การขนส่งและการเร่งอนุภาครังสีคอสมิกใกล้คลื่นกระแทกทรงกลมแบบเฉียง

นายธานินทร์ นุตโร

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต

สาขาวิชาฟิสิกส์ ภาควิชาฟิสิกส์

คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

ปีการศึกษา 2543

ISBN 974-346-667-3

COSMIC RAY TRANSPORT AND ACCELERATION NEAR AN OBLIQUE, SPHERICAL SHOCK

Mr. Tanin Nutaro

A Dissertation Submitted in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy in Physics

Department of Physics

Faculty of Science

Chulalongkorn University

Academic year 2000

ISBN 974-346-667-3

Dissertation Title	Cosmic Ray Transport and Acceleration near an Oblique, Spherical Shock
By	Mr. Tanin Nutaro
Department	Physics
Dissertation Advisor	Associate Professor David Ruffolo, Ph.D.
Dissertation Co-advisor	Assistant Professor Pornpote Piumsomboon, Ph.D.

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements of Degree of Doctor of Philosophy.

Wanchai Phothiphichitr .... Dean of Faculty of Science

(Associate Professor Wanchai Phothiphichitr, Ph.D.)

DISSERTATION COMMITTEE

A. Th .... Chairman

(Associate Professor Anantasin Techagumpuch, Ph.D.)

David Ruffolo .... Dissertation Advisor

(Associate Professor David Ruffolo, Ph.D.)

.... Dissertation Co-advisor

(Assistant Professor Pornpote Piumsomboon, Ph.D.)

Kajornyod Yoodee .... Member

(Assistant Professor Kajornyod Yoodee, Ph.D.)

.... Member

(Assistant Professor Pornchai Pacharin-Tanakun, Ph.D.)

.... Member

(Kopr Kritayakirana, Ph.D.)

ธานินทร์ นุตโร : การขนส่งและการเร่งอนุภาครังสีคอสมิกใกล้คลื่นกระแทกทรงกลมแบบเฉียง. (COSMIC RAY TRANSPORT AND ACCELERATION NEAR AN OBLIQUE, SPHERICAL SHOCK) อ. ที่ปรึกษา : รศ.ดร. เดวิด รูฟโฟโล, อ. ที่ปรึกษาร่วม : ผศ.ดร. พรพจน์ เปี่ยมสมบูรณ์, 131 หน้า. ISBN 974-346-667-3.

วิทยานิพนธ์นี้เป็นการพัฒนาสมการโฟคเคอ-แพลงค์ เพื่อที่จะใช้อธิบายพฤติกรรมของอนุภาคที่มีประจุที่เคลื่อนที่ภายใต้สนามแม่เหล็กที่มีรูปร่างเป็นลายก้นหอยแบบอะคีมีเดียนซึ่งมีการไหลของของไหลอย่างสมมาตรทรงกลม อีกทั้งได้จำลองการขนส่งอนุภาคแบบมุมขั้วและศึกษาการเร่งอนุภาครังสีคอสมิกใกล้คลื่นกระแทกทรงกลมแบบเฉียง ส่วนหนึ่งของการศึกษานี้คือการพัฒนาวิธีการที่เรียกว่า generalized total variation diminishing (TVD) จากวิธีการเชิงตัวเลขที่ใช้ในการแก้ปัญหาการพาที่เรารู้จักกันดีวิธีหนึ่ง โดยใช้วิธีการที่พัฒนาขึ้นใหม่นี้จะทำให้โปรแกรมสามารถประมวลผลได้เร็วขึ้น 10 ถึง 100 เท่าเมื่อเทียบกับโปรแกรมต้นแบบที่ได้พัฒนาขึ้นโดยรูฟโฟโลในปี 1995 ทั้งนี้ภายใต้ความผิดพลาดที่ยอมรับได้ ด้วยเหตุที่สามารถปรับค่า Courant number ได้ตามชอบใจซึ่งวิธีการ TVD แบบเก่าจะไม่สามารถปรับค่านี้ได้มากกว่า 1

ภาควิชา ฟิสิกส์ ลายมือชื่อนิสิต ....

สาขาวิชา ฟิสิกส์ ลายมือชื่ออาจารย์ที่ปรึกษา ....

ปีการศึกษา 2543 ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ....

##3972821423 : **MAJOR** PHYSICS
KEY WORD: COSMIC RAYS / FOKKER-PLANCK EQUATION / SPHERICAL SHOCK / OBLIQUE MAGNETIC FIELD CONFIGURATION / CHARGED PARTICLE ACCELERATION

TANIN NUTARO: COSMIC RAY TRANSPORT AND ACCELERATION NEAR AN OBLIQUE, SPHERICAL SHOCK. DISSERTATION ADVISOR: ASSOC. PROF. DAVID RUFFOLO, Ph.D. DISSERTATION COADVISOR: ASSIST. PROF. PORNPOTE PIUMSOMBOON, Ph.D. 131 pp. ISBN 974-346-667-3.

A suitable Fokker-Planck transport equation has been developed to describe the behavior of charged particles for an Archimedean spiral magnetic configuration and spherically symmetric fluid flow. Simulations of the pitch angle transport and acceleration of cosmic rays nearby an oblique, spherical shock have been performed. As part of this study, we have developed a generalized total variation diminishing (TVD) method based on one of the well-known numerical techniques to handle the advection problems. By using our developed spatial transport technique, the program running speed can be improved to be 1-2 orders of magnitude faster than a prototype that was developed by Ruffolo (1995), with an acceptable numerical error. The spatial step size can be fully adjusted to a desired general, Courant number ($\gamma = v\Delta t/\Delta z$), which is restricted not to exceed unity in the standard TVD scheme.

Department of Physics
Field of study Physics
Academic year 2000

Student's signature ....Tanin Nutaro........
Advisor's signature ....David Ruffolo........
Co-advisor's signature ....P. Piumsomboon........

Acknowledgements

The development of thoughts and techniques presented here is largely due to the encouragement, education, criticisms, and good environment provided by my thesis supervisor, Assoc. Prof. David Ruffolo, to whom I am deeply indebted, as well as to Assist. Prof. Pornpote Piumsomboon, my co-advisor.

The author wishes to express his deep gratitude to the thesis committee, Assoc. Prof. Anantasin Techagumpuch, Assist. Prof. Kajornyod Yoodee, Assist. Prof. Pornchai Pacharin-Tanakun, and Dr. Kopr Kritayakirana for their reading and criticizing the manuscript.

I would like to express my gratitude to so many people in the computational astrophysics research lab who have contributed to this thesis, especially, Mr. Paisan Tooprakai for computer assistance, Miss Piyanate Chuychai and Miss Kamonporn Klappong for the manuscript typing, and Mr. Chanruangrit Channok and Miss Panita Boonma for their help. The thanks are also due to Dr. Udomsilp Pinsook for his useful suggestions.

Finally, I would like to dedicate the thesis to my parents and my family for their love, especially to Miss Suratchanee Tuntrakul, for her help, hospitality and providing an appropriate environment to the author.

This work was supported by a Basic Research Grant from the Thailand Research Fund and the Thailand University Development Commission (U. D. C.).

Table of Contents

List of Figures

Preface

Recently, the use of computer simulations to study some physical systems is an attractive and sophisticated fashion. During the past decade computational physics – the use of modern high speed computers to carry out numerical modeling of physical situations which cannot be addressed by either analytic theory or by experiments – has emerged as a distinct and rapidly growing field of physics. This follows the down-sizing of the mainframe computer capability into the low-cost PC-based computers. The price performance of PC-based computers has rapidly improved in the past decade. According to the present computer technology, a normal high-end PC-based computer may have the same calculation capability as a mainframe system did ten years ago, but at a very low price. Furthermore, well developed mathematical packages have been issued, and the reliability of such programs has been improved. A few examples are Mathematica (Wolfram, 1999), Maple (Braselton, 1994) and Mathcad (Phillip, 1998). Some packages can do both symbolic and numeric calculations and most of them have programming features that allow users to create their own desired complex numerical program more easily since there are a lot of built-in functions and a higher-level language than the traditional programming languages (C, Pascal, Fortran, *etc.*). This is because of a more friendly user interfacing design. Some symbolic calculation features can help physicists who always do some boring tasks that require a whole day to carry out, making them easier to handle, e.g., to tackle a cumbersome problem in a few minutes. This thesis is one of the examples of exploiting the benefits of computer simulations. The graphic utilities in some packages were used in my thesis work, while the main calculating engine was still in the C language to achieve a good running speed, more flexibility, and maximum reliability.

The motivation of this thesis has a starting point from the rapid increase of the world's population leading to the enormous number of people existing in the world. This causes world-wide serious troubles making it more difficult for humans to survive. The majority of the world's poorest people depend on the natural environment for their survival. In several countries, people have no ability to produce enough food; therefore, under these circumstances, people are dying of hunger every day all over the world. Trouble arises when people have no food, which leads to non-stop destruction of more and more natural resources every year. This causes a direct effect on a very delicate ecosystem and therefore we may not maintain an appropriate environment much longer. Consequently, if the population growth keeps going on at this present-day rate, one day our world will be filled with people. At that time, there will be no more space in the planet Earth to appropriately handle all the people.

Since the end of the Cold War, several powerful countries, led by the United States of America, Russia, some European countries, *etc.*, have developed space research in a better way than ever before. Nowadays, there are several creative and frontier space research projects performed by in several countries. Several such programs involve cooperation between several nations. The most important and interesting project is about the settling of humans in space or other planets. This guarantees that mankind will exist in the future. This idea is possible in the near future, assuming the rapid progress in materials development and space technology improves further in the next few decades. At least the biggest space station ever is being constructed somewhere in Earth orbit. In the future, based on our recent knowledge and scientific background and the space technologies we have, we will get more freedom to go everywhere we want, not only limited by the Earth's atmosphere or confined by its gravity.

However, the ambient surroundings of the "new home" will be very far different from the Earth's atmosphere. Indeed, it will be a very harmful environment. Since our planet is shielded by the atmosphere and the Earth's magnetosphere, this suitable environment protects all of the living things inside from unavoidable objects and particles coming from the deep space. One thing that is very dangerous and harmful to all life is the "cosmic rays." (A brief description of cosmic rays and related references will be presented in Chapter 1.) We rarely worry about these effects when we are staying on the Earth. However, violent events can occur at the Sun, such as solar flares (the huge explosions on the surface of the Sun) or coronal mass ejections (CME). The latter can involve billions of tons of coronal mass immediately swirling outward from the Sun into the surrounding space (the heliosphere), releasing an enormous amount of charged particles into the heliosphere with a very high speed, up to 2000 km/s. These plasma streams can directly affect the Earth's magnetosphere and an interplanetary shock can be formed since the CME travels with a speed greater than the speed of sound into the ambient fluid flow. Now we believe that when the charged particles are repeatedly crossing the shock back and forth due to scattering from magnetic field irregularities, they can be accelerated from a low energy to a very high energy level (see more details in Chapter 1 and references therein) and these particles (or any produced by solar events) are known as Solar Energetic Particles (SEP). The shocks driven by CMEs and the cosmic rays accelerated there can have serious effects on the Earth, such as disrupting radio communications, causing electric power failures, destroying solar panels on board satellites, destroying the delicate electronic systems of the spacecraft or even causing radiation warnings on transoceanic airplane flights, *etc.*.

Our new model of spherical shock acceleration, with the contribution of a powerful spatial transport technique we had developed, helps us to perform high-efficiency computer simulations. This is a low-cost and appropriate way to learn more about the acceleration of energetic particles in our surrounding space. The information given by the computer simulations is a step toward obtaining knowledge useful to humankind in the new space era.

This thesis contains 6 chapters, with a major emphasis on numerically solving cosmic ray transport problems and possible acceleration mechanisms of charged particles (cosmic rays) under the shock circumstances, and emphasizes a spherical shock geometry. The various physical properties and behaviors of such particles in the spherical shock vicinity were studied in several situations. Chapter 1 gives a brief introduction to the fundamental ideas of cosmic rays, including their discovery, some basics and possible physical processes, and theories relevant to the acceleration mechanism of charged particles in the vicinity of a (spherical) shock. Furthermore, this chapter also gives a brief summary of spherical shock investigations from the early stage to the present day. A formal derivation of a suitable transport equation for the spherical shock is given in Chapter 2. The possible physical processes dealing with this situation are carefully taken into account, especially the adiabatic deceleration and focusing. This is the first systematic, numerical study of these effects, which do not appear at a planar shock. Chapter 3 presents appropriate methodologies to solve our transport equation. Since the transport equation we obtained is one form of a Fokker-Planck equation, and it is a linear partial differential equation and has several variables, it is impossible to find analytical solutions under our boundary conditions of interest. This chapter introduces some useful numerical techniques such as the concept of "operator splitting" to split a complex differential equation into simpler, solvable forms. Furthermore, this chapter gives the description of a new generalization of the numerical technique for solving the convection problem called "total variation diminishing (TVD)," which we have developed (Nutaro, Riyavong, and Ruffolo, 2000) from the standard scheme. Our newly modified method is called a generalized TVD scheme, and we use this scheme for the whole spatial transport simulation. In addition, the description of the particles encountering a shock, which we call the shock treatment, is also included in this chapter. Chapter 4 describes the results of our simulations in various situations of interest. Chapter 5 gives the summary and the discussion of this thesis.

This study will lead us to improve our basic knowledge relevant to particle transport and acceleration under spherical shock circumstances. Hence, the behavior of charged particles under the influence of the shock curvature effects such as adiabatic deceleration and adiabatic focusing can be examined by using our well-developed computer simulation program.