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TRF

Final Report

Particle Acceleration at Interplanetary Shocks and Related Phenomena

Principal Investigator:
Assoc. Prof. Dr. David Ruffolo

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Contract BRG4680002

Final Report

Particle Acceleration at Interplanetary Shocks and Related Phenomena

We gratefully acknowledge the researchers of this project:

1. Assoc. Prof. Dr. David Ruffolo
2. Asst. Prof. Manit Rujiwarodom
3. Dr. Alejandro Sáiz
4. Dr. Kanokporn Leerungnavarat
5. Dr. Piyanate Chuychai
6. Lect. Dr. Chanruangrit Channok
7. Lect. Paisan Tooprakai
8. Mr. Watcharawuth Norkaew
9. Mr. Kittipat Malakit
10. Mr. Jedsada Manyam
11. Mr. Kanin Aungskunsiri
12. Mr. Peera Pongkitiwanichakul
13. Mr. Nimit Kimpraphan
14. Miss Chanoknan Banglieng
15. Miss Achara Seripienlert
16. Mr. Preeksingh Anan
17. Miss Phantip Hosesomephan
18. Miss Rutairat Buakhaw
19. Miss Ketkaew Saikerdsri
20. Mr. Monchai Nimsuk
21. Mr. Jakapan Meechai
22. Mr. Pongsathon Jitsomboonmit
23. Miss Kuntida Suwatcharakunton
24. Mr. Nattapong Kamyan
25. Mr. Arak Makhathan
26. Mr. Narakorn Khawkho
27. Miss Sirinrat Sithajan
28. Mr. Teerawat Pralongkij
29. Mr. Pat Wongpan
30. Mr. Teerawong Rattanakorn
31. Mr. Rakpong Kittinaradorn

and our collaborators in Thailand:

1. Lect. Dr. Thiranee Khumlumlert (Naresuan Univ.)
2. Lect. Dr. Burin Asavapibhop (Chulalongkorn Univ.)
3. Lect. Dr. Tanin Nutaro (Ubon Rajathanee Univ.)
4. Lect. Supon Sumran (Ubon Rajathanee Univ.)
5. Lect. Maneenate Wechakama (Kasetsart Univ.)
6. Mr. Chakri Changchutoe (Chulalongkorn Univ.)

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Project Title: Particle Acceleration at Interplanetary Shocks and Related Phenomena

Principal Investigator: Assoc. Prof. Dr. David Ruffolo, Dept. of Physics, Faculty of Science, Mahidol University
E-mail address: david_ruffolo@yahoo.com
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The overall goals of this project were four-fold: 1) to investigate the processes of particle acceleration at interplanetary shocks, 2) to clarify fundamental properties of magnetic turbulence and its effects on particle transport in the solar system, 3) to work toward the establishment of a neutron monitor station at Doi Inthanon, and to analyze data from the worldwide neutron monitor network, and 4) to work toward advance warning of space weather effects, and the dissemination of information about space weather effects to the public, military, and private sectors in Thailand.

We have worked on 22 lines of research and trained/involved 31 local participants. Highlights of our results:

- Quantitative theory of effect of a finite time for shock acceleration, including charge-to-mass fractionation.
- Able to determine shock acceleration parameters from fits to data, with evidence in favor of proton-amplified waves for a strong event.
- Discovery of hardening (increased acceleration efficiency) in the simulated steady-state spectrum of shock acceleration at moderate particle energy, associated with a "mirroring peak" in the particle flux near a shock or narrow fluid compression.
- Computational determination of the steady-state spectrum of particle acceleration due to a fluid compression.
- Collected statistics on magnetic field-shock crossings, with evidence for universal behaviors.
- Proposing a mechanism for explaining particle acceleration at nearly perpendicular shocks.
- Analytic expressions, confirmed by computer simulations, indicate particle transport is dominated by 2D turbulence for strong non-axisymmetry, which is relevant to the outer heliosphere.
- Analytic expressions, confirmed by computer simulations, indicate regimes of slow diffusive and fast diffusive separation of nearly field lines.
- Explanation of observed dropouts of solar energetic particles, and a new view of the transport of energetic particles perpendicular to the mean magnetic field.
- Concept of a local trapping boundary within which turbulent field lines are temporarily trapped.
- Discovery that a general, coherent two-dimensional random walk can be suppressed by a systematic flow, which underlies the trapping of interplanetary field lines in filaments.
- Approval to set up the Princess Sirindhorn Neutron Monitor at Doi Inthanon. Successful "MicroMonitor" tests of hardware in Bangkok and at Doi Inthanon
- For solar energetic particle events with a strong anisotropy, the anisotropy x intensity profile is a good proxy for the injection profile.
- Solved a 16-year mystery: neutron monitor data are well explained by injection along both legs of a magnetic loop.
- First detailed evidence of interplanetary magnetic mirroring of energetic particles.
- First simulations of the pitch angle transport of energetic particles in an interplanetary magnetic loop.

- First inference of a flat magnetic fluctuation spectrum ($q<1$) in the transport of solar energetic particles.
- Precise timing diagnostics of relativistic particle acceleration by solar events.
- Examined the accuracy of a widely used technique to infer the start time of solar particle injection.
- Successful dissemination of space weather knowledge: Website ranked highly in Thailand for physics/astronomy, lectures, newspaper and magazine articles, TV interview.

Output of the project includes 9 articles in leading international journals (7 published, 1 in press, 1 submitted), 25 international conference presentations, 6 completed theses (3 Ph.D., 3 M.Sc.), and 2 completed B.Sc. senior projects.

Keywords: Cosmic rays, space physics, astrophysics, computer simulations, turbulence

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ชื่อโครงการ: การเร่งอนุภาคที่คลื่นกระแทกระหว่างดาวเคราะห์และปรากฏการณ์ที่เกี่ยวข้อง

ชื่อนักวิจัยหลัก: รศ.ดร.เดวิด รูฟโฟโล ภาควิชาฟิสิกส์ คณะวิทยาศาสตร์ มหาวิทยาลัยมหิดล
E-mail address: david_ruffolo@yahoo.com
ระยะเวลาโครงการ: 9 มกราคม 2546 – 8 มกราคม 2549

วัตถุประสงค์ของโครงการนี้มี 4 ข้อ: 1) การศึกษากระบวนการเร่งอนุภาคที่คลื่นกระแทกระหว่างดาวเคราะห์ 2) เพื่ออธิบายคุณสมบัติเบื้องต้นของการปั่นป่วนในสนามแม่เหล็กและผลกระทบต่อการขนส่งของอนุภาคในระบบสุริยะ 3) เพื่อพัฒนาสู่การติดตั้งสถานีตรวจวัดนิวตรอนที่ดอยอินทนนท์ และเพื่อวิเคราะห์ข้อมูลจากเครือข่ายเครื่องตรวจวัดนิวตรอนทั่วโลก และ 4) เพื่อพัฒนาสู่การเตือนภัยล่วงหน้าก่อนเกิดผลกระทบทางสภาพอวกาศ และการเผยแพร่ข้อมูลเกี่ยวกับผลกระทบทางสภาพอวกาศสู่ประชาชนทั่วไป ทหาร และภาคเอกชนในประเทศไทย

เราได้ทำโครงการย่อยจำนวน 22 เรื่อง และฝึกคนในประเทศไทยหรือให้มีส่วนร่วมในงานวิจัยจำนวน 31 คน โดยมีผลงานวิจัยสำคัญดังต่อไปนี้

- ทฤษฎีเชิงปริมาณของผลกระทบของเวลาที่จำกัดสำหรับการเร่งอนุภาคที่คลื่นกระแทก ร่วมทั้งการแยกตามประจุต่อมวล
- สามารถหาตัวแปรของการเร่งอนุภาคที่คลื่นกระแทกจากการฟิตข้อมูล โดยมีหลักฐานสนับสนุนว่ามีคลื่นที่ขยายโดยโปรตอนในกรณีเหตุการณ์รุนแรง
- การค้นพบประสิทธิภาพในการเร่งอนุภาคที่เพิ่มขึ้น จากการจำลองการเร่งอนุภาคพลังงานกลางที่คลื่นกระแทกในสภาวะคงตัว เนื่องจาก “พีคจากการสะท้อน” ในฟลักส์ของอนุภาคใกล้คลื่นกระแทกหรือบริเวณการอัดที่แคบ
- การคำนวณด้วยวิธีเชิงตัวเลขของจำนวนอนุภาคต่อพลังงาน จากการเร่งที่บริเวณการอัดของของไหลในสภาวะคงตัว
- สะสมสถิติเกี่ยวกับเส้นสนามแม่เหล็กที่ข้ามคลื่นกระแทก พร้อมด้วยหลักฐานสำหรับพฤติกรรมแบบยูนิเวอร์สัล
- เสนอกลไกเพื่ออธิบายการเร่งของอนุภาคที่คลื่นกระแทกแบบเกือบตั้งฉาก
- สูตรเชิงวิเคราะห์ ซึ่งยืนยันด้วยการจำลองเชิงคอมพิวเตอร์ บ่งชี้ว่าการขนส่งอนุภาคตามลักษณะของการปั่นป่วนแบบ 2D ในกรณีที่ไม่สมมาตรรอบแกน ซึ่งสำคัญในระบบสุริยะส่วนนอก
- สูตรเชิงวิเคราะห์ ซึ่งยืนยันด้วยการจำลองเชิงคอมพิวเตอร์ บ่งชี้ถึงสองช่วงการแยกแบบฟุ้งของเส้นสนามแม่เหล็กที่ใกล้กัน
- สามารถอธิบายการสังเกต “การตกหาย” ของอนุภาคพลังงานสูงจากดวงอาทิตย์ รวมถึงภาพใหม่ของการขนส่งอนุภาคพลังงานสูงในทิศทางตั้งฉากกับสนามแม่เหล็กเฉลี่ย
- ความคิดของขอบเขตการกักตัว โดยมีการกักเส้นสนามแม่เหล็กที่ปั่นป่วนไว้อย่างชั่วคราว
- ค้นพบว่าการเดินสุ่มแบบโคฮิเรนต์ในสองมิติโดยทั่วไป สามารถยับยั้งด้วยการไหลเชิงระบบ ซึ่งอยู่เบื้องหลังการกักตัวของเส้นสนามแม่เหล็กระหว่างดาวเคราะห์ในฟิลาเมนต์
- ได้รับอนุญาตติดตั้งสถานีตรวจวัดนิวตรอนสิรินธรที่ดอยอินทนนท์ สำเร็จในการทดสอบกระด้างภัณฑ์ด้วย “ไมโครมอนิเตอร” ที่กรุงเทพ และที่ดอยอินทนนท์
- ในเหตุการณ์ปลดปล่อยอนุภาคจากดวงอาทิตย์ที่มีแอไนสอโทรพีสูง แอไนสอโทรพีคูณกับความเข้มเป็นตัวแทนที่ดีสำหรับการปลดปล่อยนั้น
- ไขปริศนา 16 ปี โดยอธิบายข้อมูลจากเครื่องตรวจวัดนิวตรอนด้วยการปลดปล่อยอนุภาคตามทั้งสองขาของวงสนามแม่เหล็ก
- ครั้งแรกที่มีหลักฐานชัดเจนสำหรับการสะท้อนเชิงแม่เหล็กของอนุภาคพลังงานสูงระหว่างดาวเคราะห์
- ครั้งแรกที่มีการจำลองการขนส่งในมุมพิชของอนุภาคพลังงานสูงในวงสนามแม่เหล็กระหว่างดาวเคราะห์

- ครั้งแรกที่บ่งชี้ถึงสเปกตรัมการแปรปรวนในสนามแม่เหล็กแบบแบน (*q<1*) ในการขนส่งของอนุภาคพลังงานสูงจากดวงอาทิตย์
- ตัวบ่งชี้ที่แม่นยำเกี่ยวกับเวลาที่มีการเร่งอนุภาคพลังงานสูงโดยเหตุการณ์ที่ดวงอาทิตย์
- ได้ตรวจสอบความแม่นยำของเทคนิคที่ใช้อย่างกว้างขวางในการหาเวลาเริ่มต้นของการปลดปล่อยอนุภาคจากดวงอาทิตย์
- สำเร็จในการเผยแพร่ความรู้เกี่ยวกับสภาพอวกาศ โดยเวบไสท์ติดอันดับสูงในประเทศไทยในหมวดฟิสิกส์และดาราศาสตร์ และมีการบรรยาย บทความในหนังสือพิมพ์และนิตยสาร และการสัมภาษณ์ทางโทรทัศน์

ผลงานจากโครงการนี้ รวมถึงบทความในวารสารนานาชาติชั้นนำ (ตีพิมพ์แล้ว 7 เรื่อง ยอมรับการตีพิมพ์ 1 เรื่อง และส่งถึงวารสารแล้วอีก 1 เรื่อง) การเสนอที่ประชุมนานาชาติ 25 เรื่อง วิทยานิพนธ์ 6 เรื่อง (ป.เอก 3 และ ป.โท 3) และโครงการปีที่สี่ (ป.ตรี) 2 เรื่อง

คำหลัก: รังสีคอสมิก, ฟิสิกส์อวกาศ, ดาราศาสตร์, การจำลองด้วยคอมพิวเตอร์, ความปั่นป่วน

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Chapter 1

Objectives

The overall goals of this project were four-fold:

1. To investigate the processes of particle acceleration at interplanetary shocks.
2. To clarify fundamental properties of magnetic turbulence and its effects on particle transport in the solar system.
3. To work toward the establishment of a neutron monitor station at Doi Inthanon, and to analyze data from the worldwide neutron monitor network.
4. To work toward advance warning of space weather effects, and the dissemination of information about space weather effects to the public, military, and private sectors in Thailand.

The activities and results of our work are presented in the following sections, each section corresponding to one of these objectives.

The principal investigator was intimately involved in all work by our group. Specific contributions by others are noted in the following sections. All Thai research collaborators are listed, even if they are not official participants in this project (in which case their affiliation is listed in parentheses). Note also the extensive cross-referencing between these four categories of work and between individual sub-projects, indicating the strong synergy between performing all these categories of work in the same overall research project.

Chapter 2

Particle acceleration at shocks and compressions

Objective: To investigate the processes of particle acceleration at interplanetary shocks.

Note: The Principal Investigator was also involved in all of these subprojects.

2.1. Finite time shock acceleration

- Researcher: Chanruangrit Channok
- Key Points: Quantitative theory of effect of a finite time for shock acceleration, including charge-to-mass fractionation. Able to determine shock acceleration parameters from fits to data, with evidence in favor of proton-amplified waves for a strong event.
- Status: Paper published
- Output: 7, 11, 17, 24, 40, 45; Ph.D. thesis (Chanruangrit)

This work was motivated by recent progress in identifying the "seed" population of suprathermal ions that undergo acceleration at interplanetary shocks (e.g., Desai et al. 2003). In particular, we were invited by Mihir Desai (Univ. of Maryland) to help think about how to explain spectra of energetic storm particles (ESP) observed by the ACE spacecraft (Desai et al. 2004). Chanruangrit, a Ph.D. student at CU, spent 5 months in 2004 visiting U. Maryland (with support from the Commission for Higher Education) to work with Mihir and his supervisor Prof. Glenn Mason. Since then (June, 2005) Mihir has moved to the Southwest Research Institute, a non-profit research organization in San Antonio, Texas, and Glenn has moved to the Johns Hopkins University Applied Physics Laboratory in Maryland.

In this project we have developed a theory for finite-time shock acceleration, in contrast with the classical approach of an infinite available time and the assumption of a steady state. The key idea is that the residence time of particles at the acceleration site (e.g., at the shock) cannot be longer than the total duration of the acceleration process (i.e., the age of the shock). We point out that this should be the key mechanism explaining spectral rollovers of 0.1-10 MeV/nucleon in ESP ions. We have also developed a formalism in which a seed spectrum (particle density vs. momentum) is accelerated for a finite time.

In addition the total duration, other important parameters are the acceleration rate and the escape rate. For constant rates, we can use a combinatorial approach, which yields results with a simple interpretation. For more realistic, energy-dependent rates, we analytically and computationally solve the initial-value problem of a system of ODEs. (The analytic result is cumbersome, so we use it to check the computational results.) We also derive an original formula for the charge-to-mass dependence of the rollover energy. Fits to observed data provide estimates of the mean free path and its dependence on rigidity. Some events exhibit mean free paths like those found in fits to SEP data (see Chapter 4), but one event indicates very small mean free paths as hypothesized by Ng, Reames, and Tylka [1999, *Geophys. Res. Lett.*, 26, 2145] for very intense events, due to proton-amplified waves. This work has received substantial attention, e.g., a full paragraph on our work in a review of the field by *Eos*, the newsletter of the American Geophysical Union (Attachment 59). A paper has been published by *Astrophysical Journal Letters*.

2.2. Particle acceleration at fluid compressions

- Researcher: Kittipat Malakit
- Key Points: Discovery of hardening (increased acceleration efficiency) in the simulated steady-state spectrum of shock acceleration at moderate particle energy, associated with a "mirroring peak" in the particle flux near a shock or narrow fluid compression. Computational determination of the steady-state spectrum of particle acceleration due to a fluid compression.
- Status: Completed
- Output: 13, 38; M.Sc. thesis (Kittipat)

This work was begun some years ago, but was recently brought to a satisfactory conclusion by the hard work of Kittipat Malakit, as reported in his M.Sc. thesis. We present the first systematic study of steady-state particle acceleration at (non-relativistic) continuous fluid compressions.

Particle acceleration at shocks and fluid compressions is examined by numerically solving pitch angle transport equations for various magnetic field angles. The recently discovered jump in the steady-state particle density just upstream of an oblique shock (Ruffolo 1999, Gieseler et al. 1999) is much stronger for lower energy particles or greater shock obliquity. For narrow, oblique compressions the analogous feature is a peak in particle density in the compression region. We refer to both as "mirroring peaks" because for a compression we clearly see that the peak arises from magnetic mirroring and reflection of particles. Steady-state spectra of particles accelerated at an oblique shock or compression are hardened at low energy in association with the mirroring peak; magnetic mirroring leads to more effective acceleration. The spectral index at a given particle energy increases approximately linearly with compression width. Steady-state spectra from compression regions can also harden at high energy.

Kittipat presented this work at the 28^{th} ICRC in Tsukuba, Japan. It attracted extensive interest, especially among scientists who are interested in the spectral index yielded by this novel acceleration mechanism and also the possibility of a novel mechanism of charge-to-mass-dependent fractionation.

At one point, we planned to draft two international journal papers based on this work. However, they have been delayed so long that we have recently "written them off" (the only viable paper ideas that we have written off during the course of this grant). As stated in our proposal, there are many activities listed in our Methodology that could lead to output in international, refereed journals, so we have a sort of Darwinian selection process as to which actually "survive," producing the most important results and most worthy of spending time to prepare an article for a major journal. With output exceeding our stated goals, we can aim not only to publish, but to produce output with the strongest impact on the field that we can achieve. A related issue is that to maintain vitality, a research group should spend a major fraction of their time on new research of present interest to the scientific community. These particular papers were "written off" on the basis that, at this point in time, preparing journal articles on these older, more technical results (which are already documented in our conference papers and Kittipat's thesis) would draw too much time away from ongoing work that could have a substantial impact on new progress in the field.

2.3. Multiple magnetic field-shock crossings and shock drift acceleration

- Researcher: Peera Pongkitiwanichakul
- Key Points: Collected statistics on magnetic field-shock crossings, with evidence for universal behaviors. Proposing a mechanism for explaining particle acceleration at nearly perpendicular shocks.
- Status: Ongoing
- Output: 41, 50; M.Sc. thesis (Peera)

This work is in some sense an extension of the M.Sc. thesis of a previous student, but Peera has taken the work to a much higher level, producing fruitful results well beyond those envisioned by the Principal Investigator. We have developed a new computational algorithm for tracing turbulent magnetic field lines, which we believe to be faster for the same level of accuracy. This algorithm has been combined with a well-tested field-tracing code provided by Prof. William Matthaeus of the Bartol Research Institute, Univ. Delaware, USA (partially developed by Piyanate Chuychai during a trip to Bartol supported by a TRF Royal Golden Jubilee fellowship).

This project also involves new theoretical ideas, or more specifically, developing a new theory of shock acceleration of upstream energetic particles at a nearly perpendicular shock. In recent work we have improved our ideas of how to properly define the statistics of shock-magnetic field crossings, made use of the scattering mean free path as a scale length for defining whether crossings are single or multiple, and found multiple examples of universality in the results, which we are able to explain physically. These results should be of great interest to the community. In further work, Peera will develop these results, including connections with previous work, to the level of an international journal article.

Chapter 3

Magnetic turbulence and particle transport

Objective: To clarify fundamental properties of magnetic turbulence and its effects on particle transport in the solar system.

Note: The Principal Investigator was also involved in all of these subprojects.

3.1. Field line random walk in non-axisymmetric 2D+slab turbulence

- Researcher: Piyanate Chuychai
- Key points: Analytic expressions, confirmed by computer simulations, indicate particle transport is dominated by 2D turbulence for strong non-axisymmetry, which is relevant to the outer heliosphere.
- Status: Paper submitted
- Output: 9, 37; Part of Ph.D. thesis (Piyanate)

This work is partially analytic and partially computational. The computational work has verified the analytic expressions for the ensemble average diffusion of magnetic field lines (field line random walk) in 2D+slab turbulence that is non-axisymmetric. To expand on what we mean by this, the slab model of turbulence assumes wave vectors along the mean magnetic field direction, *z*. The 2D+slab model was motivated by observations of solar wind turbulence (Matthaeus, Goldstein, and Roberts, 1990). It more realistically includes a "2D" component with wave vectors along the *x* and *y* directions. That model has also been shown to provide a better explanation of the transport of cosmic rays parallel to the mean magnetic field (Bieber et al., 1994). While Matthaeus et al. (1995) considered the random walk of magnetic field lines for 2D+slab turbulence that was axisymmetric, i.e., had the same properties in the *x* and *y* directions, we now relax that assumption to consider non-axisymmetric turbulence. This has immediate application for the modulation of galactic cosmic rays in the outer heliosphere, where solar wind turbulence is indeed expected to be substantially non-axisymmetric. The analytic expressions are more complicated but still yield interesting conclusions.

Given the experience with a journal referee for related work (see 3.2), we have included computational work to confirm the analytic expressions. Piyanate, a Ph.D. student, completed the computational work during her visit to U. Delaware, with support from her TRF Royal Golden Jubilee fellowship, and with improved computer hardware purchased and set up with her Basic Research Grant. We have submitted an international journal article on this work.

3.2. Field line separation in axisymmetric 2D+slab turbulence

- Researcher: Piyanate Chuychai
- Key Point: Analytic expressions, confirmed by computer simulations, indicate regimes of slow diffusive and fast diffusive separation of nearly field lines.
- Status: Paper published

- Output: 3; Part of Ph.D. thesis (Piyanate)

In our previous Basic Research Grant, we completed the analytic work on the separation of magnetic field lines in axisymmetric 2D+slab turbulence. This is the first non-perturbative work on field line separation that considers a realistic form of turbulence with very different properties for longitudinal and transverse turbulence. We did an extensive literature search and compared and contrasted our results with those of many previous authors. A paper was submitted for publication in *Astrophys. J.* in the final days of the previous granting period.

Imagine our surprise when the referee stated that our paper is not ready for publication because it is analytic work, without computer simulations! (Usually one might expect the reverse comment ...) Essentially, we had to undertake an additional research project, to do computational work, before the analytic results could be published.

We have successfully developed this fundamentally new type of computer simulation, and the results are quite similar to the analytic results. Piyanate has finished the computational work during her visit to U. Delaware. We added another section to the paper as well as three additional figures and another table. The paper has now been published by *Astrophys. J.*

3.3. Field line random walk in isotropic turbulence

- Key point: Derived analytic expressions for the magnetic field line random walk in isotropic turbulence, with or without a DC field.
- Status: Analytic work completed

This analytic theory work was carried out by the Principal Investigator during a recent visit to U. Delaware in Oct.-Nov., 2004 (supported by an NSF grant to U. Delaware) in the context of work on particle transport in isotropic magnetic turbulence. The analytic theory for the magnetic field line random walk can be related to simulation results in progress by Prof. William Matthaeus at U. Delaware and his post-doc Pablo Dmitruk. The PI has written up the analytic results as one section of a future paper.

The results are also of theoretical interest when compared with previous results for 2D+slab turbulence. This led the PI to a general framework of intrinsic driven or extrinsically driven decorrelation, which allows one to describe in what situations exponential separation might be expected. Bill Matthaeus is encouraging me to develop a new paper on this topic, also in relation to classic results of Taylor and McNamara [1971, *Phys. Fluids,* 14, 1492].

3.4. Trapping of particles by small-scale topology of solar wind turbulence

- Researcher: Piyanate Chuychai
- Key Points: Explanation of observed dropouts of solar energetic particles. New view of the transport of energetic particles perpendicular to the mean magnetic field.
- Status: Paper published
- Output: 1, 12, 15, 36; Part of Ph.D. thesis (Piyanate)

This idea was fully explored and a paper was prepared for publication during 2003. A paper was submitted to *Nature* but was rejected (after 12 days) on the basis of not being of general interest. The paper was then revised and re-submitted to *Astrophysical Journal Letters,* the most prestigious specialized publication for astrophysics (IF=6.237). The paper has now been published there.

This work presents a fundamentally new view of the perpendicular transport of energetic particles (i.e., their transport perpendicular to the mean magnetic field) in a magnetized plasma, such as in space or in controlled fusion experiments. It also has implications for studying the topological structure of any sort of magnetohydrodynamic turbulence. Furthermore, the problem is mathematically identical to a forced Hamiltonian system in 2D phase space and thus is relevant to understanding such systems in general.

This work expresses ideas supported by computer simulations. It seeks to explain two apparently contradictory observations: 1) The *ACE* spacecraft has recorded "dropouts" of solar energetic particles, indicating a filamentary distribution in space, and also seeming to indicate very little perpendicular diffusion. 2) The *Ulysses* and *IMP-8* spacecraft have observed many solar events with very similar profiles of solar energetic particles while the spacecraft were located on opposite sides of the Sun. This seems to indicate very rapid perpendicular diffusion.

While for over 40 years the perpendicular transport of energetic particles has been considered to be a diffusive process, we can resolve the above observations by considering a non-diffusive process associated with conditional statistics of field line motion. While our other work (3.1 to 3.3) has considered ensemble average statistics, we now consider the different behavior from different starting points. In a realistic 2D+slab model of turbulence, field lines can be temporarily trapped near O-points in the 2D turbulence. On the other hand, field lines near X-points are rapidly carried away, accounting for the dropouts. Over longer scales, all field lines have escaped their temporary topological traps and then diffuse at the ensemble average rate. There are no free parameters in our theory.

Furthermore, this view gives rise to a "core-halo" picture of energetic particle transport. Solar energetic particles are initially mostly in a "core" region with a filamentary structure, while field lines escaping from regions near X-points escape to form a less dense "halo" of particles to distant locations. This can explain other observations that have previously been viewed as contradictory. There is great interest in the cosmic ray community (our results were presented and highlighted in the rapporteur session of the ICRC meeting in Japan), and we plan to widely disseminate these new concepts.

3.5. Local trapping boundaries and topology of trapping regions

- Researchers: Jakaphan Meechai, Nimit Kimpraphan
- Key Points: Concept of a local trapping boundary within which turbulent field lines are temporarily trapped. Statistical measurements of trapping and filamentation of magnetic field lines.
- Status: Ongoing
- Output: 18, 34, 42; B.Sc. senior project (Jakaphan)

Recent work by a B.Sc. student, Jakaphan Meechai, resulted in the concept of a local trapping boundary (LTB), a sharp boundary within which turbulent field lines are temporarily trapped. An LTB is defined by a local maximum in the average 2D field along a contour, and phenomenologically the LTB corresponds to trapping boundaries in the simulation results. This points to a new physical mechanism in addition to our previous concept that field lines are topologically constrained to regions around O points in the 2D turbulence. The new concept is that the field lines are seen to be actively trapped within sharp boundaries. In further work (see 3.6) it has been shown that a strong 2D field can suppress the slab random walk by which field lines escape, so we need to verify that this suppression can explain the LTBs seen in simulation results. This result will have immediate application in explaining the very sharp dropout features in ACE observations of SEP and solar electron bursts.

We also aim to describe the trapping and filamentation of magnetic field lines. We have made substantial progress in developing ideas for how to do this quantitatively.

3.6. Suppression of random walking by systematic flow in two dimensions

- Researchers: Piyanate Chuychai
- Key point: A general, coherent two-dimensional random walk can be suppressed by a systematic flow, which underlies the trapping of interplanetary field lines in filaments.
- Status: Paper published
- Output: 6, 18, 26, 42; Part of Ph.D. thesis (Piyanate)

This was a serendipitous discovery by Piyanate Chuychai while under the supervision of Prof. Bill Matthaeus at the Bartol Research Institute, U. Delaware during her visit in early 2004 (supported by a TRF Royal Golden Jubilee Fellowship). It is a clear demonstration that a strong 2D field suppresses a coherent (slab) random walk, a surprising result. In this case, the 2D field is not turbulent, but rather a systematic field (a.k.a. flow) for demonstration purposes, comprising the field generated by a Gaussian potential function $a(x,y)$. Based on possible industrial applications, we hoped to reach a wider audience and submitted the paper to *Physical Review Letters* (which typically does not publish pure astrophysics), which rejected the article without review on the basis of not being of general interest. A journal article has now been published in *Astrophysical Journal Letters* (IF=6.237).

At Bill's suggestion, Piyanate has developed a quasi-linear theory that provides a good explanation of the suppression found in her simulations. The PI has generalized this to any contour (not necessarily circular), e.g., for islands in 2D turbulence, for which the suppression should be even stronger for a given 2D field amplitude.

3.7. Improved algorithm for transport of particles in a turbulent magnetic field

- Researcher: Achara Seripienlert
- Status: Ongoing

While our work to date has been on the trajectories of magnetic field lines, what is really of most interest is the motion of the particles themselves. There is also a possible connection with the issue of exponentially decaying intensity profiles of solar energetic particles as seen in our fitting work (see 4.3). Therefore, our further computational work will stress the tracing of particle orbits. Achara is working on an improved algorithm for numerical determination of particle orbits analogous to that developed by Peera for field line trajectories (see 2.3).

3.8. Transport of particles in a turbulent magnetic field and dropouts

- *Researcher: Paisan Tooprakai*
- Key point: Investigating particle motion along temporarily trapped magnetic field lines.
- Status: Ongoing

This is another "spin-off" of the work earlier in this project about topological trapping of magnetic field lines. Indeed, at a meeting, the author of a competing theory, Randy Jokipii, said he would believe ours if we demonstrated dropouts with particle orbits. Therefore, we have started an investigation of particle orbits in a turbulent magnetic field, involving a Ph.D. student, Paisan Tooprakai (also a faculty member at Chulalongkorn U. and a previous participant in our Basic Research Grants), who has a TRF Royal Golden Jubilee fellowship. In a recent trip to U. Delaware (supported by that fellowship), Paisan and others have already demonstrated trapping effects in statistics of particle motion in a Gaussian 2D + slab turbulent field in a Cartesian geometry. Next, we aim to examine motion in a radial mean field with turbulent fluctuations, which is more similar to the true interplanetary magnetic field.

Chapter 4

Setting up a neutron monitor and data analysis

Objective: To work toward the establishment of a neutron monitor station at Doi Inthanon, and to analyze data from the worldwide neutron monitor network.

Note: The Principal Investigator was also involved in all of these subprojects.

4.1. Work toward establishing the Princess Sirindhorn Neutron Monitor (PSNM)

- Researchers: Alejandro Saiz, Manit Rujiwarodom, Paisan Tooprakai, Kanin Aungskulsiri, Preeksingh Anan, Tanin Nutaro (Ubon Rajathanee U.), Supon Samran (Ubon Rajathanee U.), Burin Asavapibhop (Chulalongkorn U.), Chakri Changchutoe (Chulalongkorn U.)
- Key Points: Royal Thai Air Force approval to set up the PSNM at the Doi Inthanon Control and Reporting Center. Successful "MicroMonitor" tests of hardware in Bangkok and at Doi Inthanon. Progress on Monte Carlo simulations.
- Status: Ongoing
- Output: 48; M.Sc. thesis (Kanin)

After our original request in July 2003, the Royal Thai Air Force has recently granted permission to site the PSNM at their Control and Reporting Center (radar base) at the summit of Doi Inthanon, the most suitable location in Thailand. An excellent site is available, with a strong base (the neutron monitor weighs 37 tons, or 41 tons if we include the planned housing in 2 shipping containers). It is good to hear that there are no termites at the mountain-top, as they are a serious problem during storage of the equipment (in wooden crates) at CU!

This project is to be mostly funded by sources other than TRF, and sufficient funding has recently been pledged by Mahidol Univ. that the financial future of the project is no longer in doubt. The project is to be managed in the framework of an MoU signed by the Presidents of Mahidol Univ., Chulalongkorn Univ., and Ubon Rajathanee Univ.

Our group was also active in pursuing national-level cooperation with the CMS collaboration at CERN, the European organization for particle physics research. Indeed, the PI is the national scientific coordinator of this effort. In the short term PSNM is a key project/facility for familiarizing Thai students with particle detection hardware, electronics, and software. Recently Preeksingh Anan, an M.Sc. student at MU, has traveled to attend a Summer School to learn more about gas counters (such as neutron monitor tubes) at CERN. However, this was on the whole disappointing, and it is possible that we may not pursue such collaboration further.

In work led by Dr. Alejandro Saiz, we have tested individual monitor tubes (each a proportional counter without the surrounding lead and polyethylene – a so-called "bare counter") at CU in Bangkok and at Doi Inthanon, representing our first hardware work on energetic particle detection in Thailand. Great improvements have been made to the point where this so-called MicroMonitor can run for weeks on end.

More importantly, it produces the characteristic signals of neutron capture by the $^{10}BF_3$ gas in the proportional counter. The signals from the Li and He reaction products include 2 peaks for the two reaction channels and wall effects for both Li and He.

There has also been substantial progress on Monte Carlo computer simulations of particle interactions in a neutron monitor, by Kanin Aungskulsiri (M.Sc. student) in collaboration with Burin Asavapibhop, a faculty member at CU (who has received a Young Research Grant from TRF). Those researchers chose to use the GEANT 4 package, which apparently has some problems with low-energy neutron simulations. In further work, Preeksingh Anan (M.Sc. student) is starting to collaborate (by long distance) with John Clem at U. Delaware, a world leader in state-of-the-art simulation of atmospheric neutrons and neutron monitor response, to use the well-tested FLUKA package.

Another student, Chanoknan Banglieng, has begun work on the analysis of possible future solar neutron signals in PSNM, with the goal of developing *a priori* statistics with which to determine the significance of any future solar neutron-like signal at PSNM. Without such *a priori* statistics, some other groups in the world are making claims that strain credibility, based on *a posteriori* statistics designed specifically for the specific type of fluctuation they observe.

4.2. Fitting SEP data: September 29, 1989 event

- Researcher: Monchai Nimsuk
- Key Points: For strong anisotropy, anisotropy x intensity profile is good proxy for injection profile. An exponential escape mechanism is necessary to fit the data.
- Status: On hold
- Output: B.Sc. senior project (Monchai)

For a long time, the Principal Investigator and Prof. John Bieber of the Bartol Res. Inst., U. Delaware have been considering fitting the neutron monitor data on solar energetic particles (SEP) above ~ 1 GeV from this event. The event is special in that it was the largest relativistic solar particle event since 1956, and there was a very strong particle anisotropy. The initial anisotropy estimate of the Bartol group was rather crude, and they have not had time to prepare more accurate estimates. Therefore, we decided to go ahead with an analysis of the existing intensity and anisotropy estimates as a student project for Monchai.

The main technical advance was an application of simulations of particle transport in a closed interplanetary magnetic loop (one suggestion for this event), previously developed by the Principal Investigator.

Although the data are not of publication quality, the analysis yielded two interesting, qualitative conclusions:

1. When the anisotropy is strong (indicating a long scattering mean free path), the anisotropy times intensity is almost identical to the relative injection profile. The idea of examining intensity and anisotropy times intensity (first Legendre coefficient) was pioneered by Ruffolo, Khumlumlert, and Youngdee (1998).
2. To fit the data well, one must postulate an exponential escape mechanism. This is exciting in that it may tie in with the trapping of particles in interplanetary turbulence (see 3.4 - 3.6).

A publication-quality analysis will be postponed until better intensity and anisotropy data are available, and until we have a better understanding of this exponential decay, which is observed in many other events (see 4.3) – an explanation of that would be an important discovery in its own right.

4.3. Fitting SEP data: April 15, 2001 event

- Researchers: Manit Rujiwarodom, Paisan Tooprakai, Thiranee Khumlumlert (Naresuan U.)
- Key Points: Most detailed directional data ever obtained for relativistic solar particles. Our analysis permits the most precise timing to date of high energy particle emission from the Sun.
- Status: Paper accepted for publication
- Output: 2, 14, 39

We were invited to participate in this analysis of data from the first relativistic SEP event observed by the full "Spaceship Earth" set of polar neutron monitors. This follows our collaboration to analyze data from the July 14, 2000 event (Bieber et al. 2002), in which there was a successful double-blind test of analysis techniques developed in Thailand (Ruffolo 1995; Ruffolo, Khumlumlert, and Youngdee 1998) against a program used in Germany (actually developed by a group in Malaysia many years ago). Spaceship Earth is a concept of using neutron monitors near the Earth's poles to detect GeV-energy particles of similar energy distribution coming from different directions in space (so the Earth functions like a scientific spacecraft). Note that Spaceship Earth aims to detect particles at the low-energy end of the range available to ground-based neutron monitors; in contrast, the PSNM at Doi Inthanon will measure the highest-energy particles available to neutron monitors, due to its location at the Earth's magnetic equator.

In addition to its excellent directional sensitivity and counting statistics (much better than those available from spacecraft), Spaceship Earth monitors (some of which were specifically set up or upgraded for the project) also have excellent one-minute time sensitivity.

The Bartol group was responsible for the raw data and for an initial analysis of the directional distribution to derive the intensity and anisotropy. We in Thailand were responsible for simulating the interplanetary transport of SEP and for simultaneously fitting the intensity and the intensity x anisotropy to determine the injection function at the Sun. We also performed an F-test of the chi-squared of the deviation of our fit from the raw station data. In addition to those of us at Chulalongkorn University (at that time), Thiranee Khumlumlert also participated in the analysis as part of her Young Research Grant from TRF. Furthermore, John Bieber was able to visit us with support from a TRF Royal Golden Jubilee fellowship, so he was able to see and discuss our analysis methods first-hand.

Scientifically, the most interesting point is that the onset of particle acceleration is consistent with indicators of CME shock formation and somewhat later than indicators of flare activity, apparently supporting the idea of acceleration by a CME-driven shock – directly addressing the goals of this research project. Another interesting point is that the spectral index of interplanetary turbulence was apparently different than that in our analysis for the July 14, 2000 event (Bieber et al. 2002). John decided to submit our paper to *Nature* but it was rejected (after 1 day) on the basis of not being of general interest. We then sent it to *Astrophysical Journal Letters* (IF=6.237), the top rapid-publication forum for astrophysics research, where it has been published.

4.4. Fitting SEP data: October 22, 1989 event

- Researchers: Manit Rujiwarodom, Paisan Tooprakai, Thiranee Khumlumlert (Naresuan U.), Maneenate Wechakama (Kasetsart U.)
- Key Points: Solved a 16-year mystery: neutron monitor data are well explained by injection along both legs of a magnetic loop. First inference of a flat magnetic fluctuation spectrum ($q<1$) in the transport of solar energetic particles.
- Status: Paper in press
- Output: 8, 16, 21, 25, 29, 46, 49

This event is interesting in the sense that there is a second peak in relativistic solar proton intensity with bidirectional flows (Cramp et al. 1987), which may indicate propagation within a bottleneck (as in the analysis of Bieber et al. 2002, for which we studied the event of July 14, 2000) or inside a closed magnetic loop. Prof. John Bieber has analyzed the intensity and anisotropy of solar energetic particles detected by various neutron monitors. The new aspects of our analysis in Thailand are the development of simulations of transport inside a magnetic loop and fitting some lower limits provided by John in addition to the usual data points with error bars.

The neutron monitor observations of relativistic solar particles from this event have been an unexplained mystery for 16 years! Our analysis initially seemed to indicate that transport within a bottleneck provides a better explanation of the data than transport inside a closed magnetic loop. (It is interesting that our simulations and fits strongly distinguish between these possibilities.) However, the required reflection coefficient (99% mirroring) was unphysical.

The solution: imagine a closed magnetic loop with two footpoints at the Sun. If particles are injected nearly simultaneously along the two legs of the loop, this implies a mirror symmetry plane in space - perfect mirroring! Thus the 99% reflecting bottleneck was mimicking this mirror symmetry plane. When we tried injection along both legs of a loop, the fits were greatly improved, and we can now explain all the unusual features of this event. (The PI is proud that he thought of this idea while holding his young baby, demonstrating that research and fatherhood are not incompatible.) Thus we can infer the large-scale magnetic configuration from neutron monitor data at Earth.

This explanation has been well accepted by the community. For example, Don Smart, one of the authors of a previous interpretation of the event, said we have now correctly solved the mystery of this event.

Further, refined fits also allow us to identify a parameter q, corresponding to the spectral index of the turbulent power spectrum. The hard work of a new collaborator within Thailand, Maneenate Wechakama (Kasetsart U.) to perform many fits was crucial to establish this result. (Note that Maneenate was not a research student of the PI, but had an interest in astronomy and volunteered to join our research.) To our knowledge, this is the first finding of $q<1$ in the transport of solar energetic particles. The implication is that closed magnetic loops have unusual magnetic fluctuations.

John Bieber has suggested that the PI be the first author, so it will now be possible for us to generate papers with a lead author in Thailand from our work analyzing neutron monitor data from abroad. A paper on this analysis has been accepted by the *Astrophysical Journal*.

4.5. Fitting SEP data: October 28, 2003 event

- Researchers: Alejandro Sáiz
- Key Point: Investigating the mystery of the fast peak and main peak in neutron monitor data, which had unusual directional distributions.
- Status: Paper published in *Astrophys. J.* (IF=6.604); further work in progress
- Output: 4, 19, 23, 28, 33, 43, 44

This major event apparently disabled two Japanese satellites, caused 50,000 people in Sweden to go without electric power, and led to aurorae as far south as Arizona (but not Thailand). It triggered a wave of public interest abroad and in Thailand.

In addition to the implications for society, there is a scientific mystery as to why the worldwide neutron monitor network showed an early peak of relativistic solar energetic particles that was beamed in a very precise direction, followed by a main peak with a wider angular spread but from a very different direction about 90 degrees away! Furthermore, the fast peak was moving *toward* the Sun, whereas the main peak was almost perpendicular to the measured local magnetic field. This is very different from the usual behavior of a peak directed away from the Sun along the local magnetic field, followed by diffusive spreading. Prof. John Bieber of U. Delaware has invited our team to provide theoretical support for their analysis.

So far the best hypotheses to explain the fast peak are:

1. Different magnetic structures passed the observer, corresponding to filaments in Section 2.2.4. These can naturally have different axes of symmetry. New corroboration comes from our new collaborators, Bernie Blake and Tamitha Mulligan at Aerospace Corporation, who have an instrument on the POLAR spacecraft.
2. Injection from the Sun along both legs of a closed magnetic loop. This would require injection first along the far leg, yielding the fast peak moving toward the Sun. Just as these particles approach the Sun and are reflected (or perhaps reaccelerated by the still-active shock), they are joined by fresh injection of particles along the near leg. These two populations together come back out along the loop and result in the main peak. This interpretation does not explain the sharp 90-degree change in the axis of symmetry between the early peak and the main peak.
3. Neutron decay protons (NDP) are deposited far from the Sun by fast-moving solar neutrons (themselves produced by nuclear collisions of solar energetic particles moving downward into the solar atmosphere) are rotated by a large-scale magnetic field (on a larger scale than that measured locally) and generate the fast peak, whereas the main peak represents simple injection along an Archimedean spiral field. One drawback is that the two peaks on Oct. 28, 2003 had similar magnitudes, whereas previous events believed to exhibit NDP (including those studied in the PI's Ph.D. thesis; Ruffolo 1991) had NDP peaks about 10,000 times less intense than the main peak. We think we have ruled out this possibility for relativistic solar particles, although there is a possible observation at lower energy in data from the POLAR and SAMPEX satellites.

In any case, this is an exciting mystery that needs to be solved, and we continue to explore these and other ideas. We have published a summary paper in *Geophysical Research Letters* as part of a special issue on the major solar events of October-November, 2003. We may develop one or more further publications based on our ongoing analyses on different aspects of this exciting event.

4.6 Fitting SEP data: August 24, 2002 event

- Researchers: Thiranee Khumlumlert (Naresuan U.)
- Key Point: Able to determine interesting timing data even from a small Ground Level Enhancement.
- Status: On hold
- Output: 20

This analysis project was suggested by the PI in order for us to join a large "campaign" of analyses by many research groups on the same solar events. Our collaborators at the Bartol Research Institute, U. Delaware agreed, and our joint analysis was presented by Paul Evenson in a poster at the Solar, Heliospheric and Interplanetary Environment (SHINE) Workshop 2004 at Big Sky, Montana, in June, 2004. Unfortunately, the campaign events received rather little attention at the workshop. Nevertheless, we are interested that we were able to derive meaningful timing information (with 2 min. precision) from this rather tiny GLE (only a 5% increase in polar neutron monitors), a result that was recently cited in a paper by the leader of the campaign. John Bieber also points out an interesting rotation in the axis of symmetry during the course of the event.

4.7 Fitting SEP data: January 20, 2005 event

- Researchers: Alejandro Sáiz, Manit Rujiwarodom
- Key Points: Largest relativistic solar particle event in 50 years. Possible explanation in terms of nonlinear transport of relativistic solar particles.
- Status: Ongoing
- Output: 27, 31, 32, 35, 51

Despite the decline in the solar cycle, the Sun produced one last ground level enhancement (GLE) of relativistic solar particles on January 20, 2005. This was a huge event, the largest GLE in 50 years! (Oddly, this event did not excite much interest among the popular press.)

We have been invited to help analyze the data from polar neutron monitors - in Antarctica, Australia, Greenland, Canada, and Russia - maintained by the Bartol Research Institute and collaborators. In addition to the directional distribution of cosmic rays, there are data from a bare monitor (similar to our MicroMonitor) maintained by Bartol at the South Pole, which provide spectral information. A ship-borne mobile monitor operated by Bartol and collaborators in Australia, for an ongoing latitude survey, was by chance at McMurdo, Antarctica at the time and also provides spectral information based on multiplicity distributions for this huge count rate.

Interestingly, the data exhibit an unusual second spike superimposed on the decay of the first. This is corroborated by a spectral feature (possibly indicating energy dispersion) in the bare counter to neutron monitor ratio. Remarkably, the second peak has a lower anisotropy than the first, indicating a change in interplanetary transport conditions after 10 minutes!

We believe this is a manifestation of self-amplified waves, in which the first particles lose some of their energy to wave generation that resonantly scatters the following particles. Such effects have been inferred previously only from compositional changes [e.g., Ng, Reames, and Tylka 1999, *Geophys. Res. Lett.*, 26, 2145] and from our own work on the spectra of shock-accelerated ions (2.1). To our knowledge it has never been seen in features of SEP time-intensity profiles, and heralds a novel nonlinear transport of relativistic solar particles. Why should it happen now? GLEs provide unparalleled timing precision to reveal such effects, and previous GLEs were not sufficiently intense. Upon the suggestion of John Bieber of Univ. Delaware, Alejandro has estimated the energy density of the particles and the existing waves. The energy density of the particles is apparently only a few times greater, so that previous events could not have substantially affected the existing wave spectrum at the relevant frequencies. It is also very interesting that the injection profile we infer from a crude analysis, with one injection function for a high value of the scattering mean free path and one for a low value, is actually continuous with only one solar injection. This is appealing because some of us view two injections as somewhat more radical than self-amplified waves. We will continue to explore this interpretation.

4.8. Examining the onsets of SEP events

- Researcher: Alejandro Sáiz
- Key Point: Examined the accuracy of a widely used technique to infer the start time of solar particle injection.
- Status: Paper published
- Output: 5, 30, 47

This work was suggested by our collaborator Paul Evenson of the Bartol Research Inst., U. Delaware. Recently it has become popular, in the worldwide cosmic ray community, to draw graphs of $(\text{velocity})^{-1}$ vs. onset time, fitting a straight line to data points. The injection onset at the Sun is inferred from the x-intercept, while the slope is said to indicate a "pathlength." In contrast, we have detailed modeling methods to simulate the transport of cosmic rays and fit data to determine the injection time. We wonder how accurate the method is and how to interpret that "pathlength." Our approach is to run transport simulations for a certain injection time and to examine the effects of solar wind convection, an extended injection function, and a rigidity-dependent mean free path. Our work in Thailand has been led by our post-doc, Alejandro Sáiz.

The results indicate that the effects of solar wind convection and a rigidity-dependent mean free path can cancel out to some extended, helping to explain why those graphs tend to yield straight lines. In other words, the straight line may be somewhat fortuitous, not an indication of a lack of any transport effects. We have examined how badly the inferred injection time and pathlength can deviate from the true quantities.

The PI has presented these results in various presentations in China and the US, and has also discussed this with various experts in the field. Our results are of great interest among those who use this analysis technique, and have been published in *Astrophys. J.* (IF=6.237). As an example of the interest they attract, Allan Tylka of the Naval Research Laboratory in Washington, DC asked Alejandro to perform further simulations at a different solar distance for use in a NASA proposal for the so-called Sentinels mission.

4.9. Minimum Free Energy Fitting

- Researcher: Jedsada Manyam, Alejandro Sáiz
- Key Point: Improved determination of the solar energetic particle injection function
- Status: Completed

This work was inspired by a talk that Jedsada Manyam gave at the 8th Annual National Symposium on Computational Science and Engineering at Nakorn Ratchasima in July, 2004. Jedsada presented his M.Sc. work in condensed matter physics at CU, in which he used a fitting technique that combined maximum entropy and chi-squared fitting. We interpret this as finding the "minimum free energy." We therefore hired Jedsada for a few months to aim to develop an improved method for fitting SEP data to determine the injection function. Several scientists abroad have inquired about the injection functions we report, which are piecewise linear functions with rather wide time spacing (a method that is efficient computationally; see Ruffolo et al. 1998). This is justified by the poor statistics, and the sharp triangular features are reasonable proxies for the sudden injection of particles at the Sun by flare/CME events, but the piecewise linear profile is admittedly not perfectly realistic.

We are satisfied with the results of Jedsada's work, supervised by Alejandro Sáiz and the PI, in that the new injection function is smoother, with error bars that are consistent with the piecewise linear injection function for a test case (the April 15, 2001 event; see 4.3). We will implement this for future analyses that do not involve nonlinear effects (i.e., not for January 20, 2005; see 4.7) as a single step of smoothing following the usual optimization with the piecewise linear method.

Chapter 5

Space weather

Objective: To work toward advance warning of space weather effects, and the dissemination of information about space weather effects to the public, military, and private sectors in Thailand.

Note: The Principal Investigator was also involved in all of these subprojects.

5.1. Modeling Forbush decreases

- Researcher: Kanokporn Leerungnavarat
- Key Point: First modeling of Forbush decreases to include pitch-angle transport at the shock.
- Status: Ph.D. thesis (Kanokporn Leerungnavarat)

This is the Ph.D. thesis work of Kanokporn Leerungnavarat, also supported by a TRF Royal Golden Jubilee fellowship. Technically, this work required extensive rewriting of our transport code. It also required an extensive literature review.

This is the first modeling of Forbush decreases to include pitch-angle transport at the shock. The aim was to comprehensively model Forbush decreases themselves, in addition to the precursors examined in our previous work (Ruffolo 1999; Leerungnavarat, Ruffolo, and Bieber 2003), which have applications to space weather forecasting. However, the Ph.D. student ran out of time, became pregnant, and decided to become a homemaker. She did get the Forbush decrease modeling program to work at some level, and had good results from previous lines of work (including a first-author paper in *Astrophys. J.*), so she was allowed to graduate. Such concerns aside, there were technical difficulties in making use of simulation output from David Lario at Johns Hopkins U., USA, because such output was somewhat ragged and not amenable to the kinds of numerical derivatives we want to perform. Overall, it is clear that this line of research requires a massive programming and computational effort without proportionate returns in terms of science, and we do not plan to continue this type of modeling.

5.2. Dissemination and understanding of information on space weather

- Researchers: Ketkaew Saikerdsri
- Status: successful dissemination of information and maintenance of website
- Output: website (www.thaispaceweather.com); invited lectures; television interview; radio interviews; magazine article

This is the "outreach" portion of our research project. We have successfully established a public-interest website, www.thaispaceweather.com, the first Thai-language website devoted to space weather, and have disseminated knowledge by other means as well. This has become one of the top websites in the nation dedicated to astronomy. Complete details of our dissemination activities are provided in section 7.8 and Attachment 52.

Statistics on website hits (mostly from Thailand, but also from numerous countries around the world) are also provided in Attachment 52. The peak interest came on June 7-8, associated with the Venus transit of the Sun (we also organized a small observing party at Mahidol U., involving our collaborators from Chulalongkorn U. as well, which attracted substantial interest). There were 128 hits on June 7 and only slightly fewer on June 8. Specifically, most of these visitors to our website followed a link from the Manager Online magazine. It turns out that site copied our Thai-language news article on the transit (from some months earlier), giving credit to us and providing a link to our site! (See Attachment 56.) That is quite a compliment and demonstrates our effective contribution to space physics news in Thailand.

There are also links to our website from various major Thai web servers, such as www.pantip.com and www.sanook.com. At present we have a steady readership of 15-30 hits every workday. We have also received good questions, addressed to our website, from multiple high school students. In one case, this led to contact with Pat Wongpan, then a high-school student, that led him to do a good-quality summer research project with our group. He has even continued working with us throughout his first two years at Mahidol U. We are quite proud that our website has inspired students to pursue research in this field.

Chapter 6

Discussion

From the preceding chapters, it can be seen that our group undertakes a large number of subprojects in parallel (22 during this three-year period), some of which quickly bear fruit in terms of international publications, some requiring a longer time before they are ready for publication, and some that never lead to an international publication. Actually, each subproject that we take on is, at the outset, potentially important enough for an international publication (or at the very least an international conference presentation), but some do not work out or do not yield sufficiently interesting results.

We believe that our approach of performing a large number of subprojects is justified because:

- It allows us to train a large number of students or other beginning researchers in research work that has the potential to produce new scientific knowledge. Indeed, the number of local researchers involved is greater than the number of subprojects (31, not counting some Thai collaborators at other universities) because most of them worked in teams, with new researchers learning from more experienced researchers, and several have worked on more than one project for a diverse experience.
- While this approach leads to a substantial fraction of subprojects that do not lead to international publications, we believe this ``inefficiency" is justified by the intellectual stimulation it provides. Furthermore, some subprojects work out very well and indeed lead us into a new and fruitful line of research. An example is the study of magnetic turbulence. In 2000, Prof. Matthaeus invited DR to work on this topic during a visit to U. Delaware in the US. Originally DR joined this work ``for fun" and intellectual stimulation; now this is one of our group's most productive lines of research, with a strong synergy with our existing experience in SEP transport, and has proven to be good ``brain food" for our students.
- We really do not know at the outset which subprojects will bear fruit. A good example is provided by our subprojects on fitting SEP data: Almost none of the key results were expected when starting to fit the data. On the other side of the coin, not every data set yields a good fit, or is complete enough to provide a unique best-fit. Even when it does, just saying ``we were able to fit the data" is not sufficient for international publication - for that, there must be convincing evidence for a non-standard (more interesting or more detailed) transport model or injection function.

Finally, the Principal Investigator would like to note that he is very happy with the Thai students who have worked on this project, and is proud to have the opportunity to train them and work with them. In addition to their actual research, our group aims to broaden their experience in various ways:

- A regular weekly meeting on student research, or for each research topic.

- A weekly Group Meeting to discuss interesting reprints that colleagues have sent to us, articles from the *Astrophysical Journal* that group members have selected, reports of solar activity during the past week, recent news items concerning astrophysics or space physics, and other matters concerning the lab.
- Graduate students typically present their work orally in at least one scientific meeting, often in English (in the case of the Annual National Symposium of Computational Science and Engineering, or meetings abroad). Before each seminar, research, or thesis presentation, everyone listens to the speaker and gives extensive comments and criticism so that they learn from the experience of presenting their results to non-specialists.

Let us close the discussion by noting that our research activities have attracted increased attention from the international scientific community. Our extensive international collaboration is evident in the author lists of our journal publications and conference presentations. Our work was specifically cited and discussed for a full paragraph in a summary of the field in *Eos*, the newsletter of the American Geophysical Union (see Attachment 59). We receive invitations to speak at international conferences and to review articles for major journals. The Principal Investigator has been told by a senior US researcher that he accomplished more by working in Thailand for 10 years (presumably because of our academic freedom and strong funding for basic research) than he would have for 10 years in the US (where he would probably have worked on multiple post-doc jobs instead of working out his own ideas). One US researcher (with whom we have not yet collaborated) recently paid us the kind compliment that he chose to attend a conference because our research results would be presented there.

Chapter 7

Output

7.1 International journal articles

Published

1. **D. Ruffolo,** W. H. Matthaeus, and **P. Chuychai**, Trapping of solar energetic particles by small-scale topology of solar wind turbulence, *Astrophys. J.*, **597,** L169 (2003) (IF=6.237)
2. J. W. Bieber, P. Evenson, W. Dröge, R. Pyle, **D. Ruffolo, M. Rujiwarodom, P. Tooprakai,** and T. Khumlumlert, Spaceship Earth Observations of the Easter 2001 Solar Particle Event, *Astrophys. J.,* **601,** L103 (2004) (IF=6.237)
3. **D. Ruffolo,** W. H. Matthaeus, and **P. Chuychai,** Separation of Magnetic Field Lines in Two-Component Turbulence, *Astrophys. J.*, **614,** 420 (2004) (IF=6.237)
4. J. W. Bieber, J. Clem,.P. Evenson, R. Pyle, **D. Ruffolo, and A. Sáiz,** Relativistic Solar Neutrons and Protons on 28 October 2003, *Geophys. Res. Lett.,* **32,** L03S02 (2005) (IF=2.378)
5. **A. Sáiz,** P. Evenson, **D. Ruffolo,** and J. W. Bieber, On the Estimation of Solar Energetic Particle Timing from Onset Times near Earth, *Astrophys. J.*, **626,** 1131 (2005) (IF=6.237)
6. **P. Chuychai, D. Ruffolo,** W. H. Matthaeus, and G. Rowlands, Suppressed Diffusive Escape of Topologically Trapped Field Lines, *Astrophys. J.*, **633,** L49 (2005) (IF=6.237)
7. **C. Channok, D. Ruffolo,** M. I. Desai, and G. M. Mason, Finite Time Shock Acceleration of Energetic Storm Particles, *Astrophys. J.*, **633,** L53 (2005) (IF=6.237)

Accepted

8. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert, M. Wechakama,** J. W. Bieber, P. Evenson, and R. Pyle, Relativistic Solar Protons on 1989 October 22: Injection and Transport along Both Legs of a Closed Interplanetary Magnetic Loop (accepted by *Astrophys. J.*)

Submitted

9. **D. Ruffolo, P. Chuychai,** and W. H. Matthaeus, Random Walk of Magnetic Field Lines in Non-axisymmetric Turbulence (submitted to *Astrophys. J.*)

7.2 International book article (non-refereed)

10. **D. Ruffolo**, Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks, in *Coronal and Stellar Mass Ejections*, Proc. IAU Symp. 226, ed. K. P. Dere, J. Wang, and Y. Yan (San Francisco: Astron. Soc. Pacific), pp. 319-329

7.3 International conference presentations (presented by first author unless otherwise indicated)

11. **D. Ruffolo and C. Channok**, Finite-Time Shock Acceleration, *Proc. 28th Internat. Cosmic Ray Conf.*, **6**, 3681 (Tsukuba, Japan, August, 2003)
12. **P. Chuychai, D. Ruffolo**, and W. H. Matthaeus, Conditional Statistics of Magnetic Turbulence and the Lateral Transport of Solar Energetic Particles, *Proc. 28th Internat. Cosmic Ray Conf.*, **6**, 3499 (Tsukuba, Japan, August, 2003)
13. **K. Malakit, K. Klappong, K. Leerungnavarat, P. Chuychai, N. Sanguansak, and D. Ruffolo**, Particle Acceleration at Fluid Compressions and What That Teaches Us about Shock Acceleration, *Proc. 28th Internat. Cosmic Ray Conf.*, **6**, 3677 (Tsukuba, Japan, August, 2003)
14. J. W. Bieber, P. Evenson, **D. Ruffolo**, W. Dröge, R. Pyle, **T. Khumlumlert, M. Rujiwarodom, and P. Tooprakai**, 'Spaceship Earth' Observations of the Easter GLE, *Proc. 28th Internat. Cosmic Ray Conf.*, **6**, 3397 (Tsukuba, Japan, August, 2003)
15. **D. Ruffolo**, W. H. Matthaeus, and **P. Chuychai**, Trapping of Solar Energetic Particles by Small-Scale Topology of Solar Wind Turbulence, *Eos Trans. Amer. Geophys. Union*, **85**(17), Joint Assem. Suppl., Abstract SH24A-05 (Montréal, Canada, May, 2004)
16. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert**, J. W. Bieber, P. Evenson, and R. Pyle, Relativistic Solar Particles on 1989 October 22: Injection along Both Legs of a Closed Interplanetary Magnetic Field Loop, *Eos Trans. Amer. Geophys. Union*, **85**(17), Joint Assem. Suppl., Abstract SH31A-04 (Montréal, Canada, May, 2004)
17. **C. Channok, D. Ruffolo** (presenter), M. I. Desai, and G. M. Mason, Finite Time Shock Acceleration at Interplanetary Shocks, *Eos Trans. Amer. Geophys. Union*, **85**(17), Joint Assem. Suppl., Abstract SH31A-05 (Montréal, Canada, May, 2004)
18. **D. Ruffolo, P. Chuychai, J. Meechai, P. Pongkitiwanichkul, N. Kimpraphan,** W. H. Matthaeus, and G. Rowlands, Sharp Trapping Boundaries in the Random Walk of Interplanetary Magnetic Field Lines, *Eos Trans. Amer. Geophys. Union*, **85**(17), Joint Assem. Suppl., Abstract SH31A-06 (Montréal, Canada, May, 2004)
19. J. W. Bieber, P. Evenson, R. Pyle, **D. Ruffolo, and A. Sáiz,** Unusual Features of the October 28, 2003 Ground Level Enhancement, *Eos Trans. Amer. Geophys. Union*, **85**(17), Joint Assem. Suppl., Abstract SH33A-02 (Montréal, Canada, May, 2004)
20. J. W. Bieber, P. Evenson (presenter), R. Pyle, **D. Ruffolo, and T. Khumlumlert**, Spaceship Earth Observations of the 24 August 2002 Event (Solar, Heliospheric and Interplanetary Environment Workshop 2004, Big Sky, Montana, June, 2004)
21. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom (presenter), T. Khumlumlert,** J. W. Bieber, P. Evenson, and R. Pyle, Relativistic Solar Particles on 1989 October 22: Injection along Both Legs of a Closed Interplanetary Magnetic Field Loop (35th COSPAR Scientific Assembly, Paris, France, July, 2004)
22. **D. Ruffolo,** Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks (Invited Talk, IAU Symposium 226, Coronal and Stellar Mass Ejections, Beijing, China, September, 2004)

23. J. M. Clem, J. W. Bieber, P. Evenson, R. Pyle, **A. Sáiz, and D. Ruffolo,** Investigation of the Solar Neutron Event at Tsumeb on 28 October 2003, *Eos Trans. . Amer. Geophys. Union*, **85**(47), Fall Meet. Suppl., Abstract SH13A-1136 (San Francisco, December, 2004)
24. **C. Channok, D. Ruffolo** (presenter), M. Desai, and G. Mason, Finite time shock acceleration and fits to ESP ion spectra (invited talk, 2005 Solar, Heliospheric, and Interplanetary Environment Workshop, Hawaii, July, 2005)
25. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert, M. Wechakama,** J. Bieber, P. Evenson, and R. Pyle, Relativistic Solar Protons on 1989 October 22: Injection along Both Legs of a Loop (2005 Solar, Heliospheric, and Interplanetary Environment Workshop, Hawaii, July, 2005)
26. **D. Ruffolo**, **P. Chuychai**, W. H. Matthaeus, and G. Rowlands, Turbulence, dropouts, and suppression of the field line random walk (2005 Solar, Heliospheric, and Interplanetary Environment Workshop, Hawaii, July, 2005)
27. J. Bieber, J. Clem, P. Evenson, R. Pyle, M. Duldig, J. Humble, **D. Ruffolo, M. Rujiwarodom, and A. Sáiz,** Record-Setting Ground Level Ehancement: January 20, 2005 (2005 Solar, Heliospheric, and Interplanetary Environment Workshop, Hawaii, July, 2005)
28. J. Bieber, J. Clem, P. Evenson (presenter), R. Pyle, J. B. Blake, T. Mulligan, **D. Ruffolo, and A. Sáiz,** Observation of Neutron and Gamma Ray Emission from the October 28, 2003 Solar Flare (2005 Solar, Heliospherio, and Interplanetary Environment Workshop, Hawaii, July, 2005)
29. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert, M. Wechakama,** J. Bieber (presenter), P. Evenson, and R. Pyle, Relativistic Solar Protons on 1989 October 22: Injection and Transport along Both Legs of a Closed Interplanetary Magnetic Loop (29th International Cosmic Ray Conference, Pune, India, August, 2005)
30. **A. Sáiz,** P. Evenson (presenter), **D. Ruffolo,** and J. Bieber, On the Estimation of Solar Energetic Particle Timing from Onset Times near Earth (29th International Cosmic Ray Conference, Pune, India, August, 2005)
31. **A. Sáiz, D. Ruffolo, M. Rujiwarodom,** J. Bieber (presenter), J. Clem, P. Evenson, R. Pyle, M. Duldig, and J. Humble, Relativistic Particle Injection and Interplanetary Transport during the January 20, 2005 Ground Level Enhancement (29th International Cosmic Ray Conference, Pune, India, August, 2005)
32. J. Bieber, J. Clem, P. Evenson, R. Pyle, M. Duldig, J. Humble, **D. Ruffolo, A. Sáiz, and M. Rujiwarodom,** Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event (29th International Cosmic Ray Conference, Pune, India, August, 2005)
33. J. Bieber, J. Clem, P. Evenson (presenter), R. Pyle, J. B. Blake, T. Mulligan, **D. Ruffolo, and A. Sáiz,** Observation of Neutron and Gamma Ray Emission from the October 28, 2003 Solar Flare (accepted by 29th International Cosmic Ray Conference, Pune, India, August, 2005)
34. P. Chuychai, **D. Ruffolo**, W. H. Matthaeus, and **J. Meechai,** Trapping, Diffusive Escape and Transport of Field Lines in Two-Component Magnetic Turbulence, *Eos Trans. Amer. Geophys. Union*, **86**(52), Fall Meet. Suppl., Abstract SH11A-0247 (San Francisco, December, 2005)

35. J. Bieber, J. Clem, P. Evenson, R. Pyle, **D. Ruffolo, M. Rujiwarodom, A. Sáiz,** M. Duldig, and J. Humble, Neutron Monitor Observations of the January 20, 2005 Ground Level Enhancement, *Eos Trans. Amer. Geophys. Union*, **86**(52), Fall Meet. Suppl., Abstract SH21A-03 (San Francisco, December, 2005)

7.4 Local conference presentations (presented by first author unless otherwise indicated)

36. **D. Ruffolo**, W. Matthaeus, and **P. Chuychai**, Conditional Statistics of Magnetic Turbulence and the Lateral Transport of Solar Energetic Particles (7th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2003)
37. **P. Chuychai**, W. Matthaeus, and **D. Ruffolo**, Computer Simulations of the Random Walk of Turbulent Magnetic Field Lines (7th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2003)
38. **K. Malakit, K. Klappong, K. Leerungnavarat, and D. Ruffolo**, Effects of Systematic Pitch-Angle Changes on Cosmic Ray Acceleration on Shocks and Compression Regions: Contribution of the Mirroring Effect (7th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2003)
39. J. W. Bieber, W. Dröge, P. Evenson, R. Pyle, **D. Ruffolo, P. Tooprakai, M. Rujiwarodom (presenter), and T. Khumlumlert**, Accurate Timing of Solar Energetic Particle Acceleration on April 15, 2001 (7th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2003)
40. **C. Channok, D. Ruffolo** (presenter), M. I. Desai, and G. M. Mason, Finite Time Shock Acceleration at Interplanetary Shocks (8th Annual National Symposium on Computational Science and Engineering, Nakorn Ratchasima, July, 2004)
41. **P. Pongkitiwanichkul and D. Ruffolo**, Effect of a turbulent magnetic field on the shock drift acceleration of particles at a nearly perpendicular shock (8th Annual National Symposium on Computational Science and Engineering, Nakorn Ratchasima, July, 2004)
42. **P. Chuychai, D. Ruffolo, J. Meechai, P. Pongkitiwanichkul, A. Sáiz, N. Kimpraphan,** W. H. Matthaeus, and G. Rowlands, Inhibition of Random Walk by Systematic Flow in Two Dimensions (8th Annual National Symposium on Computational Science and Engineering, Nakorn Ratchasima, July, 2004)
43. J. W. Bieber, P. Evenson, R. Pyle, **D. Ruffolo, and A. Sáiz** (presenter), Unusual Features of the October 28, 2003 Ground Level Enhancement (8th Annual National Symposium on Computational Science and Engineering, Nakorn Ratchasima, July, 2004)
44. J. W. Bieber, P. Evenson, R. Pyle, **D. Ruffolo, and A. Sáiz** (presenter), Unusual Features of the October 28, 2003 Ground Level Enhancement in Cosmic Rays (30th Congress on Science and Technology of Thailand, Bangkok, October, 2004)
45. **C. Channok, D. Ruffolo,** M. I. Desai, and G. M. Mason, Finite-Time Shock Acceleration and Ion Spectra from Interplanetary Shocks (30th Congress on Science and Technology of Thailand, Bangkok, October, 2004)

46. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert, M. Wechakama,** J. W. Bieber, P. Evenson, and R. Pyle, Injection and Transport of Relativistic Solar Protons along Both Legs of a Closed Interplanetary Magnetic Field Loop (9th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2005)
47. **A. Sáiz,** P. Evenson, **D. Ruffolo,** and J. W. Bieber, On the Estimation of Solar Energetic Particle Timing from Onset Times near Earth (9th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2005)
48. **K. Aungskulsiri, B. Asavapibhop, and D. Ruffolo,** The Princess Sirindhorn Neutron Monitor Simulation (9th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2005)
49. **D. Ruffolo, P. Tooprakai, M. Rujiwarodom** (presenter), **T. Khumlumlert, M. Wechakama,** J. Bieber, P. Evenson, and R. Pyle, Relativistic Solar Protons on 1989 October 22: Injection and Transport along Both Legs of a Closed Interplanetary Magnetic Loop (31st Congress on Science and Technology of Thailand, Nakorn Ratchasima, October, 2005)
50. **P. Pongkitiwanichkul and D. Ruffolo**, Sawtooth Mechanism of Particle Acceleration at Shocks in Random Magnetic Fields (31st Congress on Science and Technology of Thailand, Nakorn Ratchasima, October, 2005)
51. **A. Sáiz, D. Ruffolo, M. Rujiwarodom,** J. Bieber (presenter), J. Clem, P. Evenson, R. Pyle, M. Duldig, and J. Humble, Relativistic Particle Injection and Interplanetary Transport during the January 20, 2005 Ground Level Enhancement of Cosmic Rays (31st Congress on Science and Technology of Thailand, Nakorn Ratchasima, October, 2005)

7.5 Completed Ph.D. thesis

Kanokporn Leerungnavarat, Piyanate Chuychai, Chanruangrit Channok

7.6 Completed M.Sc. theses

Kittipat Malakit, Kanin Aungskunsiri, Peera Pongkitiwanichakul

7.7 Completed B.Sc. projects

Monchai Nimsuk, Jakapan Meechai

7.8. Invited talks, reviews, and other forms of dissemination

1. Expanded www.thaispaceweather.com, which ranks highly among Thai websites for physics and astronomy (see statistics in Attachment 52).
2. Lectures on space technology and internet training for schoolteachers, organized by the Institute for the Promotion of Teaching Science and Technology, as part of the reorganization of school curricula in Thailand:
    a. Primary school teachers from central Thailand, on March 6, 2003
    b. Secondary school teachers from central Thailand, on April 10, 2003

3. Lecture on solar storms, NECTEC Tech Talk No. 2, March 7, 2003.
4. Reviewer, April-July, 2003, for *Journal of Geophysical Research A – Space Physics* (IF=2.839)
5. Graduate seminar in physics (guest speaker), Mahidol University, June 17, 2003.
6. Lecture on "Principles of Satellites and Various Applications" as part of a TRF camp for Thai schoolchildren (สำรวจกับนักวิจัย สืบต่อลมหายใจนักคิด ครั้งที่ 7: ขงเบ้งน้อยตามรอยเต่า), October 29, 2003.
7. Newspaper articles related to the solar storm of October 28, 2003, with the help of the Public Relations Division of TRF (Attachment 53):
    a. ผู้จัดการ online, October 31, "พายุสุริยะ"มหันตภัยเงียบที่คุกคามโลก
    b. กรุงเทพธุรกิจ online, October 31, นักฟิสิกส์ทั่วโลกจับตาพายุสุริยะ ไทยเล็งตั้งศูนย์วิจัยดวงอาทิตย์
    c. สยามรัฐ, October 31, ไทยตั้งสถานีนิวตรอนตรวจสอบ'พายุสุริยะ'
    d. คม-ชัด-ลึก, October 31, พิษ'พายุสุริยะ'ระบบสื่อสารเคี้ยง
    e. โพสต์ทูเดย์, October 31, 'พายุสุริยะ' ดวงอาทิตย์ยิงก๊าซใส่โลก ภัยการสื่อสารผ่านดาวเทียม
    f. เดลินิวส์, November 4 (คอลัมน์ โลกาภิวัตน์), พายุสุริยะ
    g. พิมพ์ไทย, November 6, นักวิจัยไทยเตรียมรับมือ"พายุสุริยะ"
8. TV interview about solar storms for the program "168 hours" on Channel 3, aired December 18, 2003 at 1 AM.
9. Feature about www.thaispaceweather.com in the magazine Science Today, which mentions TRF (December 2003 issue; see Attachment 54).
10. Radio interview about Mars landers, organized by TRF, live on December 25, 2003, also aired on December 28, 2003
11. Interview about research and other topics for GM Magazine – note the references to TRF on p. 124 and p. 133 (January 2004 issue; see Attachment 55).
12. Invited lecture for the NECTEC Knowledge Mart on "Elementary Particles: The Key to the Origin of the Universe," Feb. 18, 2004.
13. Presentation on "Previous cooperation with CMS" (ที่มาของความร่วมมือกับ CMS), 1st ThaiCMS Collaboration Meeting, at NECTEC, March 2, 2004.
14. Session chair, Joint Assembly of the American Geophysical Union, Montréal, Canada, May 19, 2004.
15. Article from www.thaispaceweather.com about the Venus Transit was reprinted in Manager Online, June 7, 2004 (Attachment 56).
16. Organized public observation of the Venus Transit ("ดาวศุกร์ผ่านหน้าดวงอาทิตย์") at Faculty of Science, MU (Attachment 57).
17. On the Computational Physics Program Committee and a session chair, 8th Annual National Symposium for Computational Science and Engineering, Suranaree U. Tech., July 21-23, 2004
18. Reviewer, September, 2004, for *Astrophysical Journal Letters,* the world's premier letters journal for astrophysics (IF=6.237)

19. Invited speaker at International Astronomical Union Symposium 226 in Beijing, China on Solar and Stellar Coronal Mass Ejections (Attachment 10).
20. Invited speaker, University of Maryland Space and Cosmic Ray Physics Seminar, Nov. 8, 2004.
21. Invited speaker, University of Delaware Fluids and Plasmas Seminar, Nov. 23, 2004.
22. Invited speaker to introduce Prof. Sheldon Glashow (Nobel Prize in Physics, 1979) at the seminar "Young Researchers Meet TRF Senior Research Scholars" organized by TRF at Kanchanaburi, January 15, 2005 (Attachment 58).
23. Lead organizer for the 9th Annual National Symposium on Computational Science and Engineering (ANSCSE9) at Mahidol University, March 23-25, 2005. There were 3 international invited speakers, 92 contributed papers from 7 nations, and 268 participants.
24. Invited panelist at Mahidol Wittayanusorn School on "Astronomy and the Spark for Students to Become Scientists" to mark the opening of the MWIT-Swinburne Virtual Reality Theatre, June 17, 2005.
25. Radio interview, "Knowledge to the Community," FM 92 MHz, July 7, 2005, on the Deep Impact spacecraft's encounter with Comet Tempel-1
26. Reviewer, March-July, 2005, for *Astrophysical Journal Letters,* the world's premier letters journal for astrophysics (IF=6.237)
27. Invited speaker, Solar Heliospheric and Interplanetary Environment (SHINE) Workshop, July 11-15, 2005, Hawaii, USA
28. Reviewer, July, 2005, for *ScienceAsia*
29. Radio interview, August 7, 2005, about the apparent discovery of a 10th planet
30. Highlight speaker, Open House, Faculty of Science, Mahidol University, August 24, 2005
31. Invited speaker, August 26, 2005, Academic and Research Seminar on Thai Astronomy, at Naresuan University
32. Invited speaker, November 2, 2005, Science seminar for 1st-year students at Mahidol Univ.
33. Panelist, November 25, 2005, 1st Thailand International Science Fair, at Mahidol Wittayanusorn School
34. Mentioned by name in the article "Workshop Highlights Progress in Solar-Heliospheric Physics" in the newsletter *Eos, Transactions of the American Geophysical Union,* vol. 86, no. 50, p. 525 December 13, 2005, along with a one-paragraph discussion of our work (Attachment 59).
35. Reviewer, December, 2005 – January, 2006, for *ScienceAsia*
36. Reviewer, January, 2006, for *Astrophysical Journal,* the world's premier journal for astrophysics (IF=6.237)

The Astrophysical Journal, 597:L169–L172, 2003 November 10

TRAPPING OF SOLAR ENERGETIC PARTICLES BY THE SMALL-SCALE TOPOLOGY OF SOLAR WIND TURBULENCE

D. Ruffolo,[1,2] W. H. Matthaeus,[3] and P. Chuychai[1]
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ABSTRACT

The transport of energetic particles perpendicular to the mean magnetic field in space plasmas has long been viewed as a diffusive process. However, there is an apparent conflict between recent observations of solar energetic particles (SEPs): (1) Impulsive solar flares can exhibit "dropouts" in which the SEP intensity near Earth repeatedly disappears and reappears, indicating a filamentary distribution of SEPs and little diffusion across these boundaries. (2) Observations by the *IMP-8* and *Ulysses* spacecraft, while they were on opposite sides of the Sun, showed similar time-intensity profiles for many SEP events, indicating a rapid lateral diffusion of particles throughout the inner solar system within a few days. We explain these seemingly contradictory observations using a theoretical model, supported by computer simulations, in which many particles are temporarily trapped within topological structures in statistically homogeneous magnetic turbulence and ultimately escape to diffuse at a much faster rate.

Subject headings: diffusion — magnetic fields — Sun: particle emission — turbulence

1. INTRODUCTION

In general, energetic particles in space plasmas gyrate in helical orbits around magnetic field lines, and transport parallel to the mean magnetic field is more rapid than perpendicular transport (Parker 1963, p. 242). In particular, the interplanetary magnetic field is dragged outward from the Sun in a spiral pattern by the solar wind (Parker 1958), and the particles accelerated by violent events near the Sun (such as solar flares and coronal mass ejections) can rapidly travel to the observer when there is a good magnetic connection between them. While spatial inhomogeneities in solar energetic particle (SEP) distributions have been known for decades, they have generally been reported as occasional, sharp features attributed to magnetic discontinuities, including shocks, magnetic sector boundaries, tangential discontinuities, fast/slow solar wind boundaries, large-scale flux tubes, and magnetic clouds (e.g., Scholer & Morfill 1975; Evenson, Meyer, & Yanagita 1982; Dröge, Wibberenz, & Klecker 1990; Sanderson et al. 2000). However, the "dropouts" recently observed by the *Advanced Composition Explorer* (*ACE*) spacecraft for a large number of impulsive solar events occur so frequently and over such small scales (~0.03 AU) that they cannot be attributed to large-scale features but instead must be related to the small-scale structure of the interplanetary magnetic field (Mazur et al. 2000). Indeed, we argue that dropouts are a signature of the topology of magnetic turbulence in the solar wind and therefore are relevant to understanding magnetohydrodynamic turbulence in general.

SEPs from impulsive solar events serve as a good probe of lateral transport (in solar latitude and longitude) because they arise from a localized source (Reames, Cane, & von Rosenvinge 1990) associated with a group of sunspots. Lateral transport requires transport perpendicular to the mean magnetic field as a function of time, which is in turn attributed to the random walk of turbulent field lines as a function of distance along the mean field (Jokipii 1966). That substantial lateral transport occurs over a timescale of days is dramatized by recent observations of the same set of solar events by two spacecraft: the *Interplanetary Monitoring Platform 8* (*IMP-8*) near Earth and *Ulysses* at 2–2.8 AU (McKibben, Lopate, & Zhang 2001). The inferred magnetic footpoints of the two spacecraft were nearly opposite in solar longitude and also very different in solar latitude (equatorial for *IMP-8* and near the South Pole for *Ulysses*). Those authors presented time-dependent SEP fluxes that were very similar (in absolute terms) during the decay phases of the majority of the observed events. While in at least one of their events there was an abrupt change near the time of a shock passage, heralding the onset of temporally and spatially invariant spectra in the region downstream of the shock (e.g., McKibben 1972), some profiles were diffusive with no apparent shock passage and simply converged at late times. This indicates that SEPs can undergo rapid lateral diffusion, spreading throughout the inner solar system within a few days.

However, perpendicular transport of a diffusive nature cannot explain both the dropouts and the *IMP-8*/*Ulysses* observations; the latter, as well as previous multispacecraft observations (e.g., Palmer 1982 and references therein), imply such rapid diffusion that the small-scale dropouts would be washed out. It has been proposed that fluid motions at the solar surface lead to a field line random walk that is consistent with the dropouts (Giacalone, Jokipii, & Mazur 2000). As will be shown below, that type of random walk is too slow to explain the *IMP-8*/*Ulysses* observations. Here we propose to reconcile these observations in terms of a two-component model of solar wind turbulence that has provided a useful explanation of both its magnetic statistics and the parallel transport of SEPs. We show that in such a model, a certain fraction of low-energy SEPs is temporarily trapped within small-scale topological structures in statistically homogeneous turbulence, ultimately escaping to diffuse at a much faster rate. This view of perpendicular transport can explain both the *ACE* observations of dropouts, over short timescales, and the *IMP-8*/*Ulysses* observations of rapid dispersion after a few days.

[1] Department of Physics, Chulalongkorn University, Bangkok 10330, Thailand; david@astro.phys.sc.chula.ac.th, piyanate@corona.phys.sc.chula.ac.th.
[2] Current address: Department of Physics, Faculty of Science, Mahidol University, Rama VI Road, Bangkok 10400, Thailand.
[3] Bartol Research Institute, University of Delaware, 217 Sharp Laboratory, Newark, DE 19716; yswhm@bartol.udel.edu.

2. ENSEMBLE AVERAGE STATISTICS

We consider a two-component model of solar wind turbulence as follows:

$$\boldsymbol{B} = B_0\hat{z} + \boldsymbol{b}^{\rm slab}(z) + \boldsymbol{b}^{\rm 2D}(x, y), \quad (1)$$

$$\boldsymbol{b}^{\rm slab} \perp \hat{z}, \quad \boldsymbol{b}^{\rm 2D} \perp \hat{z}. \quad (2)$$

This assumes a constant (or slowly varying) mean magnetic field plus two components of transverse fluctuations. The "slab" component of turbulence $\boldsymbol{b}^{\rm slab}$ depends only on z, the coordinate along the mean field, while the "two-dimensional" component $\boldsymbol{b}^{\rm 2D}$ depends only on the perpendicular coordinates, x and y. The two-component model was motivated by the observation that solar wind fluctuations are concentrated at nearly parallel and nearly perpendicular wavenumbers (Matthaeus, Goldstein, & Roberts 1990). Furthermore, this model provides a good explanation of the parallel transport of SEPs (Bieber et al. 1994; Bieber, Wanner, & Matthaeus 1996; Dröge 2000), providing a solution to the long-standing discrepancy between theoretical and observed scattering mean free paths.

For the two-dimensional component, we can write

$$\boldsymbol{b}^{\rm 2D}(x, y) = \nabla \times [a(x, y)\hat{z}], \quad (3)$$

where $a\hat{z}$ is the vector potential for the two-dimensional component of turbulence and $a(x, y)$ can be called the potential function. The arbitrary constant in the vector potential is chosen so that $\langle a \rangle = 0$.

For pure two-dimensional turbulence, with no slab component, magnetic field lines can remain trapped near certain (x, y)-coordinates because they always follow contours of constant a. As an example, Figure 1 shows a contour plot of $a(x, y)$ for a specific representation of two-dimensional turbulence that was generated to have desired statistical properties, as will be discussed in detail in § 3. The circles in Figure 1 indicate O-points [local maxima or minima in $a(x, y)$] where the contours remain trapped within "islands" of the two-dimensional turbulence (or filaments in three-dimensional space). We also indicate X-points, i.e., saddle points of $a(x, y)$. This is an example of how turbulence with homogeneous statistical properties can have small-scale topological structure.

The ensemble average statistics of the field line random walk were calculated by Matthaeus et al. (1995). A diffusion coefficient, D, is defined by $\langle \Delta x^2 \rangle = 2D\Delta z$, where Δx is the change in a perpendicular coordinate over a distance Δz along the mean field. Each turbulence component is associated with a value of D; the overall value is $D = D_{\rm slab}/2 + [(D_{\rm slab}/2)^2 + (D_{\rm 2D})^2]^{1/2}$. Under normal solar wind conditions, $D_{\rm slab}$ is very small ($\approx 5 \times 10^{-4}$ AU). The total diffusion coefficient can be estimated from the *IMP-8* and *Ulysses* data sets.

For most solar events shown by McKibben et al. (2001), the 30–70 MeV proton time-intensity profiles at the two spacecraft are very similar, in shape as well as in absolute magnitude, immediately after the peak in particle intensity. Only the event of 2000 November 8 shows a distinctly diffusive rise at *Ulysses* before matching *IMP-8* data in the decay phase. Therefore, we have fitted this most diffusive event, using a Reid profile (Reid 1964) centered at the Archimedean field line of the flare site at the radial distance of *Ulysses* (2.35 AU), to provide a lower bound on the particle diffusion coefficient $\kappa_\perp$. Based on this conservative estimate, the *IMP-8* and *Ulysses* observations

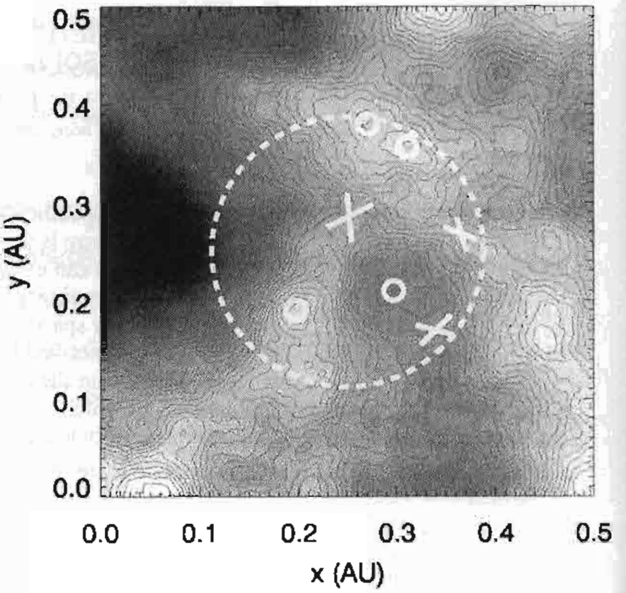

FIG. 1.—Contour plot of the potential function for a representation of the two-dimensional turbulence component. The magnetic field due to this component follows contours of constant potential. Field lines near O-points are trapped within topological "islands," while field lines near X-points or outside islands rapidly travel to other locations. In the solar wind, magnetic field lines undergo an additional random walk as a result of the slab component of turbulence, which allows them to eventually escape from islands surrounding O-points.

require an SEP perpendicular diffusion coefficient of $\kappa_\perp \geq 1.3 \times 10^{21}$ cm^2 s^{-1}, or $\kappa_\perp/\beta \geq 4 \times 10^{21}$ cm^2 s^{-1}, where β is the particle speed divided by the speed of light. This is of the same order of magnitude as previous estimates (e.g., Parker 1963; Palmer 1982). Using the field line random walk concept (Jokipii 1966), which in itself yields an underestimate of D (Matthaeus et al. 2003), one obtains a total field line diffusion coefficient of $D > 0.02$ AU, which is much greater than $D_{\rm slab}$. Conversely, since the model of Giacalone et al. (2000) uses slablike fluctuations (in the sense that fluctuations propagate in z), their model yields insufficient field line diffusion to explain the *IMP-8*/*Ulysses* observations.

Therefore, the two-dimensional component of turbulence dominates the ensemble average field line diffusion, and $\Delta x_{\rm rms} = \langle \Delta x^2 \rangle^{1/2} > 0.2$ AU at Earth orbit. However, such ensemble average statistics cannot apply to observations of dropouts because the dropouts correspond to a filamentation over ~0.03 AU, which would be completely washed out by such rapid diffusion.

3. CONDITIONAL STATISTICS

Instead of ensemble average statistics, let us now consider conditional statistics, depending on the initial location of a magnetic field line. If a field line is near an O-point, within an island of the two-dimensional turbulence (see Fig. 1), the two-dimensional contribution to the random walk is suppressed. The field line is temporarily trapped, with diffusion at the much slower rate characteristic of slab turbulence. On the other hand, magnetic field lines that start outside islands are rapidly carried far away by the two-dimensional turbulence.

In particular, suppose that particles are injected in a spatially

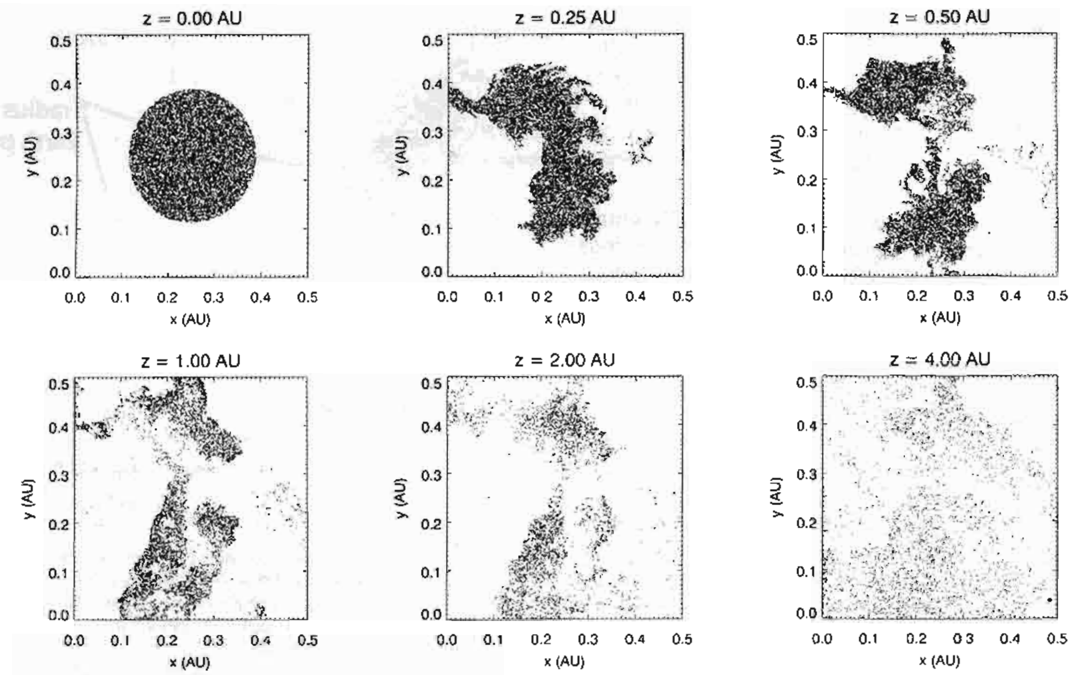

FIG. 2.—Scatter plot of the locations of magnetic field lines that are initially (at $z = 0$) located within a circle (simulating the region where particles are injected as a result of an impulsive solar flare). At intermediate-z values, field lines within islands of the two-dimensional turbulence (around the O-points shown in Fig. 1) remain trapped, while field lines in other regions spread rapidly. This explains the filamentary distribution of particles as indicated by dropout features. At large z values, all field lines diffuse rapidly, which explains the *Ulysses* and *IMP-8* observations of SEP diffusion throughout the inner solar system.

localized region, say, a circle of radius ρ. Then $z_1 = \rho^2/(4D)$ is a characteristic distance over which field lines outside islands diffuse out of the circle. If an island has diameter d, then $z_2 = d^2/(16D_{\perp slab})$ is the typical distance along the mean field over which field lines escape from the island, given diffusion due to the slab component. If slab diffusion is weak, we can have $z_1 < z_{obs} < z_2$, where z_{obs} is the distance of the observer. We suggest that dropouts are observed under these conditions. Magnetic field lines (and the low-energy particles orbiting them) that start deep within islands mostly remain trapped, while those outside the islands rapidly escape from the injection region, leaving gaps with a low density of particles. On the other hand, after a long distance ($z_{obs} > z_2$), essentially all field lines have escaped their temporary topological traps, corresponding to a rapid lateral diffusion of field lines (with the ensemble average diffusion coefficient D) and of particles.

This idea is confirmed by computer simulations that trace field line trajectories in representations of two-dimensional + slab turbulence for typical solar wind values, using Cartesian geometry for simplicity. The field line random walk is then a surrogate for particle gyrocenter motion. The simulations involve two steps:

1. The first step involves generating representations of slab and two-dimensional turbulence with desired statistical properties, such as the observed Kolmogorov power-law spectrum over the inertial wavenumber range (Jokipii & Coleman 1968), using the power spectrum of Ruffolo & Matthaeus (2003) and random phases, and then using inverse fast Fourier transforms to obtain $\boldsymbol{b}_{slab}(z)$ and $\boldsymbol{b}_{2D}(x, y)$. The transform in z used 2^{22} ($\approx 4.2 \times 10^6$) points, representing a length of 25 AU. The transform in x and y used 2048 points in each dimension, corresponding to a length of 2.5 AU. The simulations in the present work were for parameters believed to correspond to typical solar wind conditions: $b/B_0 = 0.5$, a fraction of slab turbulent energy $f_s = 0.2$ (following Bieber et al. 1994), a slab correlation length $\ell_c = 0.02$ AU, and an ultrascale of two-dimensional turbulence $\tilde{\lambda} \equiv (\langle a^2 \rangle / \langle b^2 \rangle_{2D})^{1/2} = 0.06$ AU. The ultrascale is believed to roughly correspond to the size of the largest islands, and this value corresponds to $D = 0.02$ AU, as a conservative lower limit. This lower limit is consistent with a previous estimation of $\tilde{\lambda}$ (Matthaeus, Smith, & Bieber 1999).

2. The second step involves tracing magnetic field lines, i.e., solving the coupled ordinary differential equations

$$\frac{dx}{dz} = \frac{b_x(x, y, z)}{B_0}, \quad \frac{dy}{dz} = \frac{b_y(x, y, z)}{B_0}. \tag{4}$$

We use a fourth-order Runge-Kutta method with adaptive time stepping regulated by a fifth-order error estimate step (Press et al. 1992).

Our computer simulations for several representations (several sets of random phases), different values of $\tilde{\lambda}$, and different spectral forms at low wavenumber yielded qualitatively similar results, including structures corresponding to dropouts of ~0.03 AU as in the *ACE* observations.

The results shown in Figure 2 demonstrate the behavior described above. The upper left-hand panel shows random initial locations within a circle, corresponding to the injection region where field lines are populated with SEPs. Field lines are then traced from those initial locations as a function of z. The subsequent panels, cross sections at longer distances along the mean field, show filamentary structures in the distribution of SEPs. A spacecraft near Earth ($z \approx 1$ AU) samples a transept through this highly inhomogeneous distribution. The simulation results are consistent with observed dropouts of ~0.03 AU. At longer distances, essentially all field lines (and particles) have diffused away, leading to the rapid propagation of particles throughout the inner heliosphere at later times.

4. DISCUSSION AND CONCLUSIONS

Note that we identify dropouts with topological structures that develop in solar wind turbulence, not with initial motions at the solar surface. We see the effects of islands of various sizes d due to the self-similar nature of turbulence, including islands within islands, but those much wider than ρ do not confine particles near the injection region.

For a wide injection region, $z_1 > z_{obs}$, and dropouts should not be seen. Indeed, another class of solar events, gradual flare/coronal mass ejection events, inject particles over a much wider region (Reames 1990) and do not exhibit dropouts (see the similar argument of Mazur et al. 2000 and Giacalone et al. 2000). We confirm that our model explains the lack of dropouts for gradual events by a "control run" in which field lines are randomly distributed throughout the simulation region. The distribution indeed remains uniformly random at all distances (which in the context of our model is required by Liouville's theorem).

This new view of the perpendicular transport of energetic particles in space plasmas can also reconcile another pair of apparently conflicting observations. Impulsive solar events selected for a strong SEP electron increase were shown to have a narrow distribution in solar longitude (Reames et al. 1990). This indicates only limited lateral spreading for the bulk of SEPs, which we attribute to trapping within small-scale topological islands, representing a "core" region of high particle density (Fig. 3). On the other hand, recent spacecraft observations of type III radio bursts and associated SEPs indicate that SEP electrons and ions can undergo broad lateral motion (up to ~90° in solar longitude) during their transport from the Sun to Earth orbit (Cane & Erickson 2003). In our view, this laterally extended but less intense "halo" of SEPs corresponds to particles on field lines initially located outside local islands of two-dimensional turbulence. (Note that particles observed by *Ulysses* do not necessarily correspond to this halo since they may have undergone lateral diffusion beyond 1 AU.) Indeed, the absence of these halo SEPs from the core region is manifest as dropouts.

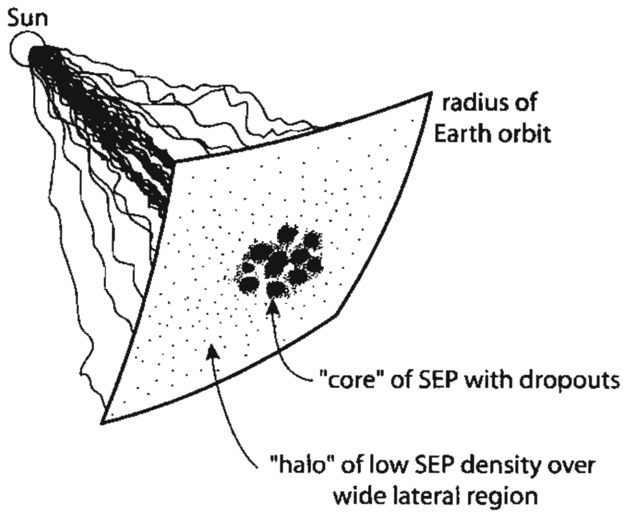

FIG. 3.—Illustration of interplanetary magnetic field lines populated with SEPs from a localized source region near the Sun, as expected for an impulsive solar flare. In the two-dimensional + slab model of solar wind turbulence, some field lines are trapped in filaments corresponding to the small-scale topology, i.e., islands of the two-dimensional turbulence, out to Earth orbit, while interstitial field lines spread laterally to large angular distances. This leads to the observed "core" region of SEPs with dropouts and an extended "halo" region.

Finally, we note that the problem considered here is directly analogous to the Hamiltonian flow of a dynamical system (in two-dimensional phase space) with time-dependent, random forcing (on the substitutions $a \rightarrow H$ and $z \rightarrow t$). Therefore, our qualitative conclusions apply to such systems in general.

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Attachment 2

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SPACESHIP EARTH OBSERVATIONS OF THE EASTER 2001 SOLAR PARTICLE EVENT

JOHN W. BIEBER, PAUL EVENSON, WOLFGANG DRÖGE, AND ROGER PYLE
Bartol Research Institute, University of Delaware, 217 Sharp Laboratory, Newark, DE 19716
DAVID RUFFOLO,[1] MANIT RUJIWARODOM, AND PAISAN TOOPRAKAI
Department of Physics, Chulalongkorn University, Bangkok 10330, Thailand
AND
THIRANEE KHUMLUMLERT
Department of Physics, Naresuan University, Science Complex, Tah Poe District, Phitsanulok 65000, Thailand
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ABSTRACT

The largest relativistic (~1 GeV) solar proton event of the current solar activity cycle occurred on Easter 2001 (April 15). This was the first such event to be observed by Spaceship Earth, an 11-station network of neutron monitors optimized for measuring the angular distribution of solar cosmic rays. We derive the particle density and anisotropy as functions of time and model these with numerical solutions of the Boltzmann equation. We conclude that transport in the interplanetary medium was diffusive in this event, with a radial mean free path of 0.17 AU. The high time resolution of the Spaceship Earth network and the fast particle speed permit accurate determination of particle injection timing at the solar source. We find that particle injection at the Sun began at 13:42 UT ±1 minute, about 14 minutes before the first arrival of particles at Earth, in close association with the onset of shock-related radio emissions and ~15 minutes after liftoff of a coronal mass ejection (CME). Our results are consistent with the hypothesis that solar particles were accelerated to GeV energies on Easter 2001 by a CME-driven shock wave.

Subject headings: acceleration of particles — solar-terrestrial relations — Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: particle emission

1. INTRODUCTION

Spaceship Earth is a network of neutron monitors strategically deployed to provide real-time three-dimensional measurements of the cosmic-ray angular distribution with excellent statistics and 1 minute time resolution. As shown in Figure 1, it comprises 11 stations on four continents sited to provide good sky coverage of the equatorial region together with a three-dimensional perspective from Thule and McMurdo. The asymptotic viewing direction shown for each station is the direction from which the primary cosmic rays were coming before encountering the distorting magnetic fields of Earth's magnetosphere. The name Spaceship Earth recognizes both the multinational scope of the project (US, Russian, Australian, and Canadian participation) as well as the similarity of the measurement strategy to that employed by modern particle detectors flown in space.

Figure 2 shows count rates recorded by five selected stations of Spaceship Earth during the solar particle event of 2001 April 15. This event was so large that it increased radiation levels at Earth's surface; hence it qualifies for designation as a "ground level enhancement" (GLE). The earliest onset was recorded at 13:56 UT at Fort Smith, Canada. The minimum detected energy is 0.4 GeV and is determined by atmospheric absorption at these high-latitude sites; the geomagnetic cutoff is below this and plays no role. Thus, all Spaceship Earth neutron monitors have the same energy response, and the differing time profiles in Figure 2 result from anisotropy of the particle angular distribution. Stations with a favorable viewing direction (e.g., Nain and Fort Smith) exhibit a rapid rise and comparatively high peak. Owing to scattering by magnetic turbulence in the interplanetary medium, however, even stations with an unfavorable viewing direction (e.g., Apatity) measure finite particle intensity.

[1] Current address: Department of Physics, Faculty of Science, Mahidol University, Rama VI Road, Bangkok 10400, Thailand.

2. MODELING RESULTS

The full power of Spaceship Earth is realized when the individual stations are analyzed in concert and the network itself becomes the observing instrument. For this event, we found that a simple first-order anisotropy provides a good description of the cosmic-ray angular distribution. Network data were fitted to the function

$$f(\theta, \phi) = n(1 + \xi_x \sin\theta \cos\phi + \xi_y \sin\theta \sin\phi + \xi_z \cos\theta), \quad (1)$$

where $f(\theta, \phi)$ is the intensity measured by a station with an asymptotic viewing direction defined by θ (colatitude) and ϕ (longitude), n is the particle density, and (ξ_x, ξ_y, ξ_z) are the three components of the anisotropy vector.

Results of the first-order fit appear as data points in Figure 3. The second panel displays the cosmic-ray density expressed as a percentage of the preevent background of Galactic cosmic rays. The bottom two panels display two representations of the anisotropy, the "weighted anisotropy" defined as $n\xi$ and the ordinary anisotropy defined as $\xi = (\xi_x^2 + \xi_y^2 + \xi_z^2)^{1/2}$.

The solid lines in Figure 3 represent a fit of the Spaceship Earth data to a theoretical model. Specifically, the density and weighted anisotropy in the second and third panel were modeled with numerical solutions of the Boltzmann equation (Roelof 1969; Ruffolo 1995) using the method of least squares. (The temporary suppression of weighted anisotropy from 14:17 to 14:32 UT is apparently a localized effect that cannot be described by our model; hence this interval was omitted from the fitting procedure.) Modeling the density and anisotropy to-

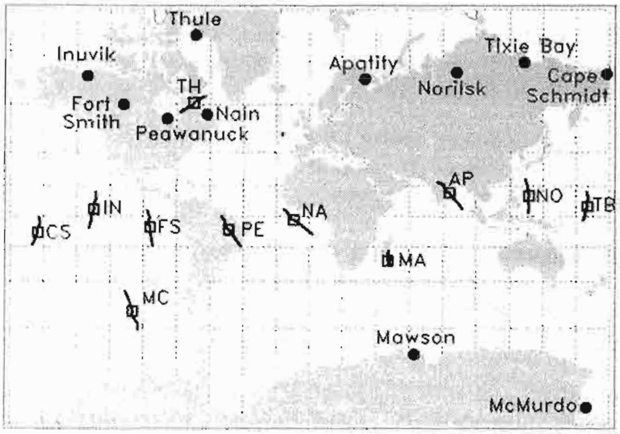

FIG. 1.—Spaceship Earth neutron monitor network. All stations (*filled circles*) are at high geographic latitudes, but nine of them view the equatorial region after accounting for bending of particle trajectories in the geomagnetic field, while Thule and McMurdo generally view the northern and southern hemispheres, respectively. Squares show asymptotic (see text) viewing directions for a median energy particle (1.3 GeV for this event), and the lines show the range of viewing directions for the central 50% of the detector energy response (0.7–2.3 GeV for this event). Two-letter station codes correspond to the first two letters of the station name or the first letter of each word in the case of a two-word name. Asymptotic directions were computed with the aid of a trajectory code (Lin, Bieber, & Evenson 1995) for a time near the start of the Easter 2001 solar cosmic-ray event.

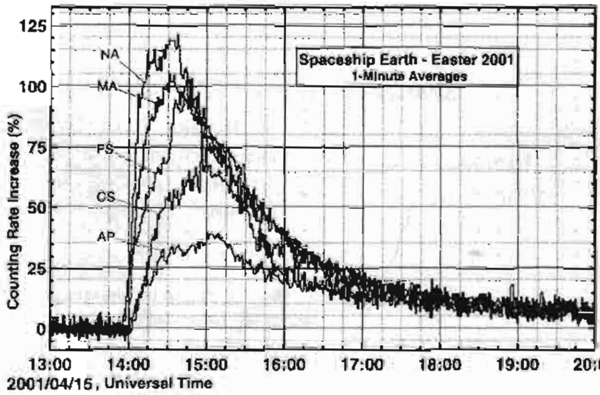

FIG. 2.—Neutron rates recorded at selected Spaceship Earth stations during the GLE of Easter 2001. All stations are shown at a time resolution of 1 minute. The detected neutrons are secondary cosmic rays generated by cascades in Earth's atmosphere. The primary cosmic rays initiating the cascades are predominantly protons. See Fig. 1 for definition of two-letter station codes.

gether is crucial for deriving the particle injection profile—otherwise, effects of prolonged injection could not be separated from diffusive delays in the interplanetary medium. The anisotropy contains key information on the strength of scattering in the interplanetary medium.

The free parameters of the fit were the radial mean free path, which was taken to be constant as a function of radius, and several parameters[2] describing a piecewise linear "injection function," defined as the rate at which particles are injected onto the solar footpoint of the Sun-Earth magnetic field line as a function of time (Ruffolo, Khumlumlert, & Youngdee 1998).

The derived injection function is shown in the top panel of Figure 3. The best-fit radial mean free path is 0.17 AU, which corresponds nominally to a parallel mean free path of 0.34 AU at Earth. Results from the χ^2 minimization method employed here are compatible with those obtained by the traditional technique of matching density and anisotropy profiles by eye (Bieber et al. 2002).

3. SPECTRUM PARAMETER

According to the quasilinear theory of particle scattering, particle transport also depends on the spectrum of the scattering turbulence (Jokipii 1966). Typically this is described via a spectral index q of an assumed power-law dependence of the one-dimensional magnetic power spectrum, $P(k) \propto |k|^{-q}$, where k is the wavenumber of the turbulence mode. The model results in Figure 3 used $q = 1$. Although turbulence in interplanetary space often has a Kolmogoroff form ($q = 5/3$) at smaller scales, there are reports of a possible shallower index at the large scales responsible for scattering particles of neutron monitor energy (Matthaeus & Goldstein 1982; Bieber & Pomerantz 1983; Bieber et al. 1993).

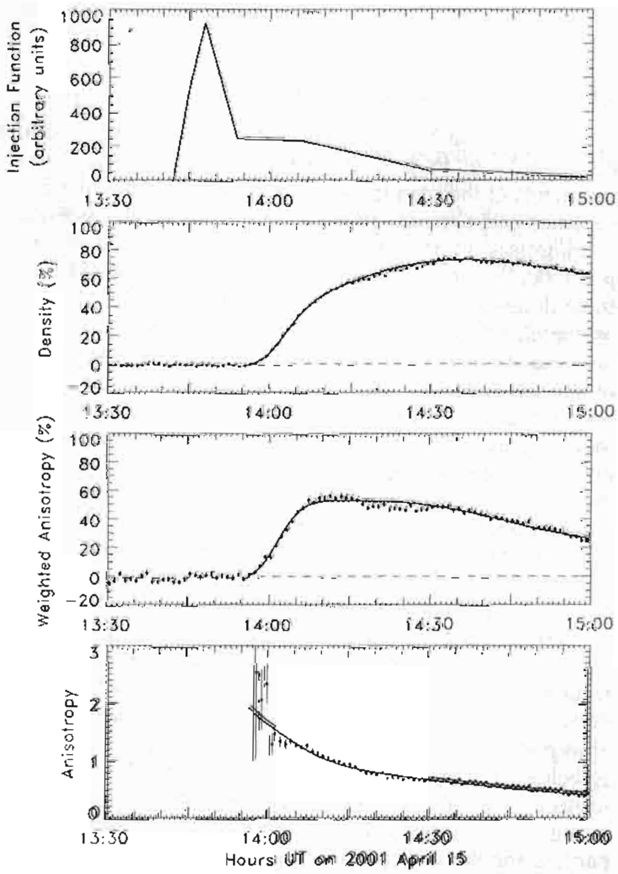

FIG. 3.—Data points (*bottom three panels*) show solar cosmic-ray density, weighted anisotropy, and anisotropy derived by fitting Spaceship Earth data to a first-order anisotropy. Curves show predictions of a model based on numerical solution of the Boltzmann equation with a best-fit radial mean free path of 0.17 AU and with the injection function shown in the top panel. The χ^2 statistic is 110 with 90 degrees of freedom, indicating a good fit.

[2] The piecewise linear injection function is described by 5 amplitudes a_i at joint times t_i, where $t_i = t_0 + 2^{i-1}\tau$ are specified by t_0 and τ.