosphere during flares, a coupling that is presumably related to transport of accelerated particles from one region to the other.

1.1.1.3 Hard X-ray and gamma-ray source geometry

Simultaneous hard X-ray and Gamma-ray images were first observed by RHESSI for the flare of 2002, July 23, as shown in Fig.1.4 [Hurford et al. 2003]. It has been established that the hard X-ray sources in this flare are spatially separated by several arcseconds from the 2.223 MeV neutron-capture Gamma-ray source. A similar, but smaller, separation was also detected for the “Halloween” flare of 2003, October 28 [Hurford et al. 2006].

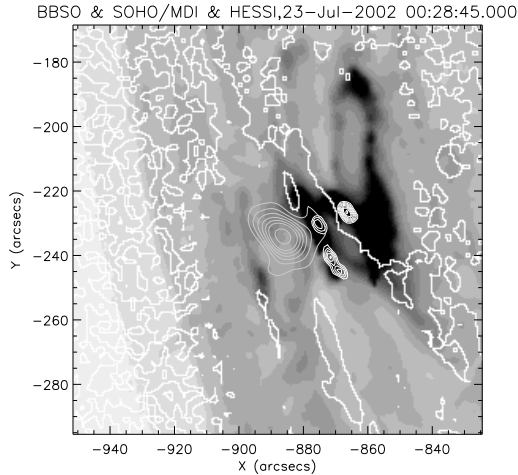


Fig. 1.3: RHESSI hard X-ray images of the flare of 2003, July 23, (white thin contours) taken at 00:28 UT, overlaid on the MDI neutral-line magnetograms (white thick contours) and $H\alpha$ images (negatives) taken at 00:28:45 UT. One extended (coronal A) and three compact (footpoint, B,C and D) hard X-ray sources are evident. From Zharkova et al. [2005b].

1.1.2 Magnetic Field Changes Associated with Flares

In Fig.1.5 there is an cartoon demonstrating the interaction of magnetic loops A and B appearing on the solar surface from beneath the existing magnetic loop C, which create two places marked as numbers 1 and 2 where the new loops touch the existing one and create reconnecting current sheets 1 and 2. These current sheets initiate the flare onset and generate energetic particles precipitating both downwards along the magnetic loops, creating all the multi-wavelength emission in HXR, SXR, UV, optical range seen from flares and upwards towards the interplanetary space and planets of solar system as solar energetic particles (SEPs).

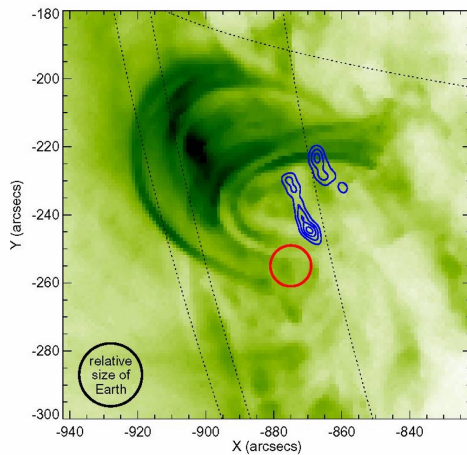


Fig. 1.4: The distant locations of HXR (blue lines) and γ -ray (red line) sources for the flare of 23 July 2003. Courtesy of Lin et al. [2003a].

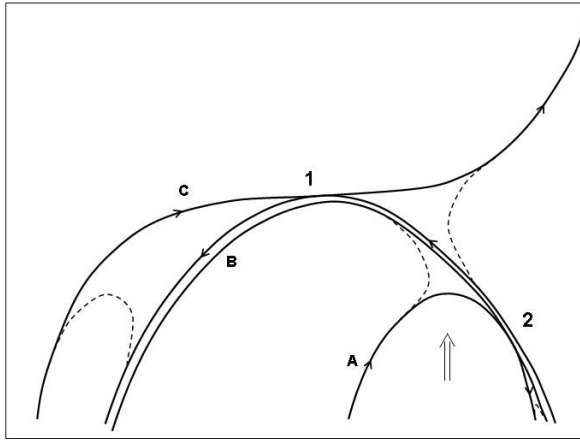


Fig. 1.5: Schematic drawings illustrating the presence of two simultaneous reconnection sites (labeled 1 and 2) in a flare. Loop system A is the main driver, and reconnection 1 is the main energy release site. Reconnected field lines are indicated by dashed curves (from Benz et al., 2005).

1.1.2.1 Overall topological magnetic field changes

The sharp temporal increases of hard X-ray emission are often closely correlated in time with the variations of a magnetic field measured on the photosphere [Kosovichev and Zharkova 2001, Sudol and Harvey 2005, Zharkova et al. 2005b]. For the flare of 2002 July 23, the magnetic flux change over the flare duration was about 1.2×10^{21} Mx; note that the magnetic flux in the areas not spanned by the magnetic inversion line do not show significant variations above the noise level (see Fig.1.6). The magnetic field changes occurring in around apparent magnetic neutral line (AMNL), in general, (see Fig.1.6) and in the locations of 3 HXR footpoint sources of the flare of 23 July 2002 [see Fig. 9 in Zharkova et al. 2005b] are irreversible, or step-like, e.g. the magnetic field reaches a new level of the steady state and does not return to a pre-flare

value [Kosovichev and Zharkova 2001, Sudol and Harvey 2005, Zharkova et al. 2005b].

The magnetic flux in the other areas of either positive or negative polarities, not including the magnetic inversion line, does not show noticeable variations above the noise level. A cross-correlation analysis with a time lag between the temporal magnetic variations of AMNL and the hard X-ray light curves, for the 23 July 2002 flare, reveals a noticeable positive correlation of 0.5-0.6, with the time lag being not bigger than 1-2 minute for all energy bands (see Fig.1.7). This observation strengthens the belief, on the theoretical grounds, that the irreversible changes in the magnetic field are responsible for the initiation and development of flare phenomena.

1.1.2.2 Local magnetic field variations

In order to detect magnetic field variations in the locations of HXR emission, the precise RHESSI hard X-ray images in the 40-80 KeV band with the four hard X-ray sources appearing during the course of the flare were overlaid onto the MDI magnetograms [Zharkova et al. 2005b]. The magnetic flux variations were extracted from the maximum areas covered by this hard X-ray emission for each minute before and after the flare onset for four hard X-ray sources (A,B,C,D) detected in the flare of 23 July 2002 (see Fig.1.8).

The source A is found not to be associated with any magnetic field changes, despite it appears in 12-25 KeV band 1 minute earlier than the other footpoint sources B, C and D, but still 1 minute later after a start of the magnetic changes. The source A is likely a projection of the top of the loop (see the TRACE image overlaid onto the H_{α} -image, Fig.1.3, the loop is embedded into the photosphere at the locations close to the footpoints (sources B, C and D, see section 1.1.1.2). The source A can be a good candidate for the site of primary electron acceleration in the corona because of the hard X-ray emission timing, energy and its relation with the radio emission discussed by Lin et al. [2003a], Krucker et al. [2003]. However, it does not show direct connections with the magnetic field locations, possibly, because of its occurrence on the loop's top and the loop tilt towards the limb.

The temporal variations of magnetic field in the footpoint sources B, C and D are presented in Fig. 1.8 (from the bottom to the top, respectively). The sources

B, C and D are clearly the footpoint locations and, hence, their connection with the magnetic field changes are much more pronounced. The changes in footpoints B and D are fully irreversible, the magnetic field in them decreases from -300 to -420 G, the source D has these changes from 00:26:00 UT for 2 minutes, which are followed at 00:29:00 UT by the magnetic changes in the sources B and C lasting for 2 and 4 minutes, respectively.

In the source C the magnetic changes are mostly reversible with the magnetic field first decreases from 400 G to 100 G and returns to about 300 G after the flare (Fig.1.8, bottom). Since in the source C a difference between the new level of magnetic field, achieved after any changes were stopped, and the pre-flare level is close to the magnitude of irreversible changes measured in the footpoints B and D, we can conclude that these changes are partially irreversible. The major part of these magnetic variations in the source C are reversible of the transient type, which are not real magnetic field changes but those caused by a short-term increase of the line intensity caused by the non-thermal excitation by precipitating high-energy electrons of the upper level of the Ni atom in the transition 6768 Å where the magnetic field is measured [see for details Zharkova and Kobylinskii 1993, Zharkova and Kosovichev 2002].

1.1.2.3 Morphology of the active region NOAA 11283

This schematic example of magnetic topology in flares shown in Fig.1.5 is demonstrated in active region (AR) NOAA 11283 which produced two X-class flares on September 6 and 7, 2011 showing the observed magnetic field changes [Liu et al. 2014a, Petrie 2016, Macrae et al. 2018] and flare energetics [Feng et al. 2013]. The X2.1 class flare occurred on September 6, 2011 produced ripples reflecting seismic response to the flare, shortly called a sunquake [Kosovichev and Zharkova 1998, Macrae et al. 2018].

The X2.1 flare starts with the activation of an S-shaped sigmoid, representing a flux rope, seen in the 94 Å AIA data (Fig.1.9, left plot)). During the flare onset (22:18:37 UT) there are observed two flaring loops and circular H α ribbon (Fig.1.9, right plot [Macrae et al. 2018]). NOAA 11283 undergoes a period of flux emergence prior to the September 6 2011 flare, leading to a fan-spine reconnection initiating the flare [Jiang et al. 2014]. This process leads to repeated eruptions with a stronger eruption to the south at 22:19 UT, followed by ribbons