DEPARTAMENT D'ASTRONOMIA I METEOROLOGIA

UNIVERSITAT DE BARCELONA

Near-relativistic electron events. Monte Carlo simulations of solar injection and interplanetary transport

Memòria presentada per
Neus Àgueda Costafreda
per optar al grau de Doctora
per la Universitat de Barcelona.
Barcelona, 20 de febrer de 2008

UNIVERSITAT DE BARCELONA

Programa de Doctorat d'Astronomia i Meteorologia

Bienni 2002–2004

Memòria presentada per **Neus Àgueda Costafreda** per optar al grau de Doctora per la Universitat de Barcelona

Directors de la tesi:

Dr. Blai Sanahuja Dr. David Lario Dr. Rami Vainio

Reconduïm-la a poc a poc, la vida,
a poc a poc i amb molta confiança,
no pas pels vells topants ni per dreceres grandiloqüents,
sinó pel discretíssim camí del fer i desfer de cada dia.

Reconduïm-la amb dubtes i projectes,
i amb turpituds, anhels i defallences;
humanament, entre brogit i angoixes
pel gorg dels anys que ens correspon de viure.

Miquel Martí i Pol

Als meus pares,

Acknowledgments

I would like to express my gratitude to all the people who have contributed to this work. I would have not been able to see its end without their support and encouragement.

I would particularly like to thank my three supervisors, Prof. Blai Sanahuja, Dr. David Lario and Dr. Rami Vainio for their guidance during these years. Thank you, Blai, for making this all possible by welcoming me into this PhD program, for your commitment and dedication, and for seeing this work through to its end.

I would like to thank David for his guidance and instruction, for asking me tough questions which I didn't always know how to answer and for all your constructive criticism. Thank you also for providing the particle data without which this thesis would not have been possible, and for your help in its understanding.

I would like to thank Rami, not only for his help and inspiration in the development of this work, but also for his personal guidance and for keeping me from being discouraged. Thank you, Rami, for helping me to face the many challenges that this project has presented.

Part of the thesis work was done while I was visiting Dr. David Lario at the Johns Hopkins University Applied Physics Laboratory. It is an honor to thank Edmond Roelof for illuminating the first steps of this project. I am also indebted to the many other people I met there who made my stay in the U.S. a pleasant one. Thank you Carole, for your friendship and care. Thank you Mary and Ed for the wonderful trips and excursions. Thank you Annemarie for opening your house and life to me, and for the countless late-night kitchen conversations.

Another part of this thesis was developed during several visits with Dr. Rami Vainio at the University of Helsinki. It is a pleasure to thank the Department of Physical Sciences for their hospitality. Thanks also to Matleena for sharing your apartment with me and for making me feel at home.

Thanks to Silja Pohjolainen for providing hard X-ray data from *Yohkoh* and *RHESSI*, and thank you for your endless patience answering my questions concerning its format. Many thanks to Michael L. Kaiser for the technical support he provided during the installation of the software required to plot radio dynamic spectra observed by the WAVES experiment on board *Wind*.

I also send my thanks to all the investigators I have met in workshops, schools and conferences, for spending your time discussing the results of this work with me and for suggesting new ideas or methods that could improve it. Special thanks to Jim Ryan, Angelous Vourlidas, Christina Cohen, Hillary Cane and Mihir Desai. I would also like to thank the Educational Office of the European Space Agency, the University of Alabama in Hunstville (U.S.) and the University of Barcelona for funding my assistance in these conferences.

Additionally, I would like to take this opportunity to express my gratitude to the Ministerio de Ciencia y Tecnología (Spain) for the financial support received and the Centre de Computació de Catalunya (CESCA) for the computational support provided.

I would like to thank the members of the Department of Astronomy and Meteorology of the University of Barcelona for the support they have provided. Special thanks to Angels, who was here from the beginning and who has followed the evolution of this project from start to finish. I appreciate the help you have given me on countless occasions and your personal support. Many thanks to Rosa for her kindness and for the adventures we have shared. Thank you also for sharing your work with me and for your continued interest in mine. Thanks to Ada for helping me solve so many of the puzzles I have come across in the course of my work.

I would also like to mention some people from the department who have provided me with invaluable support. Thanks to Jordi and Gabi for the tech support and your never-ending patience. Thanks to Josep Vila for helping me when my computer crashed in the middle of writing this manuscript. Thanks to JR and Montse for your efficiency and help in all of the administrative aspects of this thesis over the years. Thanks to former and present students of the department for your kind company. Special thanks to Aina, Guillem, Salvador, Valentí, Pol, Fransesc, Cristina, Eduard, Josep Maria, Gemma and Carme.

A special thanks as well to those people who have played a significant role in my life and whose company made my days more enjoyable and worth living. Thanks to my friends for their company over these last wonderful years; it wouldn't have been the same without all of you by my side. Special thanks to Carina for always taking care of me and for listening to all my life's ups and downs. Thanks to Chumi for his jokes and the laughs he provided. A particular thanks to Dani and Cris for the Sunday afternoon teas, to Marc for his faith and dedication, and to Xavi for the practical advice. Thanks to Pau for the hugs and the moments we have shared. Many thanks to Jordi for always being ready to take all of us to the mountains. I would never have survived without the beautiful hikes.

Thanks to my colleagues with whom I have shared lunchtime at the picnic tables in front of Geo; it was the best part of the day. Thanks to Meritxell for not getting discouraged and for insisting that we see each other during the busiest part of writing this thesis. A particular

thanks to Eva for her assistance in the graphical design. Special thanks to Montserrat Noguera and Anna Ruiz for helping me stay healthy and happy. To Fabiana, Corita and Montse my most sincere Namaste. Thanks also to JC for the hilarious final week.

I cannot finish without saying how grateful I am to my family who has encouraged and supported my studies over the years. Thanks to Anna, for providing a reference and an example to follow. Thanks to Alba, for always standing by my side. Thanks to my parents for teaching me that nothing is won without hard work and for instilling in me the stubbornness to always finish what I start.

Last but not least I would like to acknowledge Sam for putting up with me while I was finishing this manuscript. Thank you, Sam, for reading this manuscript and suggesting stylistic changes. And thank you for keeping me smiling.

Contents

1 Introduction **1**

1.1 Solar sources of near-relativistic electron events 1
1.2 Insights into solar sources from in-situ NR electron events 2
1.3 Flare associations 4
1.4 Signatures of shock acceleration 10
1.4.1 Solar type II burst associations 11
1.4.2 Correlation between intensity peaks and CME speeds 12
1.4.3 Long-duration beam-like pitch-angle distributions 12
1.4.4 Spectral variations 13
1.4.5 Multispacecraft observations 15
1.5 Observation of two-phase electron events 15
1.6 Aims of this thesis 19

2 Instrumentation and data analysis **21**

2.1 The Advanced Composition Explorer 21
2.2 The EPAM experiment. Data sets 23
2.3 Other observational data 26
2.4 Modeling sectored intensities 27
2.4.1 Definition of the sectors 27
2.4.2 Pitch-angle distributions 28
2.4.3 Angular response model of sectors 30
2.4.4 View boundaries 34
2.4.5 Sectored Green's functions 37

3 Interplanetary particle transport model **41**

3.1 Interplanetary particle transport models 41
3.1.1 Scatter-free transport 42
3.1.2 Focused transport 44
3.1.3 Diffusive transport 47
3.1.4 Numerical methods: finite-differences and Monte Carlo 48

3.2 Tracking particles . . . 49
3.3 Modeling pitch-angle scattering . . . 51
3.3.1 Isotropic scattering . . . 51
3.3.2 μ-dependent scattering . . . 51
3.3.3 Particle mean free path . . . 54
3.4 Monte Carlo radial step . . . 56
3.5 Counting particles . . . 57
3.6 Scheme of the code and simulation parameters . . . 58
3.7 Code testing . . . 60
3.7.1 Analytical solutions . . . 60
3.7.2 Comparison with a finite-differences transport code . . . 63

4 Modeling solar NR electron events 67
4.1 Fitting procedure . . . 67
4.1.1 Deconvolution of the sectored intensities . . . 67
4.1.2 Injection function . . . 70
4.1.3 Goodness of the fit . . . 71
4.2 Deconvolution test . . . 71
4.2.1 Stable synthetic magnetic field . . . 75
4.2.2 Varying magnetic field . . . 85
4.3 Measurement errors . . . 89
4.3.1 Intensity errors . . . 89
4.3.2 Magnetic field errors . . . 90

5 Study of solar NR electron events. I 95
5.1 Selection criteria . . . 95
5.1.1 Solar wind and IMF . . . 96
5.1.2 Characteristics of the NR electron events . . . 97
5.1.3 Associated electromagnetic emissions . . . 99
5.2 The 2000 May 1 event . . . 102
5.2.1 Electromagnetic emissions . . . 102
5.2.2 In-situ energetic particles . . . 103
5.2.3 Deconvolution of the NR electron event . . . 106
5.3 The 2002 October 20 event . . . 113
5.3.1 Electromagnetic emissions . . . 113
5.3.2 In-situ energetic particles . . . 114
5.3.3 Deconvolution of the NR electron event . . . 115

6 Study of solar NR electron events. II **123**
6.1 The 2004 September 19 event . . . 123
6.1.1 Electromagnetic emissions . . . 123
6.1.2 In-situ energetic particles . . . 124
6.1.3 Deconvolution of the NR electron event . . . 126
6.2 The 2001 December 26 event . . . 130
6.2.1 Electromagnetic emissions . . . 130
6.2.2 In-situ energetic particles . . . 131
6.2.3 Deconvolution of the NR electron event . . . 133
6.3 The 1998 May 27 event . . . 138
6.3.1 Electromagnetic emissions . . . 138
6.3.2 In-situ energetic particles . . . 139
6.3.3 Deconvolution of the NR electron event . . . 141
6.4 The 2000 July 14 event . . . 146
6.4.1 Electromagnetic emissions . . . 146
6.4.2 In-situ energetic particles . . . 146
6.4.3 Deconvolution of the NR electron event . . . 149
6.5 The 2001 April 15 event . . . 154
6.5.1 Electromagnetic emissions . . . 154
6.5.2 In-situ energetic particles . . . 154
6.5.3 Deconvolution of the NR electron event . . . 157

7 Discussion **163**
7.1 Comments on the method . . . 163
7.2 Discussion of the results . . . 165
7.2.1 Injection profile and solar sources . . . 166
7.2.2 Interplanetary transport conditions . . . 172

8 Conclusions and future perspectives **177**

A Parker interplanetary magnetic field **181**
A.1 Length of a field line . . . 182
A.2 Particle transverse kinetic energy change . . . 183
A.3 Transit time along the field line . . . 183
A.4 Mirror point position . . . 184

Bibliography **185**