



Final Report

Transport of Cosmic Rays in the Solar System

Principal Investigator

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Abstract and Executive Summary

Project Title: Transport of Cosmic Rays in the Solar System

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The overall goals of this project were four-fold: 1) to study the fundamental processes of energetic particle transport in turbulent magnetic fields; 2) to study the transport, acceleration, and interactions of solar energetic particles; 3) to study the transport, time variations, and interactions of galactic and extragalactic cosmic rays; and 4) to provide Thai-language information on space physics and astrophysics to the public, and to expose students to space physics research and research techniques. We have worked on 32 lines of research and trained or involved 45 local participants. Output of the project includes 6 articles for leading international journals (3 published, 1 submitted, 2 in preparation), 14 international conference presentations, 5 completed theses (2 Ph.D., 3 M.Sc.), and 9 completed B.Sc. senior projects.

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

Some highlights of our research results are:

- Discovery of other routes to Bohm diffusion, due to random ballistic decorrelation.
- Analytic calculations of the field line random walk for one-component “noisy RMHD” magnetic turbulence.
- Developed first theory of time profile of particle subdiffusion and diffusion perpendicular to the mean field, based on Brownian motion.
- A new version of NLGC theory based on random ballistic decorrelation provides a reasonable fit to simulation results, with no arbitrary parameters.
- Introduction of a novel concept for quantifying the separation of a particle guiding center from its field line.
- A particle guiding center very closely follows its local field line in 1D (slab) turbulence.
- Explanation of solar moss (bright and dark structure) in terms of the random walk of magnetic field lines connected to localized heating sources.
- Computational study of field line and particle trapping due to the topology of 2D magnetic turbulence, leading to dropouts, with a more accurate 2D MHD magnetic field model for dropout studies.
- Demonstration that particle gradients in dropouts are organized by local trapping boundaries, not current sheets.
- Discovery of a collimation effect in spherical geometry, in which particle trajectories are attracted to or repelled from O-points of the turbulence topology.
- Developed a software detector for simulated solar energetic particle transport, to provide time-intensity and directional distributions at different regions of the turbulent topology.
- Discovered an effect of the 2D turbulence topology on the parallel transport of solar energetic particles.

- Examining the radial dependence of SEP profiles, including the distances of Mars and Jupiter, with regard to radiation hazards for astronauts.
- Performed the first SEP transport simulations to include the radial dependence of the mean free path from *ab initio* turbulence models.
- Continued operation and maintenance of the Princess Sirindhorn Neutron Monitor (PSNM) at the summit of Doi Inthanon, providing neutron monitor data at the world's highest cutoff rigidity for a fixed station.
- Processing of PSNM data for real-time plots and scientific data.
- Organized semi-annual electronics training workshops.
- Intercalibrated PSNM with other neutron monitors by bringing a mobile monitor (calmon) from South Africa to Doi Inthanon.
- Collected data from the calmon in various configurations, including a measurement of the effect of the PSNM building.
- Developed a local capability to perform realistic Monte Carlo simulations of Galactic cosmic ray interactions in Earth's atmosphere and neutron monitors.
- Investigated the time dependence of the time-delay spectrum, and found an association with atmospheric pressure.
- Using FLUKA simulations to better understand the travel time and time delay distributions of neutrons in the PSNM.
- Studying the synodic variations of galactic cosmic rays in association with corotating solar wind structures.
- New global, analytic model of an interplanetary flux rope.
- Orbits of energetic particles in an interplanetary flux rope due to drifts, perpendicular diffusion, and parallel scattering.
- Successful dissemination of space weather knowledge: Website ranked highly in Thailand for physics/astronomy; involving high-school students in space science measurements; invited lectures; newspaper, radio, and TV interviews.
- Teaching laboratory experiment for undergraduate students on cosmic rays and neutron detection.

รหัสโครงการ: BRG5180004

บทคัดย่อและบทสรุปสำหรับผู้บริหาร

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วัตถุประสงค์ของโครงการนี้มี 4 ข้อ: 1) เพื่อศึกษากระบวนการพื้นฐานในการขนส่งของอนุภาคพลังงานสูงในสนามแม่เหล็กปั่นป่วน 2) เพื่อศึกษาการขนส่ง การเร่ง และปฏิกิริยาของอนุภาคพลังงานสูงจากดวงอาทิตย์ 3) เพื่อศึกษาการขนส่ง การเปลี่ยนต่อเวลา และปฏิกิริยาของรังสีคอสมิกจากกาแล็กซีและนอกกาแล็กซี และ 4) เพื่อให้ข้อมูลในภาษาไทยเกี่ยวกับฟิสิกส์อวกาศและฟิสิกส์ดาราศาสตร์สู่สังคม และเพื่อให้นักเรียนและนักศึกษารับรู้เกี่ยวกับงานวิจัยด้านฟิสิกส์อวกาศและเทคนิคการวิจัย เราได้ทำโครงการย่อยจำนวน 32 โครงการ และให้คนไทยฝึกงานหรือให้มีส่วนร่วมในงานวิจัยจำนวน 45 คน ผลงานจากโครงการนี้ รวมถึงบทความสำหรับวารสารนานาชาติชั้นนำ 6 เรื่อง (ตีพิมพ์แล้ว 3 เรื่อง ส่งถึงวารสารแล้วอีก 1 เรื่อง และเตรียมส่งอีก 2 เรื่อง) การเสนอที่ประชุมนานาชาติ 14 เรื่อง วิทยานิพนธ์ 5 เรื่อง (ป.เอก 2 และ ป.โท 3) และโครงงานปีที่สี่ (ป.ตรี) 9 เรื่อง

คำหลัก: รังสีคอสมิก, ฟิสิกส์อวกาศ, ดาราศาสตร์, การจำลองด้วยคอมพิวเตอร์, ความปั่นป่วน

จุดเด่นของผลงานวิจัยคือ

- การค้นพบเส้นทางใหม่สู่การฟุ้งแบบบอห์ม ที่เกิดจากการตีคอเรเลตแบบบัลลิสติกและสุม
- การคำนวณเชิงวิเคราะห์ของการเดินสุมของเส้นสนามแม่เหล็กสำหรับการปั่นป่วนแม่เหล็กที่มีองค์ประกอบเดียวแบบนอยซี RMHD
- การพัฒนาทฤษฎีเกี่ยวกับการอนุฟุ้งและการฟุ้งต่อเวลาของอนุภาคในทิศทางกับสนามเฉลี่ย จากพื้นฐานการเคลื่อนที่แบบบราวเนียน
- ทฤษฎี NLGC ในรูปแบบใหม่ จากพื้นฐานการตีคอเรเลตแบบบัลลิสติกและสุม สามารถพยากรณ์ผลการจำลองได้ โดยไม่มีตัวแปรเสรี
- การแนะนำเชิงขั้วใหม่เพื่ออธิบายการแยกตัวระหว่างศูนย์นำอนุภาคและเส้นสนามที่ตามอยู่
- ศูนย์นำอนุภาคตามกลศาสตร์มากับเส้นสนามในท้องถิ่นในการปั่นป่วนแบบหนึ่งมิติ (แลบ)
- การอธิบายมอสที่ดวงอาทิตย์ (โครงสร้างสว่างและมืด) ในเทอมของการเดินสุมของเส้นสนามแม่เหล็กที่เชื่อมกับแหล่งความร้อนที่โลคัลไลซ์
- การศึกษาเชิงคำนวณของการกักตัวของเส้นสนามและอนุภาคเนื่องจากทอพอโลยีของความปั่นป่วนแม่เหล็กแบบสองมิติ ซึ่งนำไปสู่ดรอปปเอาร์ท โดยใช้แบบจำลองสนามแม่เหล็กแบบ 2D MHD ซึ่งแม่นยำมากขึ้น ในการศึกษาดรอปปเอาร์ท
- เกรเดียนต์ของอนุภาคในดรอปปเอาร์ทเรียงด้วยขอบเขตการกักในท้องถิ่น ไม่ใช่แผ่นกระแส
- การค้นพบผลการคอลลิเมตในเรขาคณิตแบบทรงกลม โดยเส้นทางของอนุภาคถูกดูดเข้าสู่หรือผลักออกจากจุดโหนดในทอพอโลยีความปั่นป่วน
- การพัฒนาเครื่องวัดทางซอฟต์แวร์สำหรับการจำลองการขนส่งของอนุภาคพลังงานสูงจากดวงอาทิตย์ เพื่อให้การแจกแจงของความเข้มต่อเวลาและทิศทางในบริเวณต่างๆ ของทอพอโลยีความปั่นป่วน

- การค้นพบผลของทอพอโลยีความปั่นป่วนในสองมิติต่อการขนส่งในทางขนานของอนุภาคพลังงานสูงจากดวงอาทิตย์
- การศึกษาการที่จำนวนต่อเวลาของอนุภาคพลังงานสูงจากดวงอาทิตย์ขึ้นกับรัศมีจากดวงอาทิตย์ รวมทั้งระยะทางของดาวอังคารและดาวพฤหัสบดี เนื่องจากเกี่ยวข้องกับภัยทางรังสีสำหรับนักบินอวกาศ
- การจำลองการขนส่งของอนุภาคพลังงานสูงจากดวงอาทิตย์ครั้งแรกที่รวมถึงการขึ้นกับรัศมีของระยะอิสระเฉลี่ยตามแบบจำลองความปั่นป่วนแบบแอมบิโนซีโอ
- การดำเนินการและการบำรุงรักษาอย่างต่อเนื่องสำหรับสถานีตรวจวัดนิวตรอนสิรินธร (PSNM) ณ ยอดดอยอินทนนท์ ซึ่งให้ข้อมูลจากเครื่องตรวจวัดนิวตรอนที่คัทออฟฟิสิกส์ที่สูงที่สุดในโลกสำหรับสถานีที่อยู่กับที่
- การโปรเซสข้อมูล PSNM สำหรับรูปทันเวลาจริงและข้อมูลทางวิทยาศาสตร์
- การจัดเวิร์คชอปฝึกด้านอิเล็กทรอนิกส์สองครั้งต่อปี
- การแคลิเบรต PSNM เทียบกับสถานีอื่น โดยนำเครื่องตรวจวัดที่เคลื่อนที่ได้ (แคลมอน) จากแอฟริกาใต้ สู่ดอยอินทนนท์
- การเก็บข้อมูลจากแคลมอนในรูปแบบต่างๆ รวมทั้งการวัดผลกระทบของอาคาร PSNM
- การพัฒนาความสามารถในห้องปฏิบัติการที่จะจำลองแบบมอนทีคาร์โลเหมือนจริงสำหรับปฏิกิริยาของรังสีคอสมิกจากกาแล็กซีในบรรยากาศโลกและในเครื่องตรวจวัดนิวตรอน
- การศึกษาการขึ้นกับเวลาของสเปกตรัมเวลารอ และพบการขึ้นกับความดันในบรรยากาศ
- การใช้การจำลองด้วย FLUKA เพื่อการเข้าใจที่ดีขึ้นของการแจกแจงของเวลาเดินทางและเวลารอของนิวตรอนใน PSNM
- การศึกษาการขึ้นกับเวลาในรอบ 27 วันที่ขึ้นกับโครงสร้างลมสุริยะที่หมุนพร้อมดวงอาทิตย์
- แบบจำลองใหม่เชิงวิเคราะห์แบบทั่วถึงสำหรับเชือกฟลักซ์ระหว่างดาวเคราะห์
- เส้นทางของอนุภาคพลังงานสูงในเชือกฟลักซ์ระหว่างดาวเคราะห์เนื่องจากการลอยเลื่อน การพุ่งในทิศตั้งฉาก และการกระเจิงในทางขนาน
- สำเร็จในการเผยแพร่ความรู้เกี่ยวกับสภาพอวกาศ โดยเว็บไซต์ติดอันดับสูงในประเทศไทยในหมวดฟิสิกส์และดาราศาสตร์ การให้นักเรียนมีส่วนร่วมในการวัดข้อมูลทางวิทยาศาสตร์อวกาศ การบรรยายรับเชิญ และการสัมภาษณ์สำหรับหนังสือพิมพ์ วิทยุ และโทรทัศน์
- การทดลองสำหรับวิชาสอนนักศึกษา ป. ตรี เกี่ยวกับรังสีคอสมิกและการวัดนิวตรอน

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Chapter 1

Objectives

The overall goals of this project were four-fold:

1. To study the fundamental processes of energetic particle transport in turbulent magnetic fields.
2. To study the transport, acceleration, and interactions of solar energetic particles.
3. To study the transport, time variations, and interactions of galactic and extragalactic cosmic rays.
4. To provide Thai-language information on space physics and astrophysics to the public, and to expose students to space physics research and research techniques.

Our activities are schematically indicated in Figure 1. The activities and results of our work are presented in the following sections, each section corresponding to one of these objectives.

It will be seen that the number of lines of research that we have undertaken is greater than the number that have produced papers in international journals. In part, this is because of a time lag - some ideas developed during the course of this project will eventually lead to a publication. In part, it is because some lines of work have been terminated. This was anticipated in our research proposal, when we wrote that “there is 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.” It is key to our research philosophy to produce high-impact output – both in terms of publishing in journals with a high impact factor, and in terms of the number of citations thereafter, indicating an impact on the field. To accomplish that with limited manpower (especially manpower for writing international journal articles), it is crucial to redirect our efforts only to work that is most promising for producing novel results of substantial interest to the community. At the same time, it is important for our “intellectual health” (and for training students) to try new ideas for a while, even if we ultimately do not pursue them to the level of an international journal article.

The principal investigator was intimately involved in all work by our group; specific contributions by others are noted below. 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). Output numbers correspond to the numbered list of output in Section 7 and the Attachment numbers. Note also the cross-referencing between these categories of work and between individual sub-projects, indicating the strong synergy when performing these four categories of work in the same overall research project.

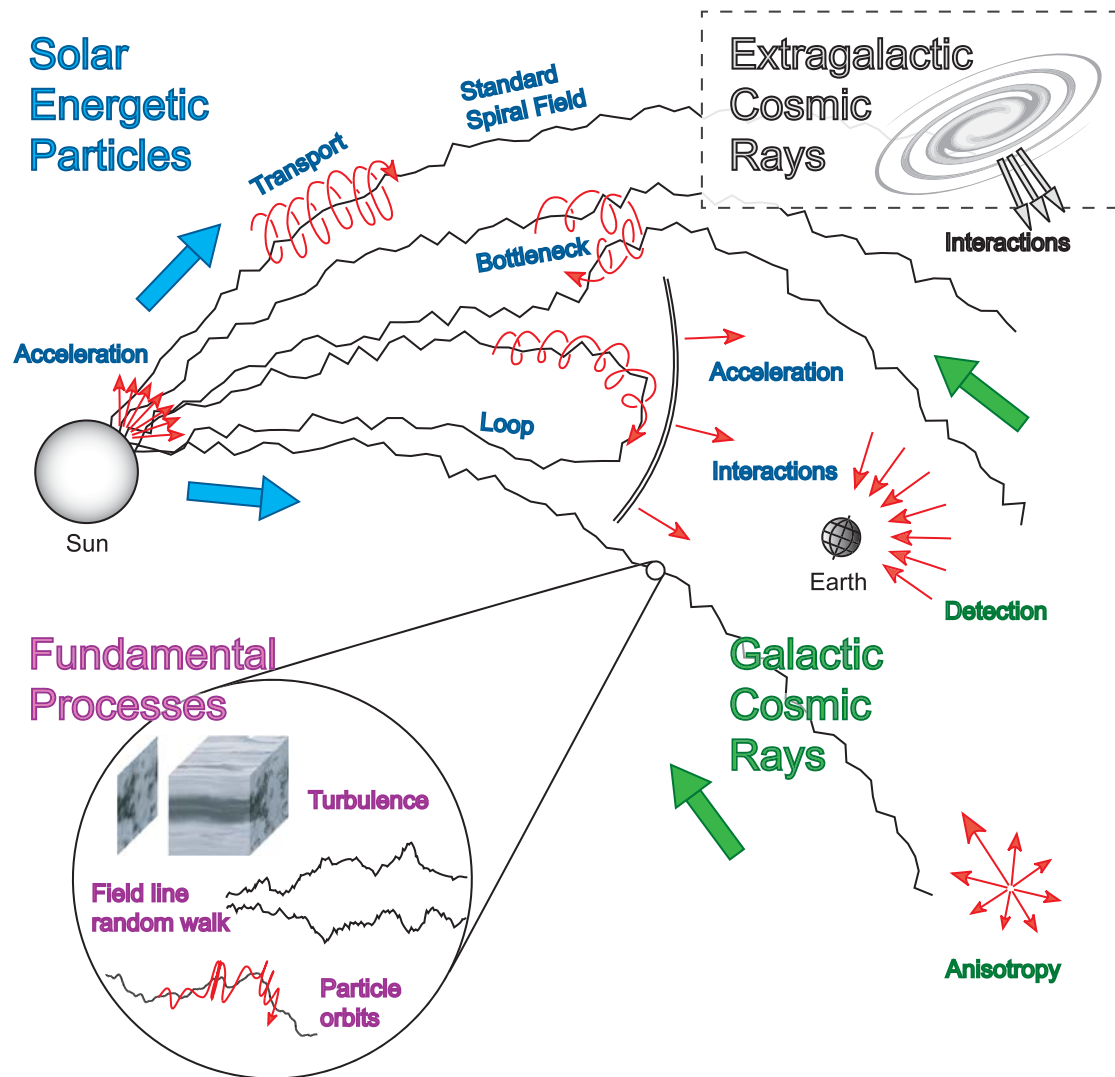


Figure 1: Illustration of the topics of this research project: 1. Magnetic turbulence, 2. Solar energetic particles, 3. Galactic cosmic rays, and 4. Dissemination and understanding of information on space weather. The solid lines refer to magnetic field lines, while arrows indicate particle motion.

Chapter 2

Magnetic Turbulence

Objective: To study the fundamental processes of energetic particle transport in turbulent magnetic fields.

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

2.1 Field line random walk in stretched isotropic turbulence

- Researcher: Pat Wongpan, Chewin Pinmuck, Wirin Sonsrettee
- Classification: Ensemble average field line random walk
- Type of work: Theory and computation
- Key Points: Analytic techniques and numerical evaluation of magnetic field line diffusion for general homogenous turbulence with a uniform mean field. Closed-form analytic solutions for limiting cases of stretched isotropic turbulence. Identified transition from quasilinear to Bohm diffusion, confirmed by numerical simulations, contrary to expectations in the community. Discovered that the standard Kubo number does not properly separate regimes of diffusion in stretched isotropic turbulence.
- Status: Ongoing
- Output: Senior project (Chewin), 22, 29, 35

In space and laboratory plasmas (ionized gases), the transport of particles and heat tends to follow magnetic field lines. Such plasmas typically have turbulent (random) fluctuations, so a magnetic field line undergoes a random walk. This affects phenomena such as the transport of galactic cosmic rays into the heliosphere and the transport of solar particles toward Earth; both types of particles are forms of natural radioactivity that pose a danger to humans and electronic circuitry in space.

The work in this section is mostly analytic research that employs Corrsin's hypothesis to explore field line diffusion for general homogeneous turbulence (see also Ruffolo et al. 2004, 2006). In general we obtain 3 implicit coupled equations involving 3-dimensional integrals, with closed-form solutions in certain limiting cases. We have developed code using the Mathematica package (Wolfram Research, Inc.) with which we produce numerical results for specific cases. This work was well suited to the abilities of Pat Wongpan, a "post-bacheloral researcher" at Mahidol U.

We are currently studying stretched isotropic turbulence, in which the omnidirectional modal energy density is constant along oblate or prolate spheroids (squashed or stretched spheres) in $\mathbf{k}$ -space. This allows us to explore limits toward reduced dimensionality, as in 2D and slab (1D) turbulence used in our previous work.

In particular, we consider turbulence that is stretched by an arbitrary factor α , including fluctuations that are quasi-1D ($\alpha \gg 1$; Figure 2c), isotropic ($\alpha = 1$; Figure 2d), or quasi-2D ($\alpha \ll 1$;

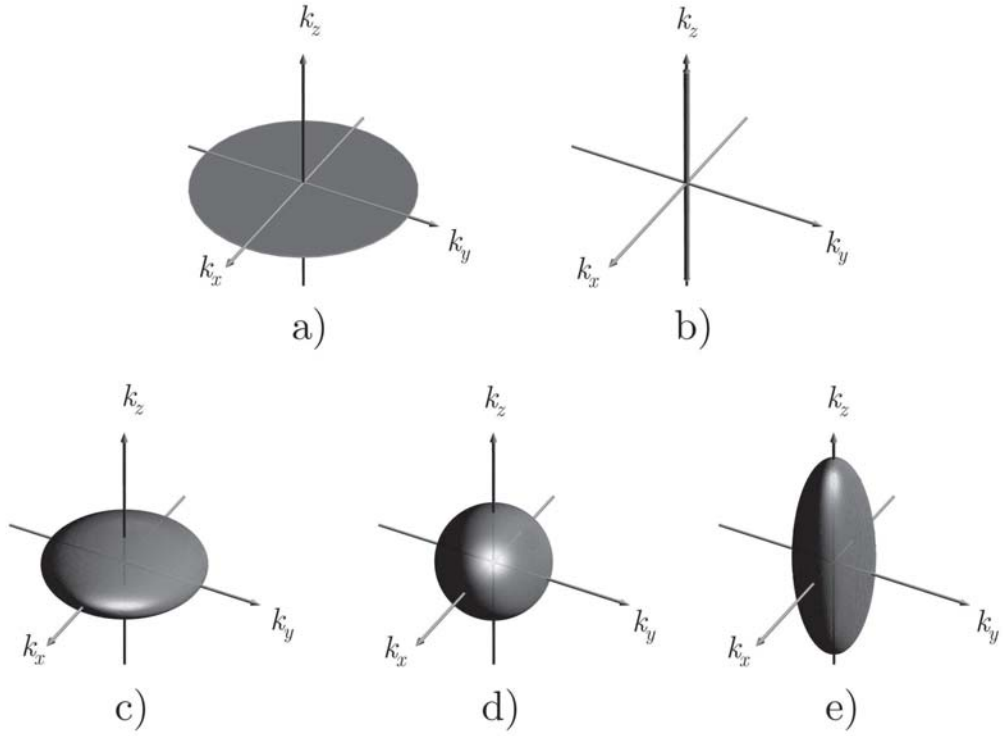


Figure 2: Different types (or components) of turbulence models in wavenumber space: a) 2D, b) slab (1D), c) quasi-2D, d) isotropic, and e) quasi-slab.

Figure 2e). Our non-perturbative approach allows us to consider a general mean field B_0 , including the interesting case of no mean field ($B_0=0$), which corresponds a Kubo number $R = (b/B_0) \alpha^{-3/2}$ of infinity.

The special case of isotropic turbulence is of substantial interest in the fusion and space plasma communities. George Rowlands, from Warwick U., UK, who visited Mahidol U. in 2005, has collaborated with us by making some suggestions. For example, he suggested that we connect our solutions for low and high mean fields by means of a Padé approximant. We now have a simple approximant that is (for our power spectrum) accurate to within 5% for all mean field values.

Furthermore, we have analytic solutions for the field line diffusion coefficient in the limit of high mean field for general stretched isotropic turbulence, and for no mean field in the limit of a very oblate spheroid (quasi-2D) or a very prolate spheroid (quasi-1D). Thus in the two limits of reduced dimensionality, we have analytic expressions for the low and high field limits.

We obtain quasilinear diffusion at high B_0 and high α and Bohm diffusion at low B_0 and low α . For $\alpha < 1$, the boundary between these two diffusive regimes corresponds to a Kubo number $R \sim 1$, but that does not hold for $\alpha > 1$. This is in contrast with a common expectation in the community of a transition to percolative diffusion instead of Bohm diffusion. However, much of that work was for very high B_0 , with a high Kubo number indicating very low α . We note that at very low α , for nearly

2D turbulence, our assumption of Corrsin's hypothesis is expected to break down, and percolative diffusion may apply in this limit.

Additional confirmation is provided by computer simulations to trace turbulent magnetic field lines, which do not employ Corrsin's hypothesis. We now have computational confirmation of our analytic results for isotropic turbulence with no mean field. However, for quasi-2D turbulence, Corrsin's hypothesis seems to be violated even for α as large as 0.25. Simulations also indicate subdiffusive behavior, which will require rethinking our analytic results for low α .

2.2 Field line random walk in 2D+slab turbulence: Trapping effects and multiple routes to Bohm diffusion

- Researchers: Marian Ghilea, Piyanate Chuychai (Mae Fah Luang U.), Wirin Sonsrettee, Achara Seripienlert, Andrew Snodin
- Classification: Ensemble average field line random walk
- Type of work: Computation and theory
- Key points: Discovery of other routes to Bohm diffusion, due to random ballistic decorrelation. Exploring transient subdiffusion and asymptotic diffusion of field lines in quasi-2D two-component turbulence, with trapping effects and apparent violation of Corrsin's hypothesis.
- Status: Paper submitted
- Output: 4, 11, 50, 59

As published by Ruffolo et al. (2008), for 99% 2D (random phase) + 1% slab fluctuations the field line diffusion coefficients $D_x = \langle \Delta x^2 \rangle / (2\Delta z)$ and $D_y = \langle \Delta y^2 \rangle / (2\Delta z)$ peaked, decreased (were subdiffusive), and then appeared to become constant (were diffusive). This was a major surprise – we were then unaware of subdiffusion in the 2D+slab field line random walk. Subdiffusion implies a memory effect, which may invalidate Corrsin's hypothesis (see discussion in Ruffolo et al. 2008). Indeed, the apparently constant values of D_x and D_y at large Δz were more than two times lower than those expected by the Matthaeus et al. (1995), marking the first known significant deviation from that theory for 2D+slab turbulence.

This work was lead by Marian Ghilea, a post-doctorate researcher from Romania, hired with support from Mahidol U. from Nov. 1, 2009 to Oct. 31, 2010. The aims and relevance of the present work are as follows: For decreasing slab fraction, f_s , we are computationally investigating the onset of subdiffusion, whether asymptotic diffusion is still present even for very low f_s , over what z-distance the subdiffusion changes to asymptotic diffusion, and the asymptotic diffusion coefficient. Hopefully simple relations will be found that will point the way to theoretical understanding and can be compared with concepts of percolation. Although strictly speaking it does not fit into the “phase diagram” of stretched isotropic turbulence (in terms of stretching parameter vs. B_0), it may be the best way to understand the quasi-2D behavior in that system, and to fully address the issue of Bohm diffusion vs. percolation for high Kubo number.

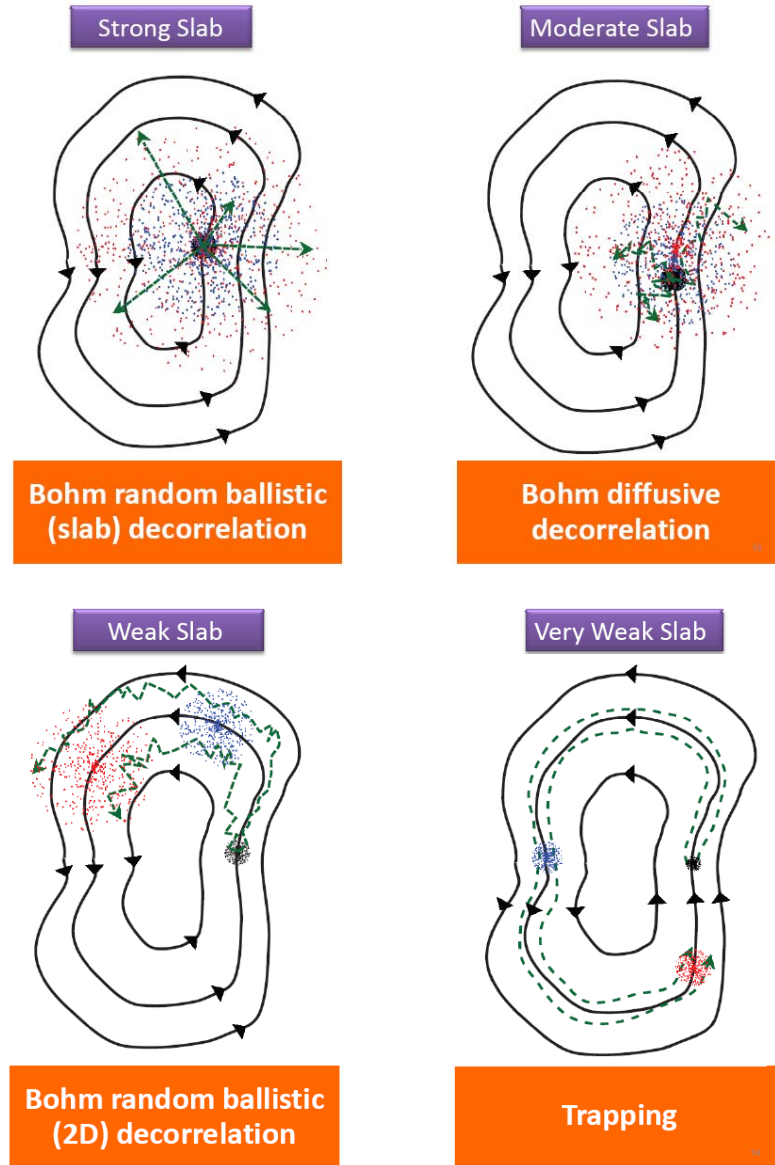


Figure 3: Illustration of four regimes of magnetic field line random walks (green dashed lines) in 2D+slab turbulence, for which different processes govern the Lagrangian decorrelation of the 2D field. The 2D field follows equipotential contours (black lines) while the slab field varies randomly with z . Colored dots illustrate the distribution of field line locations for an ensemble of slab fields at varying distance z from a common starting point (at increasing z for black, blue, and red points, respectively). (a) For a strong slab contribution, there is random ballistic decorrelation (RBD) of the 2D field due to nearly straight field line trajectories (dominated by slab fluctuations). (b) For a moderate slab contribution, there is diffusive decorrelation (DD) of the 2D field due to diffusion (again dominated by slab fluctuations). (c) For a weak slab contribution, there is RBD due to the 2D field itself. Note that (a)-(c) all represent routes to Bohm diffusion for the 2D contribution. (d) For a very weak slab contribution, field lines remain trapped along 2D flux surfaces for long distances, with “memory effects,” violation of Corrsin’s hypothesis, and in some cases, a subdiffusive field line random walk.

For higher f_s , we have made a new discovery of other routes to Bohm diffusion, with random ballistic decorrelation (in the Lagrangian correlation of the 2D field; see Figure 3). This implies that the classic theory of Matthaeus et al. (1995) is sometimes inapplicable. A paper has been submitted to the *Astrophysical Journal*. Some follow-up work on this topic, beyond what is in the paper, is being performed by our new post-doc, Dr. Andrew Snodin (supported by MU since March, 2011).

2.3 Field line random walk in noisy RMHD turbulence

- Classification: Ensemble average field line random walk
- Type of work: Computation and theory
- Key points: Analytic calculations of the field line random walk for one-component “noisy RMHD” magnetic turbulence.
- Status: Paper in preparation

This project was developed together with Prof. Bill Matthaeus during the recent visit by the PI to U. Delaware, USA. Building on the discovery of multiple routes to Bohm diffusion (see 2.2) in the context of two-component 2D+slab turbulence, we perform calculations for a one-component model. One-component anisotropic magnetic turbulence is less closely related to observations of space plasmas, but such models have been studied extensively in the community. This model is closely related to the stretched (or squashed) isotropic turbulence described in Section 2.1 (see Figure 2). Bill suggested this magnetic field model, which we call “noisy RMHD,” because his previous papers have identified that such a spectrum describes simulations of reduced magnetohydrodynamics (RMHD), which is a model of considerable interest in the fusion plasma community. The “noise” is to spread a 2D power spectrum (Figure 2a) along k_z , making it more like Figure 2c, that is, like RMHD spectra from simulation results, and for extensive spreading, we even consider a quasi-1D limit like Figure 2e. This model is more tractable analytically because the turbulence is taken to be transverse. This model will provide a strong connection with RMHD simulations in the future, and will also permit a comparison with simulations of dynamical magnetic fields, as opposed to the magnetostatic fields we have always assumed so far.

With this model, we have performed analytic calculations for two routes to Bohm diffusion. In both cases, the 1D and 2D limits are the same as for the slab and 2D limits of 2D+slab turbulence. Indeed, one can use two components of noisy RMHD turbulence, one quasi-2D and one quasi-1D, to show that results are similar to those for the 2D+slab model, thus justifying the idealization of those two components in the 2D+slab model.

2.4 Particle transport in isotropic turbulence with no mean field

- Researcher: Piyanate Chuychai (Mae Fah Luang U.)
- Classification: Ensemble average particle motion in Cartesian geometry
- Type of work: Theory and computation

- Key Point: Aim to understand the scattering of particles in isotropic turbulence over a wide range of particle energies.
- Status: On hold
- Output: 32, 36

For some years, Prof. William Matthaeus of U. Delaware has been working on this topic, as a “pure” example of treating particle transport over several orders of magnitude in particle energy. At the highest energies, a simple Fokker-Planck theory of perturbations to a straight line trajectory is effect. However, simulations are lower particle energies deviate substantially from this.

Bill invited Dr. Piyanate Chuychai (a Ph.D. graduate from the PI’s group, at that time a post-doc at U. Delaware) and the PI to participate in this work. The PI proposed that at very low particle energies, the particle motion might follow a version of NLGC theory, which is at first glance inconsistent with the Fokker-Planck framework that is successful at high energies. Recently Piyanate has performed new work (based in part on our experience working together on a recent paper, Ruffolo et al. 2008) that indicates subdiffusion at low particle speeds. However, the PI recently identified a possible error in the computational technique, so in ongoing work we will check the accuracy of these simulations.

2.5 Brownian motion model of the time dependence of perpendicular subdiffusion and diffusion of energetic charged particles

- Researchers: Chakrit Pongkitivanichkul, Theerasarn Pianpanit, Piyanate Chuychai (Mae Fah Luang U.)
- Classification: Ensemble average particle motion in Cartesian geometry
- Type of work: Theory
- Key point: Developed first theory of time profile of particle subdiffusion and diffusion perpendicular to the mean field, based on Brownian motion.
- Status: Ongoing
- Output: Senior project (Chakrit), 30, 53

This work builds on previous work (Ruffolo et al. 2008, which was supported by a previous Basic Research Grant from TRF) that used computer simulations to explore the dependence of asymptotic perpendicular diffusion coefficients (i.e., for particle motion perpendicular to the mean magnetic field) on the nonaxisymmetry, particle energy, and ratio of fluctuation energy along parallel and perpendicular wavenumbers, for an overall fluctuation amplitude b on the order of the mean field B_0 , as in the solar wind. That work also examined the time dependence of the running diffusion coefficient. The asymptotic diffusion regime is preceded by free streaming and subdiffusion, and the time dependence of the subdiffusion differs from standard concepts of compound subdiffusion. We can model the time profiles in terms of a heuristic velocity correlation function. This comprises the usual decreasing positive correlation of the perpendicular velocity plus a decaying negative

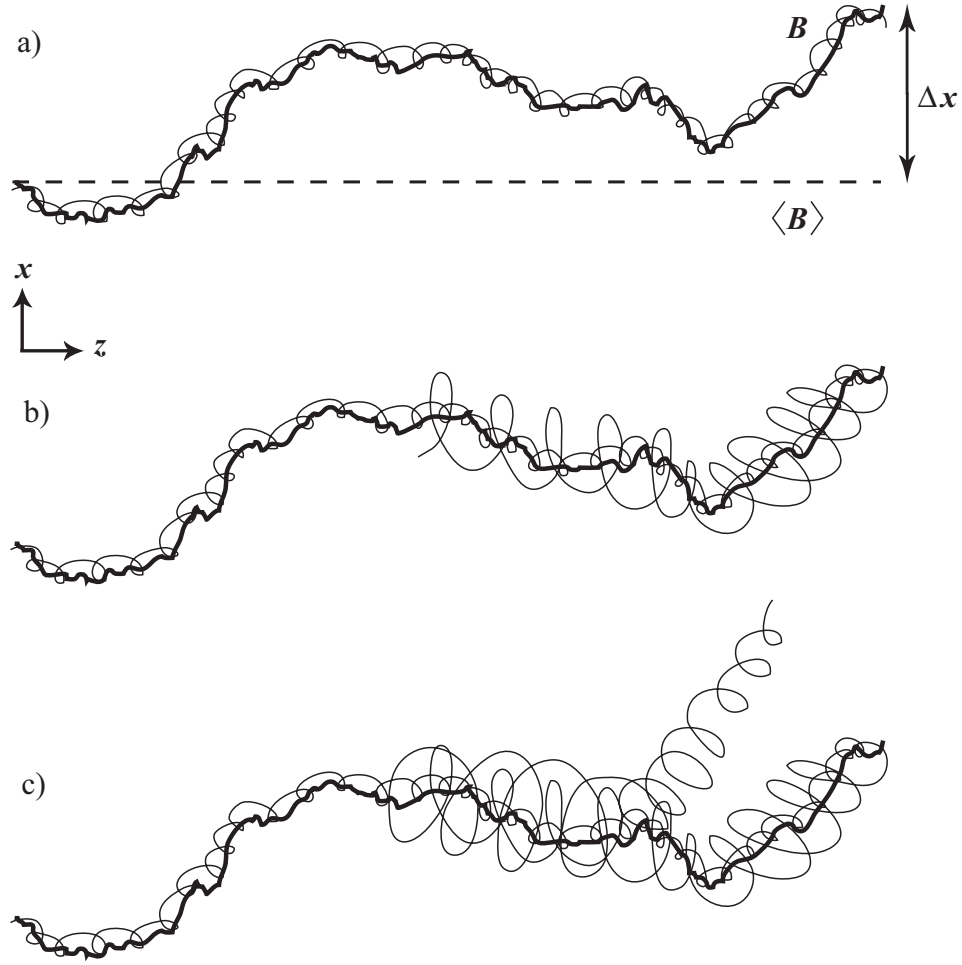


Figure 4: Illustration of perpendicular transport processes of particles in random magnetic fields. Thick lines indicate field lines and thin lines indicate particle trajectories; z is along the mean field and x is a perpendicular direction. (a) At short times, the particle gyrocenter undergoes free streaming. Next, the gyrocenter may follow the field line random walk before the onset of substantial parallel scattering, which would yield a diffusive process, sometimes called “first diffusion.” (b) Under typical solar wind conditions, parallel scattering curtails the above process, sometimes causing the particle to backtrack along the same field line. If the particle gyrocenter were strictly tied to one field line, this process would be compound subdiffusion. In our computer simulations, the particle trajectories are found to deviate from field lines, and the backtracking effect is instead manifest in a transient subdiffusive regime. (c) After a sufficiently long time, the particle trajectory deviates substantially from the field line; i.e., the particles follow field lines locally but not globally. This is the asymptotic diffusion regime (sometimes called “second diffusion”), confirmed by simulations and described by the nonlinear guiding center (NLGC) theory.

correlation due to the possibility of backtracking along the same magnetic field line (see Figure 4). After long time durations such backtracking becomes subsumed into the asymptotic diffusion process. The asymptotic diffusion coefficients are explained reasonably well by the nonlinear guiding center (NLGC) theory of Matthaeus et al. (2003). Note that we have continued to present

these results in conferences during the present grant period, which leads us to continually think about their implications.

In new work, we have developed a new Brownian motion theory to also include transient subdiffusion. This theoretical work involved a 4th-year undergraduate student at Mahidol U., Chakrit Pongkitivanichkul. We use standard theories for Brownian motion to model the joint correlation between the magnetic field and the parallel velocity, which as in NLGC theory, are used to model the perpendicular velocity. Given an unknown temporal field decorrelation parameter to model the separation of particles from field lines, we have a satisfactory explanation of the transition from pure subdiffusion (for pure slab turbulence) to subdiffusion followed by asymptotic diffusion (for 2D+slab turbulence). We are also collaborating with Dr. Piyanate Chuychai to compare our model of the velocity autocorrelation, based on analytic theory, with results from particle simulations. However, initial comparisons with simulations (see 2.6) show results that are qualitatively similar but evolve over quantitatively different timescales. More recently, we have been incorporating new theoretical ideas from the work in Section 2.7.

2.6 Perpendicular subdiffusion and diffusion of particles in nearly one-dimensional turbulence

- Researchers: Nattawit Chaiworawit, Narongpol Wichailukkana, Theerasarn Pianpanit, Lalitwadee Kawinwanichakij
- Classification: Ensemble average particle motion in Cartesian geometry
- Type of work: Computation
- Key points: Studying transition from compound subdiffusion to transient subdiffusion and asymptotic diffusion when adding a 2D component to slab turbulence. Testing the Brownian motion model of particle subdiffusion and diffusion perpendicular to the mean field.
- Status: Ongoing
- Output: Senior projects (Nattawit, Narongpol), 8, 21, 61

Undergraduates Theerasarn Pianpanit (then starting his 3rd year) and Lalitwadee Kawinwanichakij (then starting her 2nd year) worked on computer simulations to examine the rates of diffusion of field lines and particles for reduced dimensionality, which can test the theory we are developing (see 2.5). Nattawit Chaiworawit (4th-year student) then started to perform such computer simulations for his senior project at Mahidol University. We tried to statistically decide whether the diffusion coefficient vs. time, for a specific time range, changed from diffusive to subdiffusive for increasing slab fraction (reduced dimensionality). While the overall trend toward subdiffusion was clear, the fit coefficients for a linear trend were not reliable. We therefore decided that in further work, we should specify two time periods over which to find best-fit power-law trends from both simulations and theory, and to verify whether there exists a value of the temporal field decorrelation parameter that can successfully explain the two power-law exponents. This was worked on by Narongpol Wichailukkana (4th-year student). His comparisons with the theory show results that are

qualitatively similar but evolve over quantitatively different timescales. We will investigate the matter further.

2.7 Directions for improvement of NLGC theory

- Researcher: Theerasarn Pianpanit, Piyanate Chuychai (Mae Fah Luang U.)
- Classification: Ensemble average particle motion in Cartesian geometry
- Type of work: Computation
- Key Points: The perpendicular diffusion of particles in 2D+slab fluctuations can be described in terms of the 2D component alone, without considering the slab component. We have modified NLGC theory so as to include no arbitrary parameters. A version of NLGC theory based on random ballistic decorrelation provides a reasonable fit to simulation results, with no arbitrary parameters.
- Status: Paper in preparation
- Output: Senior project (Theerasarn), 6, 54

This work also concerns the widely cited nonlinear guiding center theory (NLGC) of Matthaeus et al. (2003) to describe the asymptotic diffusion of energetic charged particles perpendicular to the mean magnetic field subject to turbulent fluctuations. During the PI's visit to U. Delaware in March-May, 2010, Prof. Matthaeus asked us to think about two aspects of NLGC theory: 1) A suggestion by Shalchi (2006) that for 2D+slab fluctuations in the context of NLGC theory, there are contributions associated with the 2D and slab power spectra, and the latter lead to asymptotic subdiffusion, therefore giving zero contribution to the asymptotic diffusion coefficient. We call this the Shalchi Slab Hypothesis (SSH). 2) The original NLGC theory has an arbitrary parameter a^2 , and it would be useful to identify the physical interpretation of a^2 and develop a non-arbitrary replacement for a^2 .

Therefore, we have started this work in the current 6-month period. One subtlety is that the slab component does enter the 2D contribution by its effect on the mean free path for parallel transport. Therefore, we performed simulations for varying slab fractions but with the fluctuation amplitude "tuned" to give the same mean free path in each case. These simulations were performed quite professionally by a 4th-year undergraduate student, Theerasarn Pianpanit. The simulation results show that NLGC theory with only a 2D contribution comes much closer to the simulations results than NLGC with 2D and slab contributions. More importantly (given the arbitrary prefactor a^2), there was a nearly constant fraction difference between NLGC/2D and the simulation results, which was not the case for NLGC/(2D+slab). These results clearly support the SSH.

We have also modified the assumptions of NLGC theory so as to avoid the arbitrary prefactor. This improved the match with simulations in some parameter ranges but not in others. Finally, we have included our recent development of random ballistic decorrelation (RBD) from the work in Section 2.2 to produce a version of NLGC, which we call refined nonlinear guiding center theory (RNLGC), that provides a reasonable explanation of simulation results with no arbitrary parameters.

2.8 Particle – field line separation

- Researcher: Piyanate Chuychai (Mae Fah Luang U.), Chart Wikee (Mae Fah Luang U.)
- Classification: Ensemble average particle motion in Cartesian geometry
- Type of work: Computation
- Key Points: Introduction of a novel concept for quantifying the separation of a particle guiding center from its field line. A particle guiding center very closely follows its local field line in 1D (slab) turbulence.
- Status: Ongoing
- Output: 17, 52, 56

The concept of this work is to computationally measure the rate of separation of a particle's instantaneous location, or its guiding center location, from the magnetic field line that started at the same point. In particular, we use the 2D+slab model of turbulence, in which field lines cannot backtrack along the mean field direction (z), and therefore the z -coordinate can uniquely specify a location on a field line. Thus we define the particle – field line separation as the displacement between a particle (or guiding center) location at time t , i.e., $x(t)$, $y(t)$, $z(t)$, from the field line location at that same z , i.e., $x(z)$, $y(z)$, z . The computer simulations are being led by Dr. Piyanate Chuychai at Mae Fah Luang U. and also her M.Sc. student Chart Wikee. They started for the simple case of pure slab turbulence, and found that the guiding center follows its local field line very closely. In contrast, in 2D+slab turbulence, there is a diffusive separation between the particle and its parent field line.

2.9 Solar moss

- Researcher: Rakpong Kittinaradorn
- Classification: Dropout patterns of field line trajectories in Cartesian geometry
- Type of work: Computation
- Key Points: Provided an explanation of solar moss, the bright and dark structure in extreme ultraviolet observations of the solar transition region between the chromosphere and the corona. Our explanation involves the random walk of magnetic field lines connected to localized heating sources.
- Status: Finished; paper published
- Output: 1, 20

In our research group we used to hold weekly Group Meetings, much of which were devoted to scanning through selected articles in recent issues of the *Astrophysical Journal*, including an article (Katsukawa & Tsuneta 2005) on moss in the solar transition region (between the chromosphere and corona), with bright and dark regions interspersed. This appeared similar to our previous work on dropouts of solar energetic particles (Ruffolo et al. 2003) and therefore sparked the idea of an explanation of moss (discovered recently, in 1999) in terms of the random walk of magnetic field lines connecting the transition region to localized heating sources in the overlying coronal magnetic

loop. Soon afterwards, I learned of Rakpong Kittinaradorn, a bright undergraduate physics student at Mahidol U. in the Junior Science Talent Project (JSTP), and he agreed to do research on this topic in his spare time.

An initial literature review confirmed the feasibility of this idea. Rakpong suggested that while our explanation of dropouts involves trapping of field lines starting near O-points in the 2D turbulence structure, the explanation of moss should involve spreading of field lines that start near X-points. This makes physical sense because coronal heating (a key unsolved problem in astrophysics) could be due to magnetic reconnection near X-points. As another important ingredient, our collaborator Prof. Bill Matthaeus at U. Delaware has taken our 2D component of the magnetic field, based on random phases in Fourier space, and has run it through his 2D MHD code to produce more realistic magnetic fields, including current cores and current sheets. Assuming that current sheets provide more heating, we can infer patterns of magnetic connection to heating regions that appear similar to moss patterns (see Figure 5). We have published our results in the *Astrophysical Journal Letters* (IF=7.364), the world's top journal for rapid communications in astrophysics.

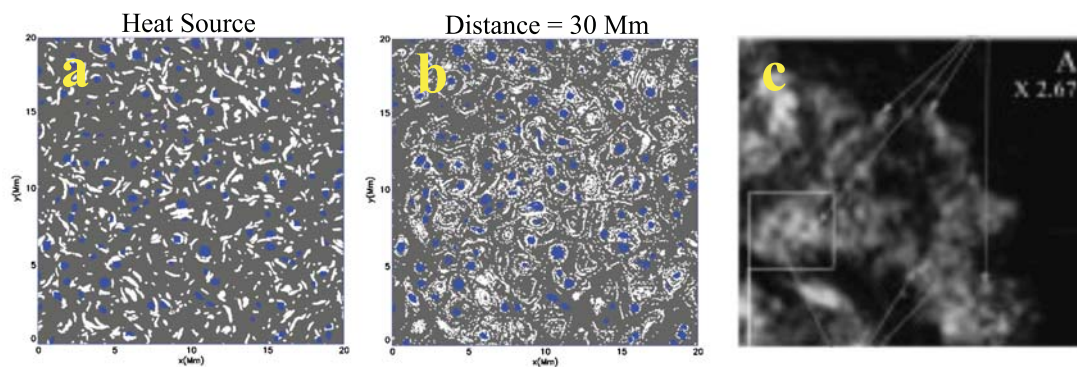


Figure 5: Left panel: 2D MHD simulation output, based on random-phase input. White regions indicate current sheets where heating takes place. Blue regions indicate current cores with less heating. Subsequent panels show traces of field lines from white and blue regions at the heat source to midway down a coronal loop and to the footpoint. For comparison, the rightmost panel shows an extreme ultraviolet image of moss taken by the TRACE spacecraft [Berger, T. A., et al. 1999, *Solar Phys.*, 190, 409], to the same scale as the other panels.

2.10 Local trapping boundaries

- Researchers: Achara Seripienlert, Piyanate Chuychai (Mae Fah Luang U.)
- Classification: Dropout patterns of field lines and particle trajectories in Cartesian geometry
- Type of work: Computation
- Key Points: Computational study of field line and particle trapping due to the topology of 2D magnetic turbulence, leading to dropouts, in a Cartesian geometry. Use of a more accurate

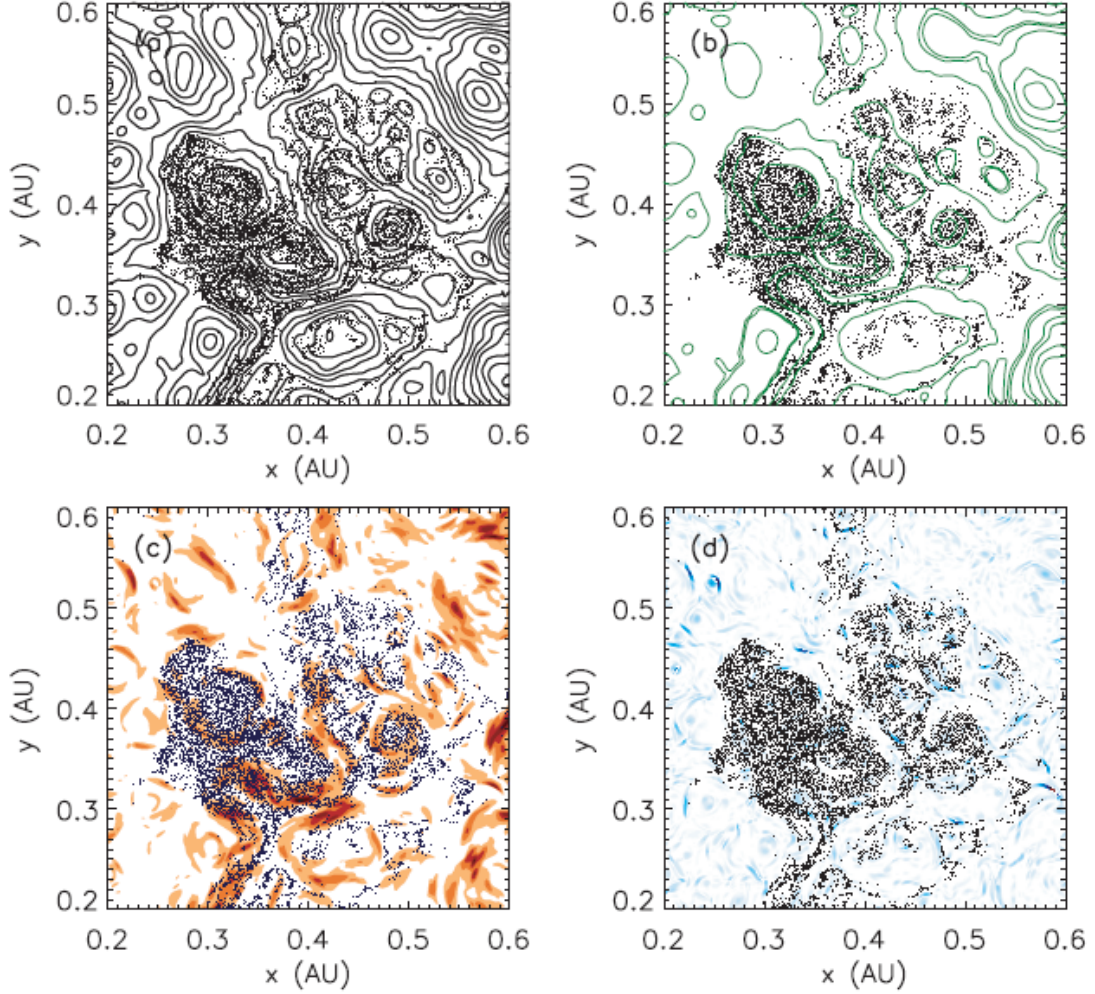


Figure 6: For a mean magnetic field along z and two-component magnetic turbulence, we trace 10,000 magnetic field lines from initial locations within a circle of radius 0.1 AU. These scatter plots show (x, y) locations of field lines after a distance z of 1.0 AU, superimposed with indications of (a) contours of constant potential $a(x, y)$ at equal intervals Δa , (b) LTBs (contours; green), (c) b^2 (red), and (d) j^2 (blue). Sharp gradients in magnetic connection to the source, i.e., dropout features, are seen to be associated frequently with LTBs, sometimes with large b^2 , and infrequently with current sheets.

2D MHD magnetic field model for dropout studies. Demonstration that particle gradients in dropouts are organized by local trapping boundaries, not current sheets.

- Status: Finished; paper published
- Output: Ph.D. thesis (Achara), 3, 24, 28, 34

In previous work, we developed the concept of a local trapping boundary (LTB), a sharp boundary within which turbulent field lines are temporarily trapped (Chuychai et al. 2007). 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.

One criticism of our work by others in the community is that observations due not indicate that particle gradients (i.e., trapping boundaries) correspond to current sheets, i.e., sudden changes in the magnetic field, or strong magnetic fields. Actually we do not expect them to. The present work aims to clarify whether LTBs, strong fields, or current sheets provide a better indicator of particle gradients. Our usual random-phase models are not appropriate, because current sheets only develop in more sophisticated 2D MHD models. We now employ such a model, supplied by Prof. Bill Matthaeus of U. Delaware.

In the past year, Miss Achara Seripienlert, a Ph.D. student at MU, has led the field line tracing work, and developed an improved method for finding LTBs. We have explored the difference between the 2D random phase fields and 2D MHD fields. We have also traced particle orbits in a 2D MHD + slab field to clarify the relationships between particle gradients, LTBs, and current sheets. We found that sharp gradients in the particle distribution are frequently associated with LTBs, sometimes with 2D magnetic fields, and infrequently with current sheets (Figure 6). We have published a journal article on this work in the *Astrophysical Journal*, the world's top journal for full-length articles in astrophysics.

2.11 Collimation of particle beams by two-dimensional turbulent structure

- Researchers: Achara Seripienlert, Paisan Tooprakai, Pattana Chintarunguangchai, Piyanate Chuychai (Mae Fah Luang U.)
- Classification: Dropout patterns of particle trajectories in spherical geometry
- Type of work: Computation
- Key Points: Computational study of field line and particle trapping due to the topology of 2D magnetic turbulence, leading to dropouts, in a spherical geometry. Discovery of a collimation effect, in which particle trajectories are attracted to or repelled from O-points of the turbulence topology.
- Status: Ongoing
- Output: Senior project (Pattana), 18, 38, 41, 45, 57

In this work, we have continued to develop simulations of solar energetic particle motion in random magnetic fields, in particular with regard to observations of dropouts, in which the particle intensity measured at a spacecraft suddenly increases or decreases. This is believed to be associated with a filamentary connection of magnetic fields to a localized particle source near the Sun. We employ a spherical geometry with a radial mean field so as to account for focusing of particle trajectories, especially near the Sun. We perform simulations of particle trajectories at various energies in 2D MHD + slab magnetic turbulence by solving the Newton–Lorentz equations in spherical coordinates, using a fourth-order Runge-Kutta method with adaptive stepsize control. We use the 2D MHD procedure because we believe it provides a more accurate description of the 2D fluctuations in an astrophysical plasma. A senior project student at Chulalongkorn U., Pattana Chintarunguangchai, performed simulations to explore how rapidly particles spread in the angular coordinates.

In recent work, we have found that charged particles of relativistic energies are systematically drawn toward potential maxima of the 2D turbulence structure. We call this a “collimation” effect because it tends to produce collimated particle beams. This work may have implications for high energy particles in space physics and astrophysics, especially with regard to spectral variability of ground level enhancements (GLEs) of relativistic solar particles.

2.12 Software detector for simulated solar energetic particle transport

- Researchers: Charong Buachan, Naruepon Weerawongphrom
- Classification: Dropout patterns of particle trajectories in spherical geometry
- Type of work: Computation
- Key Point: Developed a software detector for simulated solar energetic particle transport, to provide time-intensity and directional distributions at different regions of the turbulent topology. Discovered an effect of the 2D turbulence topology on the parallel transport of solar energetic particles.
- Status: Ongoing
- Output: M.Sc. thesis (Charong), Senior project (Naruepon), 42, 46

We are building upon the work of Section 2.11 to consider motion in a radial mean field with turbulent fluctuations. This spherical geometry is more similar to the true interplanetary magnetic field than a Cartesian geometry, especially by including the effect of particle focusing in spreading magnetic field lines. For the typical energy range of solar energetic particles, we have found that the locations at which particles arrive to 1 AU from the Sun (the distance of Earth’s orbit) are quite similar to the locations of field lines. Particles at higher energy do exhibit dropouts; they are not washed out at high particle energy as might be expected.

We have developed a software “detector” to find the time-intensity profile of solar energetic particles in the simulation, and also to measure directional distributions. The goal is for simulations to make these “measurements” in different regions of the turbulent topology. This allows us to use the techniques of work in Section 3 to infer the parallel mean free path of particles at various points in the 2D turbulent structure, as well as a possible understanding of the unusual orientations of directional distributions found in observations. This represents a new type of research on the transport of solar energetic particles.

A “detector” has been constructed by an undergraduate student, Naruepon Weerawongphrom, with help from a Ph.D. student, Achara Seripienlert. An independent detector was constructed by Charong Buachan, an M.Sc. student, who has collaborated with our “fitting” team to determine the mean free path of interplanetary scattering from the output of the software detector. In his M.Sc. work, Charong has made the discovery that the 2D turbulence structure indeed does affect the parallel transport, with a much longer mean free path near O-points of the turbulence. In further work we will develop a journal article on this work.

Chapter 3

Solar Energetic Particles

Objective: To study the transport, acceleration, and interactions of solar energetic particles.

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

3.1 Fitting SEP data: January 20, 2005 event

- Researcher: Alejandro Sáiz (Mahidol U.)
- Type of work: Computation, data analysis
- Key Points: Largest relativistic solar particle event in 50 years. Explanation of the January 20, 2005 ground level enhancement in terms of nonlinear transport of relativistic solar particles and/or a magnetic bottleneck configuration beyond Earth.
- Status: Paper in preparation
- Output: 5, 7, 9, 10, 15

Despite the decline in the solar cycle, the Sun produced a giant 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 at that time by Bartol at the South Pole, which provide spectral information.

Interestingly, on January 20, 2005, 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 show that this can be explained by 1) 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, or 2) a magnetic bottleneck configuration due to a previous coronal mass ejection then located beyond Earth.

In our most recent fits to the data, the bottleneck hypothesis provides a better fit. At present, we are working toward preparing 2 journal articles about our results for this event. The PI has prepared a draft of the first paper (to be led by Prof. Bieber), and several collaborators have provided figures.

3.2 Fitting SEP data: August 14, 1982 event

- Researchers: Alejandro Sáiz (Mahidol U.), Pornsak Sommart
- Type of work: Computation, data analysis
- Key Points: Our modeling and fitting techniques are also applied to fit data on relativistic electrons from a solar storm.
- Status: Ongoing

In this work, we apply similar analysis techniques to study the remarkable solar electron event of August 14, 1982 as observed by the MEH instrument on the ISEE-3 spacecraft. A qualitative analysis was published by Kane et al. (1985). With its remarkable intensity and anisotropy of relativistic electrons, this event should be particularly amenable to a quantitative analysis, and our collaborator Prof. Paul Evenson of U. Delaware recommended that we use our techniques to do so. This work is largely being carried out by an M.Sc. student, Pornsak Sommart.

3.3 Transport of GLE particles to Mars and Jupiter

- Researchers: Alejandro Sáiz (Mahidol U.)
- Type of work: Computation
- Key Point: Examining the radial dependence of SEP profiles, including the distances of Mars and Jupiter, with regard to radiation hazards for astronauts. Performed the first SEP transport simulations to include the radial dependence of the mean free path from *ab initio* turbulence models.
- Status: Ongoing
- Output: 12, 13, 16, 26, 43

This work was suggested by Prof. John Bieber at U. Delaware, USA. John submitted a grant proposal to NASA, with David and Alejandro as co-investigators, to examine the radial dependence of SEP profiles, including the distances of Mars and Jupiter. This is of interest to NASA's manned space program, with regard to future human exploration of Mars, for which solar energetic particles represent an important and unpredictable radiation hazard. With regard to radiation hazards, ions in the energy range detected by neutron monitors at Earth, i.e., ~500 MeV to 5 GeV, are particularly important. Although astronauts in present-day missions are still protected by Earth's magnetosphere (and humans at ground level are very well protected by Earth's atmosphere), there is no good plan for protecting astronauts from SEP and GCR above 500 MeV, and the flux of such particles can increase by more than ten-fold during a major solar event.

In some sense, this is something we in Thailand can already study, using the simulation programs and procedures developed here (Ruffolo 1995, Nutaro et al. 2001). In collaboration with Bieber and others at U. Delaware, we have fit neutron monitor data from several solar events (Bieber et al. 2002, 2004, 2005, Ruffolo et al. 2006; see also Section 3.1), so we could use the fit parameters for such an event to compute the expected time-intensity profiles at greater distances, including the orbits of Mars and Jupiter.

A potential weak point in such work is the lack of observational data concerning the mean free path of solar energetic particles as a function of radius (distance) from the Sun. A valuable suggestion by John Bieber is to incorporate a state-of-the-art theoretical estimation by his group at U. Delaware, using an *ab initio* model incorporating a model of the radial evolution of solar wind turbulence. They find that the mean free path varies as $r^{-0.5}$, so we have compared models with a mean free path that is constant (the standard assumption) or varying as $r^{-0.5}$. For the example of the injection function and transport parameters inferred for the event of Jan. 20, 2005 (see 3.1), we have determined inferred time-intensity profiles at the orbits of Mercury, Venus, Earth, Mars, Ceres, and Jupiter.

3.4 Particle acceleration at a coronal mass ejection

- Researcher: Chanruangrit Channok (Ubon Rajathanee U.)
- Type of Work: Theory, computation, data analysis
- Key Point: Aim to explain time-intensity profiles of energetic storm particles.
- Status: On hold

This line of work was begun after Chanruangrit Channok finished his Ph.D. thesis work with our group and returned to Ubon Rajathanee University. For a while he would occasionally visit us in Bangkok, especially after he obtained a Young Researcher Grant from TRF.

Our idea is to investigate a recent observation that the presence of two coronal mass ejections (CMEs) in space leads to greatly enhanced particle acceleration. We plan to model the particle acceleration at a “broad-brush” level, using a diffusion convection equation, instead of a pitch angle transport equation as in our fitting work. We will also need to take into account the generation of waves (and turbulence) by the particle acceleration. We think the secret to understanding the enhanced particle acceleration is the reflection of waves and particles in the space between the two CME-driven shocks. We developed this idea in part because one of the events studied by Chanruangrit in his thesis work (Channok et al. 2005) had a constant particle intensity in between the two shocks, as if particles were trapped there, which might possibly cause more wave generation and concentration.

As a step toward the modeling of pairs of CMEs, we aim to first explain in better detail the acceleration at a single CME, in conjunction with Mihir Desai at Southwest Research Institute in the US. We have achieved some theoretical understanding of time profiles observed by the ACE spacecraft, which in some sense correspond to spatial distributions of particles near the shock structure as it moves past the Earth. The work was aiming toward a quantitative comparison with observed time profiles, but is now on hold as Dr. Chanruangrith Channok apparently does not have time to do it.

Chapter 4

Galactic Cosmic Rays

Objective: To study the transport, time variations, and interactions of galactic and extragalactic cosmic rays.

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

4.1 Princess Sirindhorn Neutron Monitor operation and data processing

- Researchers: Nattapong Kamyam, Thana Yeeram, Usanee Tortempun, Teerawong Rattanakorn, Siraprapa Sanpa-arsa, Narumon Kalayanamitra, Manit Rujiwarodom, Paisan Tooprakai, Alejandro Sáiz (Mahidol U.), Tanin Nutaro (Ubon Ratchathani U.), Nicha Leethochawalit (U. Chicago), Taweewat Somboonpanyakul (U. Chicago), Manunya Likamonsavad (Prince of Songkla U.), Chanpeng Angchakan (Ubon Ratchathani U.), Cherdchai Wuttiya (Ubon Ratchathani U.), Nolan Essigmann (High school in Massachusetts), Yanee Kieokaew (High school in Phitsanulok Province)
- Type of work: Experiment, data processing
- Key Points: Continued operation and maintenance of the Princess Sirindhorn Neutron Monitor (PSNM) at the summit of Doi Inthanon, providing neutron monitor data at the world's highest cutoff rigidity for a fixed station. Made improvements to the PSNM building. Verified the accuracy of the PSNM pressure correction and checked for other atmospheric effects. Processing of PSNM data for real-time plots and scientific data.
- Status: Ongoing
- Output: 37

4.1.1 Overview

On January 21, 2008, Her Royal Highness Princess Sirindhorn graciously presided over the Opening Ceremony of the Princess Sirindhorn Neutron Monitor at the summit of Doi Inthanon (see Figure 7). Thailand is an excellent location for a neutron monitor because this is the part of the world where the Earth's magnetic field selects cosmic rays of the highest energy, which then collide with the atmosphere to produce secondary neutrons that can be detected by a neutron monitor. The goal is to monitor time variations in the galactic cosmic ray flux from the order of minutes to decades (i.e., the 11-year solar cycle). A neutron monitor is indeed sufficiently stable to make such long-term measurements. A high altitude is crucial – for every 500 m in altitude we gain ~50% in count rate. Fortunately we were granted a site at the summit of Thailand's highest mountain, Doi Inthanon (see Figure 8). With 18 counter tubes, this station has one of the world's top five neutron monitor counting rates.



Figure 7: HRH Princess Sirindhorn as she presides over the opening ceremony of the Princess Sirindhorn Neutron Monitor on January 21, 2008.



Figure 8: The Princess Sirindhorn Neutron Monitor after additional construction in April, 2010.

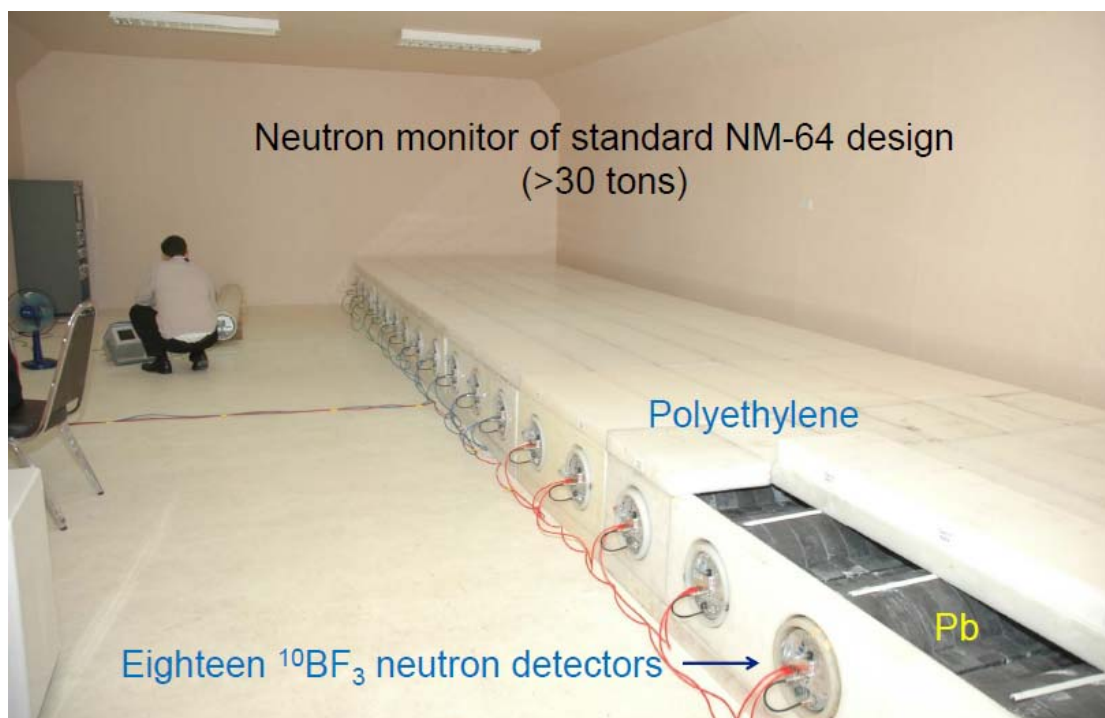


Figure 9: The inside of the Princess Sirindhorn Neutron Monitor station. One slab of polyethylene reflector has been removed in order to show the lead producer inside. At the far end of the station, one of the three bare counters is visible.

4.1.2 Hardware

A neutron monitor comprises the following components (Figures 9 & 10): Lead (~29 tons!), in which an atmospheric neutron (created by a cosmic ray) leads to fragmentation of a lead nucleus, producing more neutrons. Polyethylene, which serves two functions: to moderate energetic neutrons to thermal energies so they can be detected in the counter tubes, and to block low energy neutrons from the environment. (These are also astrophysical in origin, but are much more sensitive to the surroundings of the station, so their exclusion helps provide long-term stability.) Neutron counter tubes, proportional counters filled with BF_3 gas enriched with the (stable) isotope ^{10}B . Neutrons are detected after the reaction $n + ^{10}\text{B} \rightarrow ^7\text{Li} + ^4\text{He}$, and the Li and He nuclei ionize the gas, giving a distinctive electronic signal.

PSNM data collection with the full set of 18 counter tubes began in December, 2007. Three additional tubes are operated as bare counters (with a polyethylene moderator but no lead producer or polyethylene reflector) at Doi Inthanon, in the hope of obtaining some spectral information, particularly for Forbush decreases. Two more bare counters are being used at MU and UBU for testing, training, and undergraduate laboratory courses (see 5.2).

Because of endemic problems with rainwater entering the station, and especially the front vestibule between two sets of glass doors, in April, 2010 we ordered additional construction to add another vestibule surrounded entirely by metal (mainly funded by the Thailand Center of Excellence in Physics, ThEP). This has solved the rainwater problem. Unfortunately, we decided to paint the

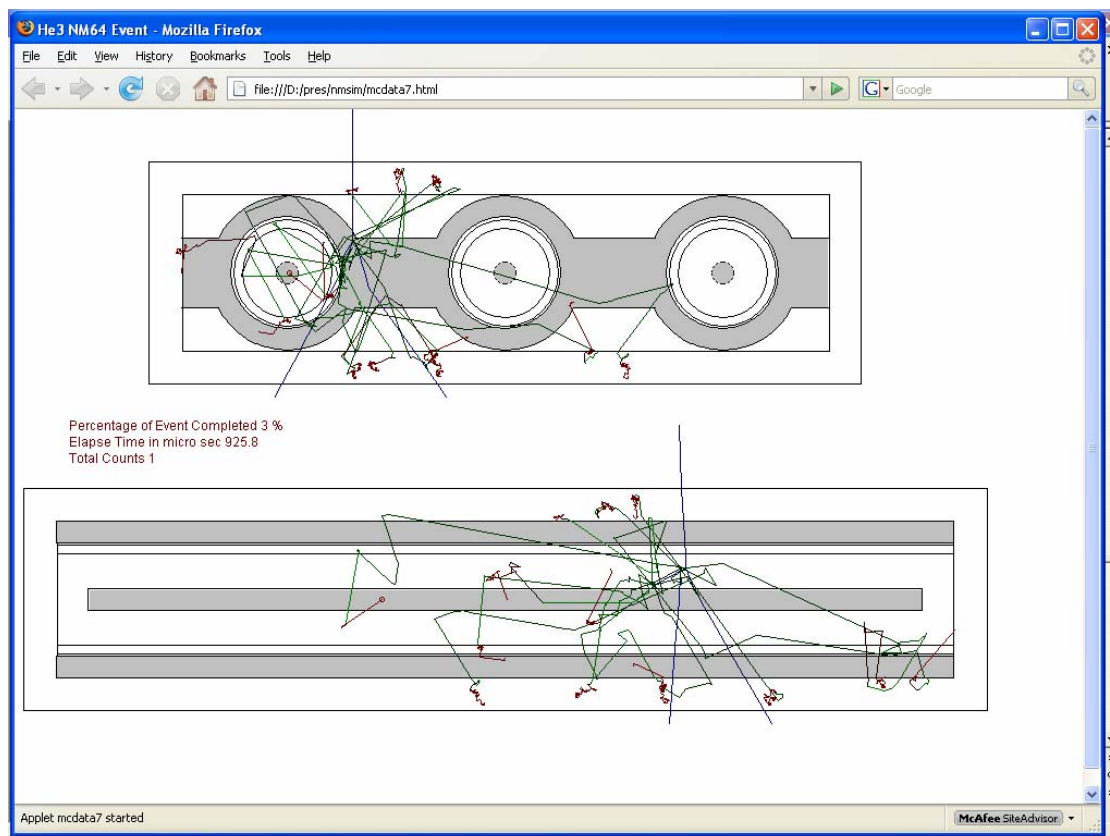


Figure 10: Schematic of the components of a neutron monitor, and simulation of the motion of neutrons produced in the lead by a single atmospheric neutron. End view (top) and side view (bottom). Components, from the outside in: Polyethylene reflector (white), lead producer (gray), polyethylene moderator (white), and neutron counter tubes (gray; however, at Doi Inthanon the counter tubes are of larger diameter than those shown here) [<http://neutronm.bartol.udel.edu>].

interior of the station at the same time, which caused occasional noise in the electronics of several tubes for the next several months. Such problems with individual tubes had to be identified and removed during subsequent data processing.

We have obtained some additional hardware to check the accuracy of our pressure correction, and to check for any further atmospheric effects on our count rate. For a static atmosphere, the pressure is simply the weight of overlying air; neutrons generated by cosmic rays are absorbed in the atmosphere, so a higher pressure implies a lower count rate. If not corrected, variations due to pressure dominate the neutron monitor count rate. Thus for neutron monitor data to be meaningful for space physics, they must be corrected for variations in atmospheric pressure. Precise pressure measurement is critical to neutron monitor operation.

Thanks to some support from Chulalongkorn U., we purchased and installed a new weather station, replacing one we had borrowed from Ubon Ratchathani U. (which they had as part of a nationwide project coordinated by Walailak U.). With improved weather data, we found a correlation between a higher wind speed and a lower pressure-corrected count rate. This was disturbing, and our collaborators at U. Delaware suspected that our pressure measurement system was insufficiently accurate and was affected by the wind speed. The wind can affect the local pressure because of

the Bernoulli effect, so that the local pressure deviates from the weight of the overlying air, causing an improper pressure correction. From the start, the PI had decided to measure the pressure in a storage room to the side of the station (where the triangular roof comes down to the ground) with the idea that this room could serve as a “Bernoulli cup” to block direct access from the wind, while it still has enough holes to allow reasonable ease of access to outside air.

Our Delaware colleagues purchased a special pressure head for us, shaped like a flying saucer, designed to provide accurate pressure measurements that are independent of (moderate) wind speed. This was installed in January, 2011. At the same time, we were able to purchase a spare high-precision Digiquartz barometer (with ThEP funding), which we put into use in parallel with our original Digiquartz barometer. With one barometer hooked up to the “flying saucer” pressure head outdoors and the other open to the storage room, we found only a tiny difference with even tinier and insignificant daily variations (presumably due to sunlight heating the roof), with no evidence of an effect of wind speed. Therefore we finally concluded that our original technique of pressure measurement is sufficiently accurate. We have shown that the original correlation between wind speed and count rate is due to a physical, daily variation of both parameters – the time of day when the wind speed is typically high is the same time when the Earth’s rotation brings our “look direction” to where the cosmic ray flux is lowest (see Section 4.10).

To facilitate our study of the time-delay spectrum (Section 4.8), we requested our collaborator Prof. Paul Evenson of U. Delaware to upgrade the microcontroller code in order to transmit pulse height data for our full data rate (34 Hz per tube) instead of the previous 16 Hz per tube. The count rate data were always complete, but having complete pulse height data as well provides us with better statistics for the time-delay spectrum. This upgrade, installed by Paul in person during a visit in January, 2011 (supported by ThEP) was basically successful, but has a glitch that individual tubes occasionally report crazy count rates, which have to be removed from the data during our processing. Paul is kindly working to fix this.

One other hardware purchase (with funding provided by the Ph.D. fellowship of Thana Yeeram) was a new dehumidifier. We installed this in January, with the old one still available as a spare. In July, 2011, a few days before this writing, the new dehumidifier failed, causing the humidity to rise above 60% and causing occasional noise on some tubes. We are working to get this fixed.

4.1.3 Operation and data processing

PSNM is generally operated remotely, thanks in part to an IPstar satellite link provided gratis by TOT. Routine maintenance is provided by RTAF soldiers, for a small monthly fee. Our team has set up automated software so that the PI and other scientists receive automated warnings of inability to access the data for over 5 minutes and daily e-mail reports on the previous day’s data. When a project scientist (typically the PI) notices a problem with the data, he takes action, most typically to ask an RTAF soldier to reset IPstar by physically switching it off/on, which usually solves the problem. Recently, our collaborator Tanin Nutaro (Ubon Ratchathani U.) had a cable extended from

our station to a nearby building where soldiers are stationed, and they can now reset the IPstar switch upon request without having to walk over to our station.

We continue to maintain our own data processing software and procedures. A key researcher is Nattapong Kamyan, an M.Sc. student at Mahidol U., who has written most of the software (with substantial help from our collaborator Alejandro Saiz at Mahidol U.) and who has developed our key data set, called PRELIM (for “preliminary”) data, which is prepared on a monthly basis. Nattapong has now graduated and our new post-doc Andrew Snodin has agreed to carry on with this work.

At the suggestion of Roger Pyle (formerly at U. Delaware), we have learned how to use the Igor software for data analysis (optimized for time series, such as our data on the cosmic ray flux vs. time). Alejandro took the lead, and conducted an internal workshop on how to use Igor. This was very successful, and now several members of our group use this very powerful software package.

There is a strong tradition in the neutron monitor community that the 40+ active detectors worldwide make their data available to other scientists. For our part, we have posted the data from Doi Inthanon at our website and informed World Data Centers of the posting location, so other researchers can make use of the data.

In coordination with Roger Pyle and Prof. John Bieber (U. Delaware), we helped to develop a real-time spectral plot (Figure 11). Real-time data from various stations around the world are ordered by cutoff rigidity (related to cosmic ray energy), with Doi Inthanon at the highest rigidity. We are able to provide such data using a real-time output capability in the software provided by Paul Evenson, and Roger Pyle’s program automatically downloads the data by FTP. We consult this plot frequently, and it helps us to visualize the Earth’s cosmic ray environment.

4.1.4 Student involvement

Numerous Thai students (and one American student) have been involved in work regarding PSNM and data processing during the past 3 years. The following participated as part of work for a thesis or a student project: Thana Yeeram (MU, Ph.D.), Waraporn Nuntiyakul (MU, Ph.D.), Usanee Tortempun (MU, Ph.D.), Nalineei Aiamsa-ad (Naresuan U. or NU, Ph.D.), Charong Buachan (MU, Ph.D.), Preeksingh Anan (MU, M.Sc.), Nattapong Kamyan (MU, M.Sc.), Teerawong Rattanakorn (MU, M.Sc.), Cherdchai Wuttiya (UBU, M.Sc.), Narumon Kalayanamitra (MU, B.Sc.), Patdanai Puvacharoonkul (MU, B.Sc.), Lalitwadee Kawinwanichakij (MU, B.Sc.). During the Thai summer break, Manunya Likamonsavad (Prince of Songkla U.) and Yanee Kieokaew (High school in Phitsanulok Province) have requested to do research training with us. In addition, Nicha Leethochawalit (U. Chicago or UC, B.Sc.), Taweewat Somboonpanyakul (UC), Nolan Essigmann (High school in Massachusetts) have come to do summer training with us during US summer vacations.

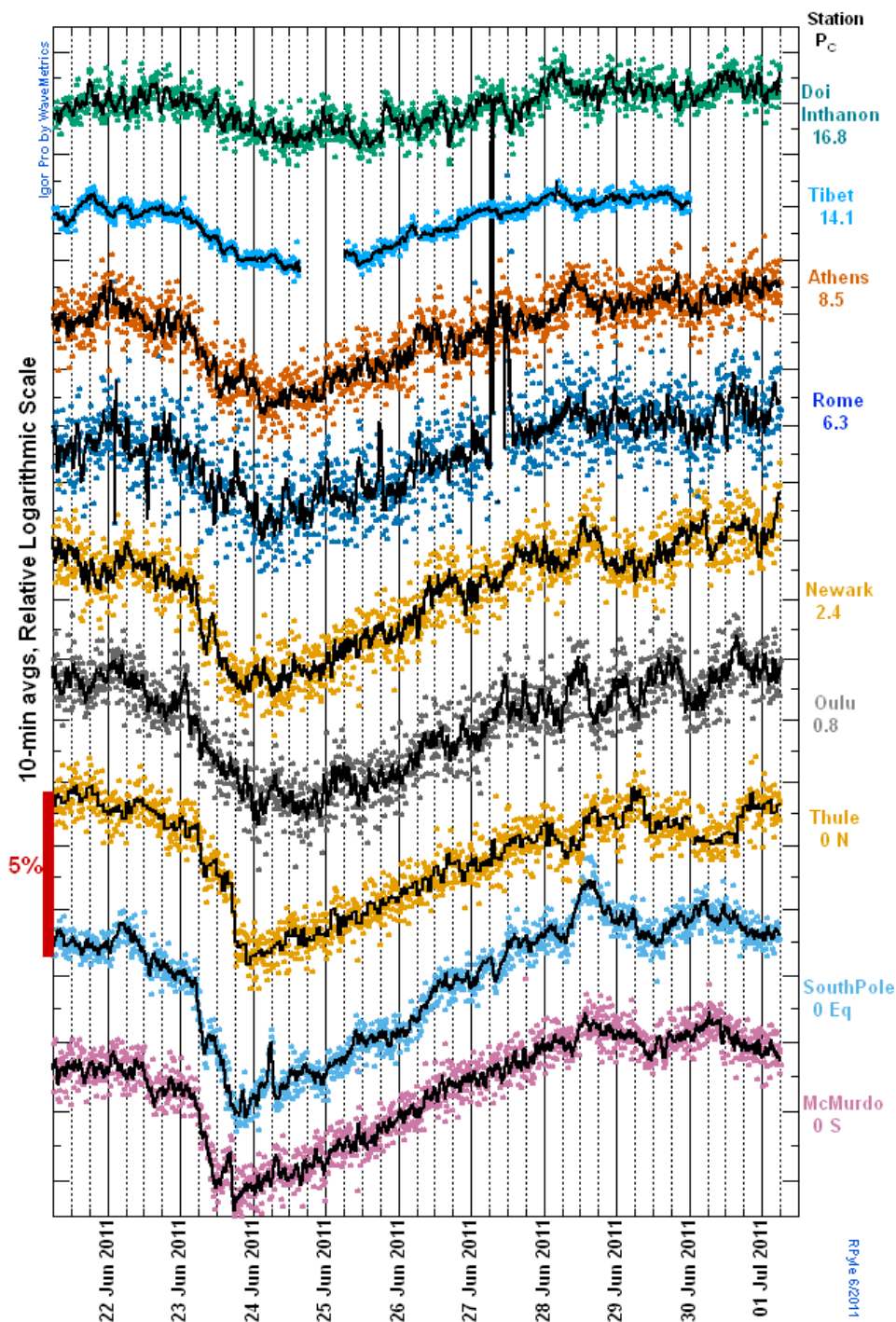


Figure 11. An example of a real-time plot from <http://neutronm.bartol.udel.edu/~pyle/Spectral.gif> that shows data from selected fixed neutron monitors around the world, including the PSNM at Doi Inthanon, which has the world's highest cutoff rigidity (cosmic ray momentum per charge, related to energy). At right is the station name and vertical geomagnetic cutoff rigidity in GV (note that detection at ground level also requires that cosmic rays exceed an atmospheric cutoff rigidity of ~ 1 GV), sometimes with a comment about the "look" direction in space (N=North, Eq=Equatorial, S=South; most other stations "see" cosmic rays from directions with a wide angular spread about the Equator). At this time there was a Forbush decrease due to a solar storm passing the Earth; such effects are stronger at lower rigidity. Diurnal (daily) variations are also evident, due to the rotation of the Earth and the look direction in space. As in all real-time data, there are occasional glitches that have not been "cleaned" from the data in real time. Note that data from Tibet have the best statistical accuracy because of the high altitude and large number of counter tubes (28), but the data are not available in real time and are downloaded once per day.

4.2 Electronics training workshops

- Instructors: Paul Evenson (U. Delaware), David Ruffolo, and Alejandro Sáiz (Mahidol U.)
- Topics: Real time data acquisition, analog electronics, digital circuits, and microcontrollers
- Frequency: Approximately every 6 months

In the long term, we aim to achieve a better understanding of our electronics (purchased from U. Delaware) and data acquisition software (donated by U. Delaware). The software was written in Visual Basic by our collaborator Prof. Paul Evenson of U. Delaware, and he supervised the development of the electronics. Paul has kindly offered to visit us once every 6 months to conduct electronics & software workshops. These are arranged as a repeating series of 4 workshops, so that a student can experience all 4 over a period of 2 years. The first of these was held in June, 2008. The first few visits indeed used Paul's funding, but more recently they have been supported by ThEP. Collaborators from Chulalongkorn U. and Ubon Ratchathani U. have also attended these workshops, and one workshop (January, 2011) was coupled with a visit to Doi Inthanon in order for Paul to install new microcontroller code there (see Section 4.1.2). Each workshop is held over two days, involving both lectures and hands-on practice.

The aim is for us in Thailand to have a level of self-sufficiency for maintaining or modifying the software and electronics used in our station. To this end, after Paul completed the first cycle of 4 workshops by himself, now in the second cycle, the PI (David) and Alejandro have delivered parts of the lectures under Paul's supervision, which strongly reinforces our understanding. Strategically, this knowledge is crucial for our group to "carry the torch" of neutron monitor science into the future, especially given that the project engineer at U. Delaware has retired and Paul is nearing retirement.

4.3 Intercalibration with other neutron monitors

- Researchers: Alejandro Sáiz (Mahidol U.), Tanin Nutaro (Ubon Rajathanee U.), Nattapong Kamyam, Waraporn Nuntiyakun
- Type of work: Experiment and data analysis
- Key Points: Intercalibrated PSNM with other neutron monitors by bringing a mobile monitor (calmon) from South Africa to Doi Inthanon. Collected data from the calmon in various configurations, including a measurement of the effect of the PSNM building.
- Status: In progress

We contacted Prof. Harm Moraal of Northwest U. (NWU; formerly Potchefstroom U.), South Africa to bring his group's mobile calibration monitor ("calmon") to Doi Inthanon. The concept is that this mobile and relatively small monitor (only 265 kg), with one ^3He counter tube surrounded by polyethylene moderator, lead producer, and polyethylene reflector, is taken to various neutron monitor sites around the world, while an identical unit is run continuously in South Africa. The international shipping costs were covered by South African funding sources, and we covered local expenses with Thai funding. We obtained the bulk of the Thai funding from ThEP, and also used



Figure 12: The calibration monitor (“calmon”) being installed at the summit of Doi Inthanon. The calmon is the white cylinder at the left. It is installed above a swimming pool so that the water provides a standard environment. The Principal Investigator is at the right, and a corner of the Princess Sirindhorn Neutron Monitor (PSNM) station is seen at the far left.

part of the existing “expenses” budget of this TRF Basic Research Grant. The shipment left South Africa in June, 2009 and arrived in July, emerging from Customs in August.

The main operating configuration of the mobile monitor should have no obstructions overhead, down to within 20° of the horizon in all directions, in a small swimming pool with at least 50 cm of water, which moderates the effect of the surface below. This standard setup avoids the configurational effects on a full neutron monitor station such as PSNM, so the count rate should depend only on altitude, latitude, and longitude. On the other hand, the mobile monitor has a low count rate, and must be run for several days to achieve sufficient statistical accuracy to calibrate a neutron monitor such as PSNM.

The goal is to calibrate various stations around the world. PSNM is particularly important to this plan because it has the world’s highest cutoff rigidity, i.e., it measures the most energetic particles. The cutoff is reasonably “sharp” in energy, so each monitor measures a sort of integral count rate for energies above its threshold. When comparing ~ 10 monitors at different cutoffs, one can put together an energy spectrum, and variations in the spectrum (e.g., with the 22-year solar magnetic cycle) could be tracked with the amazing statistical accuracy of the individual neutron monitor stations ($\sim 0.1\%$ for an hourly count rate, ~ 0.02 for a daily count rate).



Figure 13: The calmon at the summit of Doi Inthanon. From left to right: Dr. Tanin Nutaro, Dr. Alejandro S  iz, Dr. Emanuele Simili (a visitor), and the PI (Prof. David Ruffolo). The PSNM station is in the background.

In addition to those scientific goals, there were certain “developmental” goals for our group. In setting up PSNM, we received equipment that was mostly donated and we had to put it together and make it work. In order to study long-term effects, such as 22-year solar cycle effects, a neutron monitor should not be “tinkered” with, so it is difficult to use PSNM to further develop our group’s experimental skills. (Previously, our work has been mostly computational or theoretical.) This intercalibration project is a special opportunity for us to gain further hands-on experience with novel neutron detection equipment. We operated the calmon both inside and outside the PSNM station, to measure the effect of the station itself on the count rate, which can hopefully be compared with future FLUKA simulations (see 4.6). Hosting the calmon is also helping us to develop “socially” in the neutron monitor community, putting our station “on the map” of serious neutron monitor stations.

With some effort, we got the calmon working in our lab at Mahidol U. In September, 2009 during an initial field trip, we successfully installed the calmon hardware on the top of a bunker near the PSNM station, with the help of some soldiers of the Royal Thai Air Force (Figures 12 and 13). This location satisfied the requirements above. Unfortunately, the S. African electronics failed during that trip (the reason is unknown); they recovered when taken back to Mahidol U. and were successfully installed during another field trip. We were belatedly informed that the calmon is sensitive to the height of its support pillars and the water height, so in another field trip our students supervised a

change to a different calmon height. However, the S. African electronics have some problems, including a bad count rate every 10 seconds during most time periods and non-statistical fluctuations in the rate of “good” counts. Therefore, a colleague at U. Delaware, Prof. Paul Evenson kindly brought a set of his electronics (during a trip to conduct an electronics workshop; see 4.2), which we installed during a field trip in January, 2010. In this set of electronics, the normal count rate was noisy almost every afternoon when sunlight heated the electronics to as high as 60°C but there is a pulse height output that provided non-noisy data unless the temperature in the electronics rose above 51°C , and these electronics were also able to measure the time-delay spectrum (see 4.8).

We finally moved the calmon inside the station and obtained extensive counting statistics, again with the Delaware electronics. The goal of this was to obtain precise data on the influence of being inside the station on the neutron count rate, compared with a location outside the station. In total, about 14 field trips to Doi Inthanon were required for the entire calibration run. Finally, in June, 2010 we transported the calmon back to Bangkok and in July we sent it by ship back to S. Africa, within the one-year Customs deadline for equipment on loan from abroad. We later analyzed the data obtained at Doi Inthanon and the data will be included in a presentation led by the NWU group at the International Cosmic Ray Conference in Beijing in August, 2011.

4.4 Simulation of particle interactions in the Princess Sirindhorn Neutron Monitor

- Researchers: Alejandro Sáiz (Mahidol U.), Paisan Tooprakai, Nattapong Kamyam, Lalitwadee Kawinwanichakij
- Type of Work: Computation
- Key Point: Developed a local capability to perform realistic Monte Carlo simulations of particle interactions in a neutron monitor.
- Output: M.Sc. thesis (Preeksingh)
- Status: Ongoing

With guidance from Dr. John Clem at U. Delaware, we have learned how to use the existing FLUKA simulation program based on the Monte Carlo method to study the yield function of galactic cosmic ray detection at Doi Inthanon. In the M.Sc. thesis work of Preeksingh Anan, we modeled the interactions of atmospheric secondary neutrons after they enter the PSNM building. At one point we encountered an obstacle to further progress: the previous version of FLUKA expired, and we had to adapt all our input files for the new version of FLUKA. That obstacle has now been overcome, and next we will improve FLUKA simulations of the Princess Sirindhorn Neutron Monitor for higher statistical accuracy, to also model atmospheric showers of cosmic rays (M.Sc. thesis work of Nattapong Kamyam; see 2.3.5). Work in this direction is currently being carried out by Lalitwadee Kawinwanichakij, a 4th-year undergraduate student.

4.5 Simulation of Galactic cosmic ray interactions in the atmosphere

- Researchers: Nattapong Kamyam, Alejandro Sáiz (Mahidol U.), Patdanai Puvacharoonkul
- Type of Work: Computation

- Key Point: Developed a local capability to perform realistic Monte Carlo simulations of Galactic cosmic ray interactions in Earth's atmosphere.
- Status: Ongoing
- Output: M.Sc. thesis (Nattapong), Senior project (Patdanai), 47, 62

In addition to modeling the interaction of atmospheric neutrons in the PSNM station (see 4.4), we are also undertaking the more difficult task of FLUKA simulations of cosmic ray interactions in the atmosphere. This made up the bulk of the M.Sc. thesis work of Nattapong Kamyam (MU). This work is key to developing an independent simulation capability and better interpreting PSNM results. As a "spin-off," when a chemistry student, Patdanai Puvacharoonkul, asked for a senior project topic, we asked him to calculate the atmospheric ionization due to cosmic ray showers and its dependence on altitude and cutoff rigidity, which he did well.

4.6 Simulation of particle interactions in the calibration monitor

- Researchers: Naline Aiensa-ad (Naresuan U.), Nattapong Kamyam, Charong Buachan, Alejandro Sáiz (Mahidol U.), Thirane Khumlumert (Naresuan U.)
- Type of Work: Computation
- Key Point: Undertaking Monte Carlo simulations of particle interactions in the intercalibration monitor.
- Status: Ongoing

In the same vein as Section 4.4, we are working to simulate particle interactions in the intercalibration monitor. In particular, we believe that we have obtained high-quality data from the recent calibration run at Doi Inthanon, both outside and inside the PSNM station, and we should be able to observe a difference in count rate (normalized to the PSNM count rate). With FLUKA simulations, we could also model that difference, and hopefully gain quantitative understanding of the observed difference. This work has been begun by a Ph.D. student from Naresuan U., Naline Aiensa-ad, with help from some other members of our team and her advisor, Dr. Thirane Khumlumert.

4.7 Temperature dependence of the neutron monitor count rate

- Researchers: Manit Rujiwarodom, Alejandro Saiz (Mahidol U.)
- Type of work: Data analysis
- Key point: Investigating the temperature dependence of the neutron monitor count rate.
- Status: On hold
- Output: 14, 31

During the visit of Paul Evenson for an electronics workshop in December, 2008, we came to appreciate that the Spaceship Earth neutron monitors require a temperature correction. In part that is because they mostly use ^3He tubes instead of $^{10}\text{BF}_3$ tubes such as ours. The $^{10}\text{BF}_3$ tubes are less sensitive to temperature, because the gas is optically thin to neutrons, and the probability of

absorption in 1) the gas and 2) the other components of the monitor have similar temperature dependences, which mostly offset. However, the U. Delaware group claims to measure a temperature coefficient for $^{10}\text{BF}_3$ tubes as well.

In our data analysis so far, we think we can detect a small dependence on temperature, and during a couple times out of the year, the temperature inside the lead changes by a few degrees. (The change is so small because of the huge heat capacity of over 30 tons of lead!) The effect is barely above our threshold for systematic effects. We would like to correct our data for this (small) temperature effect, and also to better understand the results of the temperature dependence of Spaceship Earth. However, while we can detect the existence of a temperature effect in the Princess Sirindhorn neutron monitor, we are as yet unable to estimate it to better than an order of magnitude.

4.8 Time-delay spectrum of the Princess Sirindhorn Neutron Monitor

- Researchers: Alejandro Saiz (Mahidol U.)
- Type of Work: Data analysis
- Key Point: Investigated the time dependence of the time-delay spectrum, and found an association with atmospheric pressure. Determination of the short-term pressure coefficients for the PSNM multiplicity ratios.
- Status: Ongoing
- Output: Senior project (Narumon), 48, 55

This work is one aspect of learning what we can (or cannot) do with data from the PSNM. The multiplicity is the number of neutrons detected by the same counter tube in a certain time window. The PI had hopes to make a new type of measurement of cosmic rays (after 60 years of neutron monitors) by examining time variations in multiplicity, which we can measure given our modern electronics, and which may be particularly scientifically interesting as a higher multiplicity should be associated with a higher primary cosmic ray energy, and our monitor has the world's highest cutoff rigidity so the multiplicity could extend our energy "reach" further than any previous neutron monitor study. It is not yet clear whether these hopes will be realized.

In the meantime, we thought we saw 27-day variations (see 4.9) in multiplicity ratios, which turned out to be associated with atmospheric pressure. We therefore assigned a senior project student, Narumon Kalayanimit, to examine the more fundamental time-delay spectrum, from which the multiplicity is derived. We have data in the form of time-delay histograms from every day, and more recently every hour, with very good statistics. According to Bieber et al. (2004), the time delay spectrum has two clearly separated components: at large time delays, the spectrum is dominated by chance coincidence between unrelated neutrons, but at low time delays, it reveals the time delay spectrum of neutrons from a single interaction in the lead. We therefore examined the time-delay spectrum by using measurements at high time delay to subtract out the random-coincidence background component, leaving the lead-interaction time spectrum. A characteristic of this time-

delay spectrum, the leader fraction L , has been found to vary with atmospheric pressure. There is a hint of a long-term variation, which will require further investigation.

4.9 Simulation of the time-delay spectrum

- Researchers: Lalitwadee Kawinwanichakij, Alejandro Sáiz (Mahidol U.)
- Key Point: Using FLUKA simulations to better understand the travel time and time delay distributions of neutrons in the PSNM.
- Status: Started

Study of the time-delay spectrum is a relatively new field, and we may be the first group to perform Monte Carlo simulations in order to better understand these spectra. This is the senior project work of Lalitwadee Kawinwanichakij (MU), who has developed simulations with very large numbers of particles, controlling the output to provide only what we need. She is investigating a claim by a Russian group (Balabin et al. 2008) that the coincidence-subtracted spectrum comprises two exponential functions, corresponding to knock-on and evaporation neutrons from interactions in the lead.

4.10 Synodic variations of Galactic cosmic rays

- Researchers: Thana Yeeram, Alejandro Sáiz (Mahidol U.)
- Type of work: Data analysis
- Key Points: Studying the synodic variations of galactic cosmic rays in association with corotating solar wind structures.
- Status: Ongoing
- Output: 25, 49, 60

After correcting PSNM data for pressure effects, one can observe variations in the galactic cosmic ray (GCR) flux. In addition to diurnal (daily) variations related to Earth's rotation and the small anisotropy of GCR in space (slightly more come into the solar system than go out), one can easily see variations in association with corotating solar wind structures (Figure 11). The solar wind has low- and high-speed streams, which are observed repeatedly as the Sun rotates with a 27-day period. Thus these can be called "synodic" or "27-day" variations.

When a high-speed solar wind stream overtakes a low-speed stream, they come into contact with a compression that is observed as a sudden increase in the solar wind speed. That compression sometimes steepens into a shock. Such compressions/shocks are called corotating interaction regions (CIRs) because they corotate with the Sun. Roughly speaking, faster solar wind is better at "pushing" on GCRs to prevent them from entering the inner solar system, so the PSNM count rate goes down. However, there is not a direct quantitative relationship between the solar wind speed and neutron monitor count rate.

At present, we have noticed that the diurnal variation changes from before to after a CIR. The flux of incoming cosmic rays (moving toward the Sun) seems to decrease more slowly than the flux

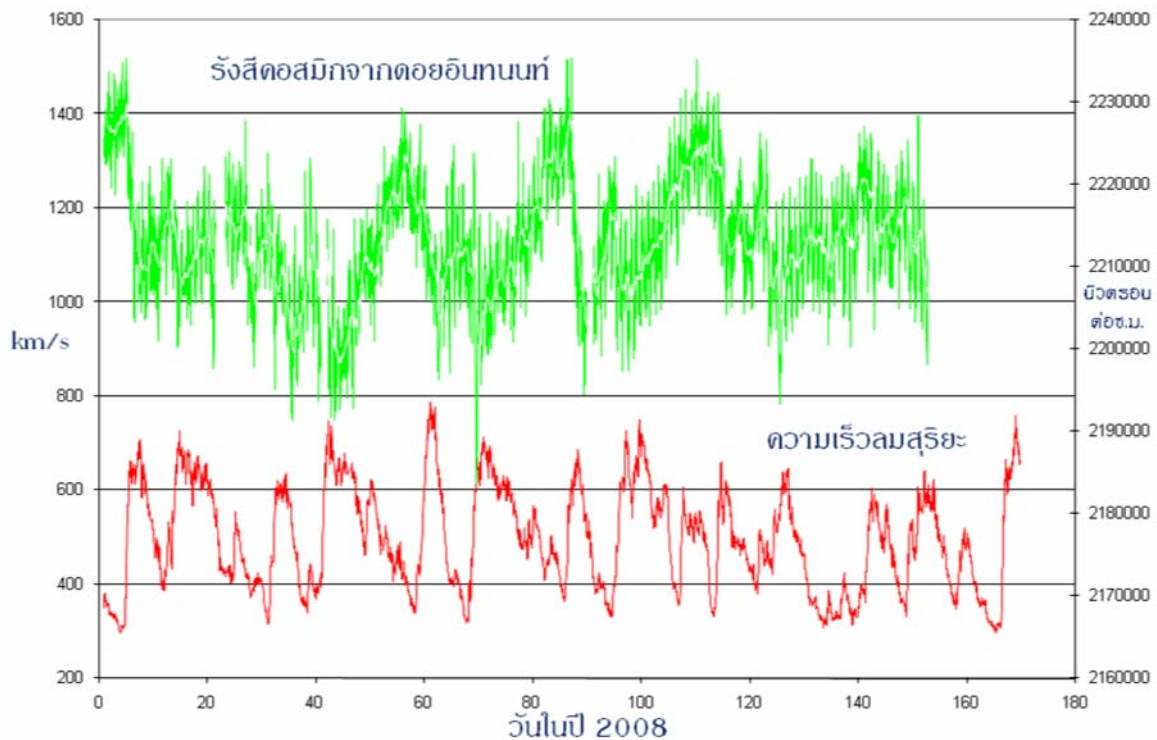


Figure 14: The pressure-corrected neutron monitor hourly count rate in comparison with the solar wind speed near Earth (measured by the WIND spacecraft) during January-May, 2008. The count rate decreases during high-speed solar wind streams, which repeat every 27 days as the Sun rotates.

of outgoing cosmic rays. This could be because the CIR reflects and accelerates some particles. There are more particles at lower energy, so acceleration from the lower-energy population implies an increase in flux at the energy of interest. Thus the compression/shock is a source of enhanced particle flux, which tends to move outward. However, more data analysis is needed to confirm that this is a general trend.

4.11 Analysis of neutron monitor data from a latitude survey

- Researchers: Waraporn Nuntiyakul
- Type of work: Data analysis
- Key Points: Studying changes in the cosmic ray spectrum over the course of a solar cycle.
- Status: Started

This work is designed as the Ph.D. work of Waraporn Nuntiyakul. This student was awarded a Royal Golden Jubilee Fellowship from TRF, and her US co-advisor is Prof. Paul Evenson of U. Delaware. Paul therefore suggested this project, for Waraporn to help analyze data from a 3-tube neutron monitor that operated on an icebreaker ship for about 10 years, during its annual runs from Seattle, USA to Antarctica and back. This is called a latitude survey because the neutron monitor is carried over a wide range of latitudes, including high latitudes (with low vertical cutoff rigidity, i.e., particles can arrive more easily) and low (equatorial) latitudes (with high vertical cutoff rigidity, i.e.,

particles arrive with more difficulty). If the neutron monitor response is understood, the derivative of the count rate with cutoff rigidity provides a rather direct measure of the cosmic ray rigidity spectrum. This will be a good research project for Waraporn and will extend the knowledge and experience of our research group as a whole, which has never worked on a latitude survey or on measuring of the Galactic cosmic ray spectrum.

4.12 Drift orbits of energetic particles in a magnetic cloud

- Researcher: Watcharawuth Krittinatham
- Type of work: Computation
- Key Points: New global, analytic model of an interplanetary flux rope. Studied drift orbits of energetic particles in an interplanetary flux rope.
- Status: Finished; paper published
- Output: Ph.D. thesis (Watcharawuth), 2, 27, 33, 40

This project, led by a Ph.D. student, Watcharawuth Krittinatham, aimed to set a realistic, global, analytic model of an interplanetary magnetic flux rope and examine the drift orbits of energetic particles. This work has strong synergy with our work toward Objectives 1 and 2. It was motivated by work under a previous grant to analyze SEP data on October 22, 1989. For that event we found an extended 3-hour decay time, apparently the timescale for relativistic protons to escape from an interplanetary magnetic flux rope. (We are unaware of any previous measurements of this timescale.) It is not clear whether time is associated with outflow due to drifts or perpendicular diffusion. However, it does seem that drifts could explain the bidirectional outflow anisotropy in the SEP data on October 22, 1989.

Conversely, during a second-stage Forbush decrease of galactic cosmic rays, particles take some time to get *into* a flux rope. Again, bidirectional inflow anisotropies are commonly observed. We wish to examine whether the inflow/outflow of energetic ions (of ~ 1 GV) to/from magnetic flux ropes can be attributed to drifts, and whether these drifts have a particular pattern that might be observable in the unidirectional or bidirectional anisotropy.

Amazingly, there was no pre-existing analytic model of interplanetary flux ropes that had the key features we want, namely $B \sim 1/r^2$ near the Sun, a wider flux rope farther from the Sun, a stronger winding farther from the Sun (due to the stretching of field lines in the legs of the loop, connecting back to the Sun), and the basic requirement of $\text{div } B = 0$. We have developed such a model. We have determined the guiding center drift velocity throughout the flux rope, and it is predominantly along flux surfaces, with a small component outward or inward.

Conclusions of the work include the following: For a flux rope with no winding of the magnetic field lines, energetic particles (e.g., SEPs) can rapidly escape from the entire flux rope. With winding of at least 1.5 complete circuits over the flux rope, there is an inner portion of the flux rope where drift orbits are trapped, and an outer portion where they rapidly escape. SEPs can escape from the inner portion of a flux rope with $|w| > 1.5$ by means of perpendicular diffusion or embedded open field structures, and drifts can rapidly remove them from the outer portion of the flux rope.

Conversely, when there is a higher density of SEPs or GCRs outside the loop, they can readily enter the outer portion of the flux rope by means of drifts and the inner portion by means of diffusion or embedded open field structures. We have found a resonance effect for values of the winding number w close to integral multiples of a certain value, where there is a complex boundary between the inner portion of the flux rope with trapped drift orbits and the outer portion with escaping drift orbits, and some orbits from deep inside can rapidly escape.

Furthermore, the drifts across the boundary of the flux rope are predominantly inward along one leg of the loop and predominantly outward along the other. For a second-stage Forbush decrease in GCRs, we expect the guiding center drifts to contribute to a net unidirectional flow (anisotropy) of GCRs in a direction determined by the sign of the poloidal field B_θ . This also applies to situations with a higher density of SEPs outside the loop. An article on this work has been published in the *Astrophysical Journal*, the world's top journal for full articles in astrophysics. In the first 2 years since publication, this work has already been cited 5 times by other authors.

4.13 Diffusion and scattering of energetic particles in a magnetic cloud

- Researcher: Watcharawuth Krittinatham (NARIT)
- Type of work: Computation
- Key Point: Orbits of energetic particles in an interplanetary flux rope due to drifts, perpendicular diffusion, and parallel scattering.
- Status: Ongoing
- Output: 19, 23, 44, 51, 58

During December, 2007 to May, 2008, Watcharawuth had funding from his DPST fellowship to visit U. Delaware and work with Prof. John Bieber. During that time, he worked toward adding the processes of diffusion and scattering to his drift model (Krittinatham et al. 2009). These are calculated using knowledge from turbulence work in our group. While this work was on hold for a while as Watcharawuth completed his work on drifts, he has now returned to this work, especially after graduating with a Ph.D. from Mahidol U. and going to work at NARIT in Chiang Mai. Recently we have been aiming to use more realistic model assumptions for spatial dependence of turbulence parameters, based on the concept of a once-uniform flux rope near the Sun that was stretched and expanded non-uniformly to obtain an interplanetary flux rope.

4.14 Extragalactic electron-positron haloes

- Researchers: Anant Eungwanichayapant (Mae Fah Luang U.), Wiraporn Maithong (Mae Fah Luang U.)
- Type of work: Computation
- Key Point: Predicted X-ray spectra and distributions due to extragalactic electron-positron haloes.
- Status: Ongoing

- Output: 39, 63

Dr. Anant Eungwanichayapant at Mae Fah Luang U. received his M.Sc. under the supervision of the PI, and then pursued a Ph.D. in Heidelberg, Germany on the study of active galactic nuclei (AGNs). The present work examines how an electron-positron halo around an AGN (which is expected but has not been observed) could emit X-rays due to synchrotron emission. As Mentor for Dr. Anant's TRF Young Researcher Grant, the PI has been consulted and has participated in this work. One suggestion is to predict X-ray spectra due to the central and outer regions of the halo. Further work will also take projection effects into account to calculate the areal brightness profile of this optically thin system.

Chapter 5

Outreach

Objective: To provide Thai-language information on space physics and astrophysics to the public, and to expose students to space physics research and research techniques.

Note: The Principal Investigator was also involved in both of these subprojects. In addition to the two specific topics below, the PI has also given invited lectures and television, newspaper, and radio interviews (see 7.7).

This is the “outreach” portion of our research project. In addition to the two specific topics below, we have also given invited lectures and radio and TV interviews (see 3.3).

5.1 Thaispaceweather.com

- Researchers: Luerluck Pimsuwan, Autcharapun Treegate, Achara Seripienlert, Watcharawuth Krittinatham, Paisan Tooprakai, and others
- Type of Work: Dissemination
- Key point: Successful dissemination of information on space weather and space physics.
- Status: Ongoing
- Output: website (www.thaispaceweather.com)

We maintain a public-interest website, www.thaispaceweather.com, the first Thai-language website devoted to space weather. This has become one of the top websites in the nation dedicated to astronomy, with regular news items in Thai (though the frequency has decreased since the graduation of Watcharawuth Krittinatham). During January, 2010, our website received over 26,000 unique visitors in one month. Further statistics are provided in Attachment 72. This website has even been included in a set of links to Thai news sites, and it is the number one link found by Google for “Earth’s magnetic field” (in Thai).

There are links to our website from various major Thai web servers, such as www.pantip.com and www.sanook.com. During the teaching term, we have a steady readership of over 900 visits per weekday. 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 continued working with us throughout his four years as an undergraduate student at Mahidol U., and for a time as a “post-bacheloral researcher” as he prepared for graduate study abroad. We are quite proud that our website helped inspire a student to pursue research in this field.

5.2 Teaching laboratory experiment on cosmic rays and neutrons

- Researchers: Alejandro Saiz (Mahidol U.), Thana Yeeram
- Type of Work: Experiment, teaching
- Key point: Teaching laboratory experiment for undergraduate students on cosmic rays and neutron detection.
- Status: Ongoing

For the Princess Sirindhorn Neutron Monitor (see 4.1), we have received donations of a total of 23 neutron counter tubes. We have decided to deploy 18 tubes inside lead and polyethylene to make up a full “supermonitor” at Doi Inthanon. Three more tubes are “bare” counters (i.e., without lead and polyethylene) in the station building at Doi Inthanon. The bare / neutron monitor count ratio could provide some spectral information, as the monitor has enhanced sensitivity to more energetic atmospheric secondary neutrons. The 2 remaining tubes have been placed at Mahidol U. and Ubol Ratchathani U. for purposes of teaching and training, including the electronics workshops (see 4.2).

As the Department of Physics at Mahidol U. has a required laboratory course for 3rd-year students, who rotate to perform labs with different research groups, we have set up a teaching laboratory experiment called “Cosmic Rays and Neutrons” for this course. We start with a PowerPoint presentation about our research and neutron monitors. The students then take data from a neutron counter tube (we call it a MicroMonitor) and a pressure sensor (purchased for this purpose by Dr. Alejandro Sáiz using his TRF Young Researcher Grant). They also view counter pulses on an oscilloscope, examine pulse height analysis data from PSNM, and perform a pressure correction to analyze the MicroMonitor data. We intend to continue this in the future in order to expose all undergraduate students in the department to space physics research and research techniques.

Chapter 6

Discussion

From the preceding chapters, it can be seen that our group undertakes a large number of subprojects in parallel (32 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, with the exception of outreach, the workshops, and detector maintenance, 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 (29, not counting another 16 researchers at other Thai universities or summer research students) is almost as large as the number of subprojects because most of them worked in teams, with new researchers learning from more experienced researchers. At the same time, several students 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 help 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.
- Graduate students typically present their work orally in at least one scientific meeting, almost always in English. Before each seminar, research, or thesis presentation, group members listen to the speaker and give 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. 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 (at that time) 9 years (presumably because of our academic freedom and strong funding for basic research) than he would if he spent that time working 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

Researchers working in Thailand are indicated in bold type, and 2009 impact factors are given in parentheses.

7.1 International journal articles

Published

1. **R. Kittinaradorn, D. Ruffolo**, and W. H. Matthaeus 2009, Solar Moss Patterns: Heating of Coronal Loops by Turbulence and Magnetic Connection to the Footpoints, *Astrophys. J.*, **702**, L138 (7.364)
2. **W. Krittinatham and D. Ruffolo** 2009, Drift Orbits of Energetic Particles in an Interplanetary Flux Rope, *Astrophys. J.*, **704**, 831 (7.364)
3. **A. Seripienlert, D. Ruffolo**, W. H. Matthaeus, and **P. Chuychai** 2011, Dropouts in Solar Energetic Particles: Associated with Local Trapping Boundaries or Current Sheets?, *Astrophys. J.*, **711**, 980 (7.364)

Submitted

4. **M. C. Ghilea, D. Ruffolo, P. Chuychai, W. Sonsrettee, A. Seripienlert**, and W. H. Matthaeus 2011, Magnetic Field Line Random Walk for Disturbed Flux Surfaces: Trapping Effects and Multiple Routes to Bohm Diffusion (submitted to *Astrophys. J.*, IF=7.364)

In preparation

5. J. W. Bieber, J. Clem, P. Evenson, R. Pyle, **A. Sáiz, and D. Ruffolo**, Giant Ground Level Enhancement of Relativistic Solar Protons on 2005 January 20. I. *Spaceship Earth* Observations (in preparation for *Astrophys. J.*, IF=7.364)
6. **D. Ruffolo, T. Pianpanit, P. Chuychai**, W. H. Matthaeus, and G. Qin, Directions for Improvement of the Nonlinear Guiding Center Theory of the Perpendicular Diffusion of Energetic Charged Particles (in preparation for *Astrophys. J.*, IF=7.364)

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

7. **D. Ruffolo, A. Sáiz**, J. W. Bieber, P. Evenson, R. Pyle, P. Chuychai, and W. H. Matthaeus, Modeling the Transport of Solar Energetic Particles to 1 AU (Invited talk, SHINE 2008 workshop, Midway, Utah, June, 2008)
8. **D. Ruffolo**, P. Chuychai, **P. Wongpan**, J. Minnie, J. W. Bieber, and W. H. Matthaeus, Perpendicular transport of energetic charged particles in nonaxisymmetric two-component magnetic turbulence (SHINE 2008 workshop, Midway, Utah, June, 2008)

9. **D. Ruffolo**, J. W. Bieber, J. Clem, P. Evenson, R. Pyle, **A. Sáiz**, and **M. Wechakama**, Relativistic Solar Protons on 2005 January 20 and 2006 December 13 (SHINE 2008 workshop, Midway, Utah, June, 2008)
10. J. W. Bieber, J. Clem, P. Evenson, R. Pyle, **D. Ruffolo**, **A. Sáiz**, and **M. Wechakama**, Solar Particle Transport in Extreme Events: Lessons from Cycle 23 (37th COSPAR Scientific Assembly, July, 2008, Montréal, Canada)
11. J. W. Bieber, P. Chuychai, W. H. Matthaeus, J. Minnie, and **D. Ruffolo**, Diffusion Confusion: Field Line Random Walk in Magnetic Turbulence *Eos Trans. Amer. Geophys. Union*, **89**(53), Fall Meet. Suppl., Abstract SH42A-05 (San Francisco, December, 2008)
12. **A. Sáiz**, **D. J. Ruffolo**, J. W. Bieber, and P. A. Evenson, Effects of a Radial Dependence in Transport Parameters on the Estimation of Solar Particle Fluence at Jupiter's Orbit (2009 Fall Meeting of the American Geophysical Union, San Francisco, December, 2009)
13. **A. Sáiz**, **D. Ruffolo**, J. W. Bieber, and P. Evenson, On the Estimation of Solar Particle Fluence at Jupiter's Orbit (2nd Southeast Asian Astronomy Network Meeting, Manila, the Philippines, February, 2010)
14. **M. Rujiwarodom**, **A. Sáiz**, **D. Ruffolo**, **N. Kamyan**, **T. Nutaro**, H. Krüger, and H. Moraal, Temperature Effects on ¹⁰BF₃ and ³He Neutron Monitor Counter Tubes at 16.8 GV Cutoff Rigidity (European Geophysical Union General Assembly 2010, Vienna, Austria, May, 2010)
15. **D. Ruffolo**, **A. Sáiz**, J. W. Bieber, J. Clem, P. Evenson, and R. Pyle, Transport Modeling and Injection time Profile of Relativistic Solar Protons on 2005 January 20 (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)
16. **A. Sáiz**, **D. Ruffolo**, J. W. Bieber, and P. Evenson, Modeling Relativistic Solar Protons in the Inner Solar System During the 2005 January 20 Event (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)
17. **P. Chuychai**, **D. Ruffolo**, and W. H. Matthaeus, Separation of charged particles from magnetic field lines in two-component magnetic turbulence (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)
18. **P. Tooprakai**, **A. Seripienlert**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Collimation of Particle Beams by the Structure of Two-Dimensional Magnetic Turbulence (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)
19. **W. Krittinatham**, **D. Ruffolo**, and J. Bieber, Spatially dependent turbulence and particle diffusion in an interplanetary magnetic flux rope (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)
20. **R. Kittinaradorn**, **D. Ruffolo**, and W. H. Matthaeus, Solar Moss Patterns: MHD Turbulence, Reconnection Heating in Coronal Loops, and Magnetic Connection to the Footpoints (2010 Fall Meeting of the American Geophysical Union, San Francisco, December, 2010)

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

21. **D. Ruffolo**, P. Chuychai, **P. Wongpan**, J. Minnie, J. W. Bieber, and W. H. Matthaeus, Perpendicular Transport of Energetic Charged Particles in Nonaxisymmetric Two-Component Magnetic Turbulence (34th Congress on Science and Technology of Thailand, Bangkok, October, 2008)
22. **P. Wongpan**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Field Line Random Walk Simulation in Arbitrarily Stretched Isotropic Turbulence (34th Congress on Science and Technology of Thailand, Bangkok, October, 2008)
23. **W. Krittinatham**, J. W. Bieber, and **D. Ruffolo**, Calculating the Perpendicular Diffusion Coefficient of Particles in a Magnetic Cloud with Nonlinear Guiding Center Theory (34th Congress on Science and Technology of Thailand, Bangkok, October, 2008)
24. **A. Seripienlert**, **D. Ruffolo**, W. H. Matthaeus, and **P. Chuychai**, Trapping Boundaries as Distinguished from Current Sheets in Magnetic Turbulence (34th Congress on Science and Technology of Thailand, Bangkok, October, 2008)
25. **D. Ruffolo**, **A. Sáiz**, **N. Kamyan**, **T. Naturo**, **S. Sumran**, **C. Chaiwattana**, **N. Gasiprong**, **C. Channok**, **M. Rujiwarodom**, **P. Tooprakai**, **B. Asavapibhop**, J. W. Bieber, J. M. Clem, P. Evenson, and K. Munakata, Effect of Corotating Interaction Regions on the Diurnal Anisotropy of Galactic Cosmic Rays (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
26. **A. Sáiz**, **D. Ruffolo**, J. W. Bieber, and P. Evenson, Effects of a Radial Dependence in Transport Parameters on the Estimation of Solar Particle Fluence at Jupiter's Orbit (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
27. **W. Krittinatham** and **D. Ruffolo**, Drift Motions of Energetic Protons in an Interplanetary Magnetic Cloud (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
28. **A. Seripienlert**, **D. Ruffolo**, W. H. Matthaeus, and **P. Chuychai**, Local Trapping Boundaries, Current Sheets, and Their Roles for Dropout Features (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
29. **P. Wongpan**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Field Line Random Walk Simulation in Arbitrarily Stretched Isotropic Turbulence (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
30. **C. Pongkitivanichkul**, **D. Ruffolo**, and W. H. Matthaeus, Perpendicular Subdiffusion and Diffusion of Energetic Charged Particles Due to Parallel Brownian Motion (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
31. **M. Rujiwarodom**, **D. Ruffolo**, **A. Sáiz**, and **N. Kamyan**, Temperature Effects on Count Rate of the Princess Sirindhorn Neutron Monitor at Doi Inthanon (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)

32. **P. Chuychai**, W. H. Matthaeus, P. Dmitruk, and **D. Ruffolo**, Diffusion of Charged Particles in Three-Dimensional Isotropic Magnetic Turbulence (Siam Physics Congress and Thai National Astronomy Meeting 2009, Cha-am, March, 2009)
33. **W. Krittinatham** and **D. Ruffolo**, Drift Motions of Energetic Protons in an Interplanetary Magnetic Cloud (13th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2009)
34. **A. Seripienlert**, **D. Ruffolo**, W. H. Matthaeus, and **P. Chuychai**, Local Trapping Boundaries, Current Sheets, and Their Roles for Dropout Features (13th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2009)
35. **P. Wongpan**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Field Line Random Walk Simulation in Arbitrarily Stretched Isotropic Turbulence (13th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2009)
36. **P. Chuychai**, W. H. Matthaeus, P. Dmitruk, and **D. Ruffolo**, Diffusion of Charged Particles in Isotropic Magnetic Turbulence (13th Annual National Symposium on Computational Science and Engineering, Bangkok, March, 2009)
37. **D. Ruffolo**, High Energy Physics and Its Relation to Astrophysics (Invited talk, 4th Siam Symposium on General Relativity, High Energy Physics, and Cosmology, Phitsanulok, July, 2009)
38. **A. Seripienlert**, **P. Tooprakai**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Collimation of Particle Beams by Two-Dimensional Turbulent Structure (4th Siam Symposium on General Relativity, High Energy Physics, and Cosmology, Phitsanulok, July, 2009)
39. **W. Maithong**, **A. Eungwanichayapant**, and **D. Ruffolo**, X-Ray Flux Distribution from a Pair Halo (35th Congress on Science and Technology of Thailand, Bangsaen, October, 2009)
40. **W. Krittinatham** and **D. Ruffolo**, Drift Orbits of Energetic Particles in an Interplanetary Magnetic Flux Rope (35th Congress on Science and Technology of Thailand, Bangsaen, October, 2009)
41. **A. Seripienlert**, **P. Tooprakai**, **D. Ruffolo**, **P. Chuychai**, and W. H. Matthaeus, Collimation of Particle Beams by Two-Dimensional Turbulent Structure (35th Congress on Science and Technology of Thailand, Bangsaen, October, 2009)
42. **C. Buachan**, **D. Ruffolo**, **A. Sáiz**, **A. Seripienlert**, and W. H. Matthaeus, The Effect of Magnetic Turbulence Structure on the Parallel Transport of High Energy Particles (35th Congress on Science and Technology of Thailand, Bangsaen, October, 2009)
43. **A. Sáiz**, **D. Ruffolo**, J. W. Bieber, and P. Evenson, On the Estimation of Solar Particle Fluence at Jupiter's Orbit (14th Annual Symposium on Computational Science and Engineering, Chiang Rai, March, 2010)
44. **W. Krittinatham**, **D. Ruffolo**, and J. W. Bieber, Diffusion of Galactic Cosmic Rays in an Interplanetary Magnetic Flux Rope (14th Annual Symposium on Computational Science and Engineering, Chiang Rai, March, 2010)

45. **A. Seripienlert, P. Tooprakai, D. Ruffolo, P. Chuychai,** and W. H. Matthaeus, Collimation of Particle Beams by Two-Dimensional Turbulent Structure (14th Annual Symposium on Computational Science and Engineering, Chiang Rai, March, 2010)
46. **C. Buachan, D. Ruffolo, A. Sáiz, A. Seripienlert,** and W. H. Matthaeus, Effect of Magnetic Turbulence Structure on the Parallel Transport of High Energy Particles (14th Annual Symposium on Computational Science and Engineering, Chiang Rai, March, 2010)
47. **N. Kamyan, D. Ruffolo, A. Sáiz, and P. Tooprakai,** Secondary Neutrons from Cosmic Rays in Earth's Atmosphere above the Princess Sirindhorn Neutron Monitor (14th Annual Symposium on Computational Science and Engineering, Chiang Rai, March, 2010)
48. **D. Ruffolo, A. Sáiz, N. Kamyan, T. Naturo, S. Sumran, C. Chaiwattana, N. Gasiprong, C. Channok, M. Rujiwarodom, P. Tooprakai, B. Asavapibhop,** J. W. Bieber, J. M. Clem, P. Evenson, and K. Munakata, Diurnal Variation of Multiplicity in the *Princess Sirindhorn Neutron Monitor* (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
49. **A. Sáiz, D. Ruffolo, N. Kamyan, T. Yeeram, and T. Naturo,** Effects of corotating interaction regions on the diurnal anisotropy of galactic cosmic rays (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
50. **M. C. Ghilea, D. Ruffolo, P. Chuychai, A. Seripienlert,** and W. H. Matthaeus, Magnetic field line random walk for perturbed flux surfaces: trapping effects and two routes for Bohm diffusion (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
51. **W. Krittinatham, D. Ruffolo,** and J. Bieber, Model of spatially dependent turbulence in an interplanetary magnetic flux rope (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
52. **P. Chuychai, D. Ruffolo,** and W. H. Matthaeus, Separation of charged particles from magnetic field lines in 2D+slab turbulence (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
53. **C. Pongkitivanichkul, D. Ruffolo,** and W. H. Matthaeus, Perpendicular subdiffusion and diffusion of energetic charged particles due to parallel Brownian motion (36th Congress on Science and Technology of Thailand, Bangkok, October, 2010)
54. **D. Ruffolo, T. Pianpanit (presenter), P. Chuychai,** W. H. Matthaeus, and G. Qin, On the Assumptions of Nonlinear Guiding Center Theory (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
55. **A. Sáiz, D. Ruffolo, N. Kamyan, T. Nutaro, S. Sumran, C. Chaiwattana, N. Gasiprong, C. Channok, M. Rujiwarodom, P. Tooprakai, B. Asavapibhop,** J. W. Bieber, J. M. Clem, P. Evenson, and K. Munakata, Neutron Time Delay Analysis at the Princess Sirindhorn Neutron Monitor (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)

56. **P. Chuychai, D. Ruffolo, C. Wikee,** and W. H. Matthaeus, Effect of Reduced Dimensionality of the Magnetic Field Fluctuations on the Cross-Field Motion of Charged Particles (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
57. **P. Tooprakai, A. Seripienlert, D. Ruffolo, P. Chuychai,** and W. H. Matthaeus, Collimation of Particle Beams by the Structure of Two-Dimensional Magnetic Turbulence (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
58. **W. Krittinatham, D. Ruffolo,** and J. Bieber, Recovery of Galactic Cosmic Ray Intensity after a Forbush Decrease in an interplanetary magnetic flux rope (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
59. **M. C. Ghilea, D. Ruffolo, P. Chuychai, W. Sonsrettee, A. Seripienlert,** and W. H. Matthaeus, Magnetic field line random walk for disturbed flux surfaces: Trapping effects and two routes for Bohm diffusion (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
60. **T. Yeeram, D. Ruffolo, A. Sáiz, N. Kamyan, and T. Naturo,** Effects of Corotating Solar Wind Structures on 27-Day Variations in Galactic Cosmic Rays Observed by the Princess Sirindhorn Neutron Monitor (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
61. **N. Wichailukkana, D. Ruffolo, C. Pongkitivanichkul, and N. Chaiworawitsakul,** Verifying a Theory of Particle Transport in Quasi-1D Turbulence (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
62. **P. Puvacharoonkul, A. Sáiz, N. Kamyan, and D. Ruffolo,** Calculating Ionization Due to Cosmic Rays in Earth's Atmosphere (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)
63. **W. Maithong, A. Eungwanichayapant, and D. Ruffolo,** X-Ray Flux Distribution from a Pair Halo (Siam Physics Congress and Thai National Astronomy Meeting 2011, Pattaya, March, 2011)

7.4 Completed Ph.D. theses (Dept. of Physics, Mahidol U.)

Watcharawuth Krittinatham, Achara Seripienlert

7.5 Completed M.Sc. theses (Dept. of Physics, Mahidol U.)

Preeksingh Anan, Nattapong Kamyan, Charong Buachan

7.6 Completed B.Sc. projects (Dept. of Physics, Mahidol U., unless noted)

Naruepon Weerawongphrom, Chakrit Pongkitivanichkul, Nattawit Chaiworawit, Narumon Kalayanimit, Pattana Chintarungruangchai (Dept. of Physics, Chulalongkorn U.), Theerasarn Pianpanit, Narongpol Wichailukkana, Chewin Pinmuck, Patdanai Puvacharoonkul (Dept. of Chemistry, Mahidol U.)

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

1. Updated www.thaispaceweather.com, which ranks highly among Thai websites for physics and astronomy (see statistics in Attachment 72). This website has even been included in a set of links to Thai news sites (Attachment 64).
2. Reviewer, April-May, 2008, for *J. Geophys. Res. A* (Space Physics), the world's premier journal for space physics (IF=2.602)
3. Radio interview (live, in Thai) on Global Warming, FM 97, May 27, 2008
4. Guest lecturer, Mahidol Wittayanusorn School, June 2, 2008
5. Reviewer, June-July, 2008, for the *Astrophysical Journal*, the world's premier journal for astrophysics (IF=6.119)
6. Advisor, Space Exploration Exhibit, Science Exhibition, BITEC, August 8-22, 2008
7. Reviewer, four TRF Young Researcher Grant proposals, September-October, 2008
8. Past reviewer: In October, 2008, the Director of the US National Science Foundation expresses his gratitude for previous reviews (see Attachment 65)
9. TV interview as part of a telethon for the 50th anniversary of the Faculty of Science, Mahidol U., October 19, 2008
10. Lecturer for the course "Generic Skills in Science Research," an interdisciplinary graduate course for the Faculty of Science, Mahidol University, on the topic "Responsible Conduct in Science," October 21, 2008
11. Reviewer and Session Chair for Physics (Section D), 34th Congress on Science and Technology of Thailand, Bangkok, October 31 – November 2, 2008
12. Lecturer for the course "History of Science" at Chulalongkorn University, on the topic "Structure of Scientific Revolutions," November 6 & 13, 2008
13. Advisory Board Member, Journal of Science and Technology of Ubonrajathanee University, 2008.
14. Reviewer, TRF Distinguished Research Professor, December, 2008 – February, 2009
15. Lecturer for the course "History of Science" at Chulalongkorn University, on the topic "Structure of Scientific Revolutions," January 29 & February 5, 2009
16. Reviewer, February, 2009, for the *Astrophysical Journal*, the world's premier journal for astrophysics (IF=6.119)
17. Reviewer, M.Sc. program in Computational Science for Mae Fah Luang University
18. Reviewer, M.Ed. program in Physics for Srinakarin Wirot University
19. Radio interview for Mahidol University, June 24, 2009, on Solar Storms
20. Radio interview for Radio Thailand (FM 88) on the Partial Solar Eclipse, July 21, 2009
21. Plenary speaker and member, scientific organizing committee, GR+HEP+Cosmo Meeting, Phitsanulok, July 28, 2009
22. Lecturer for the course "History of Science" at Chulalongkorn University, on the topic "Structure of Scientific Revolutions," 3 times during August-September, 2009

23. Lecture on "Responsible Conduct in Research" for the course Generic Skills in Science Research, Faculty of Science, Mahidol University, September 22, 2009
24. Reviewer and Committee Member for Physics (Section D), 35th Congress on Science and Technology of Thailand, October 15-17, 2009
25. Session chair, TRF Annual Meeting, Cha-am, October 16, 2009
26. Lead Editor, Secondary school textbook on astrophysics, Institute for the Promotion of Science and Technology Teaching, 2009
27. Commentator, Grad Expo, Faculty of Science, Mahidol University, October 28, 2009
28. TV interview for NBT, on solar storms and 2012 disaster theories, Nov. 16 & 23, 2009
29. Reviewer, 3 grant applications for the Basic Research Division, TRF
30. Organized activities on "Exploring Space," Children's Day activities, Faculty of Science, Mahidol University, January 9, 2010
31. Radio interview for Radio Thailand (FM 88) on the Partial Solar Eclipse, January 15, 2010
32. Viewing partial solar eclipse and lecture on solar physics, Faculty of Science, Mahidol University, January 15, 2010
33. Lecturer for the course "History of Science" at Chulalongkorn University, on the topic "Structure of Scientific Revolutions," 3 times during January-February, 2010
34. TV interview for TNN 24, on solar storms and 2012 disaster theories, February 17, 2010
35. Reviewer of application for the position of Professor, Chiang Mai University
36. Reviewer for an international journal, Physics of Plasmas
37. Online interview on solar storms for the popular educational website Vcharkarn.com, <http://www.vcharkarn.com/varticle/40405>, posted Feb. 23, 2010
38. Lecturer for the course "Generic Skills in Science Research," an interdisciplinary graduate course for the Faculty of Science, Mahidol University, on the topic "Responsible Conduct in Science," March 2, 2010
39. Reviewer and committee member, 14th Annual Symposium on Computational Science and Engineering, March 23-25, 2010
40. Invited speaker, Colloquium, Department of Physics and Astronomy, University of Delaware, April 21, 2010
41. Invited speaker, Plasma and Fluids Seminar, Department of Physics and Astronomy, University of Delaware, May 7, 2010
42. Reviewer for an international journal, Astroparticle Physics, July, 2010
43. Invited lecture, Mahidol Wittayanusorn School, August 2, 2010
44. Lead Editor, Secondary school textbook on astrophysics, Institute for the Promotion of Science and Technology Teaching, 2010
45. Presentations for high school students, Open House, Faculty of Science, Mahidol University, August 18, 2010
46. Lecturer for the course "History of Science" at Chulalongkorn University, on the topic "Structure of Scientific Revolutions," 2 times during August-September, 2010

47. TV interview (live, in Thai, by telephone), "Kon lang kao," TNN 24 News (True Visions Channel 7), September 23, 2010
48. Lead panelist, press conference at Chulalongkorn University on solar storms, September 30, 2010
49. Newspaper articles (print and/or online):
 - "มหิดลนำทีมนักฟิสิกส์ 3 มหาวิทยาลัย วิจัยพายุสุริยะ" เนชั่นทันข่าว วันที่ 30 กันยายน 2553 เวลา 18:06 น. (Attachment 66)
 - "จับตาพายุสุริยะผลกระทบโลก" เดลินิวส์ หน้า 1 วันที่ 1 ตุลาคม 2553 (Attachment 67)
 - "นักวิทยไทยจับตาพายุสุริยะ ระบบเตือนภัยเร็วกว่านาซา" กรุงเทพธุรกิจ หน้า 9 วันที่ 1 ตุลาคม 2553 (Attachment 68)
 - "นักวิชาการเฝ้าดูพายุสุริยะ1-7ปีหน้า" เดลินิวส์ หน้า 14 วันที่ 2 ตุลาคม 2553 (Attachment 69)
 - นักวิชาการเตือนอย่าตื่นตูม มหันตภัย "พายุสุริยะ" โพสต์ทูเดย์ หน้า 8 (เต็มหน้า), 9 วันที่ 2 ตุลาคม 2553 (Attachment 70)
50. TV interview (live, in Thai), "Komchadluek," Nation TV Channel, October 1, 2010
(<http://www.oknation.net/blog/kcltv/2010/10/01/entry-1>)
51. Radio interview (in Thai), Nation radio, October 2, 2010
52. Reviewer of the Computational Science M.Sc. Curriculum, Mae Fah Luang University, September-October, 2010
53. External examiner, Ph.D. course presentations, SIIT, Thammasat University, October 5, 2010
54. Invited speaker, TRF Annual Meeting, Cha-am, October 15, 2010
55. Radio interview (in Thai), MU radio, October, 2010
56. "พายุสุริยะ" ภัยธรรมชาติชนิดใหม่รับมืออย่างไร? กระทบถึงไทย! เดลินิวส์ หน้า 4 (บน) วันที่ 19 ตุลาคม 2553 (Attachment 71)
57. Reviewer and committee member, 36th Congress on Science and Technology in Thailand, October 26-28, 2010
58. Convener of Session #1 and member of SOC of (APRIM 2011) since November, 2010
59. Reviewer of application for the position of Associate Professor, Chiang Mai University
60. ThaiPBS TV interview on evening news of Feb. 18, 2011 about the solar storm of Feb. 15
61. Proposal defense and External examiner, Ph.D. course presentations, SIIT, Thammasat University, March 3
62. Invited speaker, Walailak U., March 4, 2011