PRELIMINARY INDIRECT MEASUREMENT OF COSMIC-RAY PROTON SPECTRUM USING EARTH'S γ-RAY DATA FROM *FERMI* LARGE AREA TELESCOPE

PATOMPORN PAYOUNGKHAMDEE

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE (PHYSICS)
FACULTY OF GRADUATE STUDIES
MAHIDOL UNIVERSITY
2021**

Thesis
entitled

....
Mr. Patomporn Payoungkhamdee
Candidate

....
Asst. Prof. Warit Mitthumsiri,
Ph.D. (Physics)
Major advisor

....
Prof. David Ruffolo,
Ph.D. (Physics)
Co-advisor

....
Dr. Alejandro Sáiz,
Ph.D. (Physics)
Co-advisor

....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University

....
Assoc. Prof. Kittiwit Matan,
Ph.D. (Physics)
Program Director
Master of Science Program in Physics
(International Program)
Faculty of Science
Mahidol University

Thesis
entitled

was submitted to the Faculty of Graduate Studies, Mahidol University
for the degree of Master of Science (Physics)
on
May 18, 2020

....
Mr. Patomporn Payoungkhamdee
Candidate

....
Assoc. Prof. Paisan Tooprakai,
Ph.D. (Physics)
Chair

....
Asst. Prof. Warit Mitthumsiri,
Ph.D. (Physics)
Member

....
Prof. David Ruffolo,
Ph.D. (Physics)
Member

....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University

....
Assoc. Prof.P̃alangpon Kongsaree,
Ph.D. (Organic Chemistry)
Dean
Faculty of Science
Mahidol University

ACKNOWLEDGEMENTS

First of all, I would like to express my special gratefulness to my advisor Asst. Dr. Warit Mitthunsiri for the wisely advise, providing guidance, and constant support through the program. Thanks for instructing me how to manage with a towering stack of data, challenged coding and for all Python tips. This work would not finish without many suggestions from Prof. David Ruffolo, the head of the space physics and energetic particles laboratory for helping me successfully achieve the goal for each phase of this project and for a great opportunity to work on this field of Physics. Particular thanks to the other co-advisor, Dr. Alejandro Sáiz, the first teacher who has inspired me on computer simulation including helpful suggestions and discussions relating to this work. Many thanks to Dr. Waraporn Nunthiyakul for the cutoff-rigidity program and various tricks of FLUKA simulation, valuable comments about this work and for sharing excellent experiences. I deeply appreciate my Ph.D. Committee for their time and scientific expertise to review my work.

Thanks to the members of space physics laboratory for academic discussions and sharing experiences which was an essential ingredient in the completion of this thesis. Thanks the Department of Physics, Mahidol University for an exceptional experience. Last not least, sincere appreciation goes to my colleagues and friends for their support and encouragement throughout. I acknowledge the financial support I received over these years to the Science Achievement Scholarship of Thailand (SAST) and the Thailand Research Fund (TRF). Ultimately, I would like to thank my parents, my sister, and brothers for their constant support and patient.

Patomporn Payoungkhamdee

PRELIMINARY INDIRECT MEASUREMENT OF COSMIC-RAY PROTON SPECTRUM USING EARTH'S γ-RAY DATA FROM *FERMI* LARGE AREA TELESCOPE.

PATOMPORN PAYOUNGKHAMDEE 5736149 SCPY/D

M.Sc. (PHYSICS)

THESIS ADVISORY COMMITTEE: WARIT MITTHUMSIRI, Ph.D. (PHYSICS), DAVID RUFFOLO, Ph.D. (PHYSICS), ALEJANDRO SÁIZ, Ph.D. (PHYSICS)

ABSTRACT

Cosmic rays (CRs) are high-energy particles, mostly protons, propagating in space. The rigidity (momentum per charge) spectrum of CRs is well described by a power law for which the spectral index is approximately 2.8 around 30 - 1000 GV. Recent measurements by PAMELA and AMS-02 indicate an abrupt change of the CR proton spectral index at about 340 GV. When CRs interact with the Earth's upper atmosphere, γ rays can be produced and detected by space-based detectors. Here we use the Earth's γ-ray data collected by the *Fermi* Large Area Telescope along with a proton-air interaction model to indirectly determine the CR proton spectral index and compare against observations by other instruments.

KEY WORDS: EARTH'S GAMMA RAYS / COSMIC RAYS/ GEOMAGNETIC FIELD

19 pages

CONTENTS

CONTENTS (cont.)

LIST OF TABLES

LIST OF FIGURES

CHAPTER I
INTRODUCTION

1.1 Overview

The space is full of questionable amazing phonomenon starting from why we have day and night, why the star bright to the advance question about existence of the dark matter. This influence to the mankind to start asking how it happen. Human curiosity bring us so far that now we could observe the sky with high resolution technique. However, the research to gather new knowledge by studying the space is endless and the answering one thing usually bring another mystery. Study of physical science also drag the technology for further step because the limitation of the instrument or technique to explore the nature is another challenging task.

Astrophysical research boundary is expanding through time pass by because the exploration of one thing does open the new door with the darky room waiting for human to shine a light to explore. There are various branch of astrophysical science from theoretical foundation, simulation and experimental physics where they are compliment each other for pushing the frontier of the human knowledge. To study high energy particle accelerators in the universe, the possibility of probing the source is nearly impossible in terms of current technology and resource that required to reach multiple galactic sources that could produce high energy particle called cosmic-rays (CRs). Nevertheless, the technology of observing the particles that arriving the Earth is more plausible for the scientist.

The way to observe cosmic-ray (CR) particles has divided into two ways. One way is measuring the incoming charge particles on ground with a ground-base detector. Alternative way is gathering CRs on the space or basically orbiting spacecraft. Performing analysis on CRs data allow us to interpret the physical properties of CRs particle for both quantatively and qualitatively by taking simulation and experimental results to compare.

Typically, the spectrum of the CRs would follow the power law with a specific spectral index depending on the rigidity of the charged particles where it was accelerated by a specific source. It is obvious that there will be multiple sources of the CRs in the space including unknown sources. The characteristic of spectrum would be indicated by the source from theoretical simulation and derivations. Consequencely, changing of the spectral index from one rigidity to another rigidity will find the discontinuity if there are the translation from one source type to another source from the superposition of multiple spectrums.

Fermi-LAT has been launched into the sky and orbiting around the Earth and looking around the space in γ-rays regions. It found that the ring of brightness around the Earth's limb where the major factor that cause this phenomenon is the intereaction of incoming CRs with the Earth's upper atmosphere as analyzed in Abdo et al. (2009). Then the spectrum of γ-rays that was induced by the incoming CRs highly related on the spectrum of CRs.

The first indirect measurement was conducted with 5 years of observations and indicate that there is breaking of spectral index around 302 GV with a significant level 1 σ. The significant level at this stage is not so strong to conclude the study. The reasons probably came from the nature of the CRs if there is no discontinuity in the incident CRs spectrum, the indirect could measurement distort the information so that the significant could be reducing or the exposure time during the observations is still not enough. In order to confirm that we did our best on the data collection side, performing the analysis with more data could also put us out doubt for the last clue.

1.2 Objectives

The objectives of this study are to

- To indirectly measure the cosmic ray proton spectrum in rigidity range gigaelectronvolt (GV)

- To put the weight on the previous study with more dataset
- To improve the optimizaiton technique by using heuristical methodology
- To reduce the calculation time by inventing a whole new parallel code in low level from scratch

1.3 Outline of Thesis

The dissertation would provide the various information from the overview introductory context to the technical detail that employ in this study as well as the result and interpretation. It is structured as follows.

Chapter I will introduce the reader about the overview of the long track from the historical analogy and zooming into the specific branch of research to get the reader to see where we are and what we are doing to fullfill the frontier of the research.

Chapter II is the background knowledge that will be used in this study. This chapter also have a brief of history in cosmic ray research community which contains an important finding and the impactful experiment that bring us to this far in the research field. Some theoretical detail will be provided on par with the historical discovery but the subchapter of the specific topic will describe more detail in depth of astroparticle physics that involving the high energy physics. Not only the concept of physical process but this chapter also have the apparatus informations where the majority of the content covering the detector part in the spacecraft to demonstrate how the apparatus gather the γ-rays data.

Chapter III is mainly consist of multiple literature reviews involving the study to clarify the theoretical idea as well as for filling the fundamental concept that takes reader to understand the next chapter in detail.

Chapter IV would cover the article reviewing. The content is staring from pioneering article of the field and the evolution that inspire this work.

Chapter V consists of datasets selection, flux calculation , problem optimizaiton and interpretation.

CHAPTER II
BACKGROUND

2.1 Cosmic-ray

This section consists of historical discovery, from the origin on this field of study until the latest impactful experiment. Not only historical content, it also contains the physical explaination with phenomenon that involving the CR reserch.

2.1.1 History

In 1909, the famous experiment that pioneer the study of CR has been led by Theodor Wolf who take conduct the experiment of altitude variation by taking the apparatus to measure the rate of ionization from the ground to the top of the Eiffle Tower in Paris (Gray (1949)). The result shown that there the ionizaiton rate was slightly increase when the altitude is higher which gives the clues that the origin of cosmic-rays was came from the outer space rather than Earth's inner shell.

However, the experiment of measuring the affect of altitude variation with a tiny altitude scale comparing to the Earth's atmosphere would not enough to consolidate the theory. In the same year, the ballon with a similar instrument has been released up to 1.3 kilometers by Karl Bergwitz to put more weight on the first experiment. They found that the ionization has increased by a quater comparing to ground level (De Angelis (2014)). Three years later, suicidal investigation was conducted by an Australian gentleman who brought the detector and himself to fly with the balloon. His name is Victor Hess, people might have no doubt why this name went so famous because he risk his life with the experiment and he was flying over 5 kilometers above the ground (Hess (1912)). Definitely, the result is strongly significant and impactful to the astrophysical research community. Risking life In 1914, Werner Kolhörster repeated the balloon experiment with higher altitude which around 9 kilometers from the sea level and the ionizaiton rate still does increase when the ballon flown higher. This emphasize that the source of those ionizing ray came from Earth's upper atmosphere or the outer space.

Not only the altitude variable that related to the intensity of the CRs, but the geographic location of the obvervation also does affect to the measurement. The first experiment has done done John Clay who sailed the ship across the ocean from Holland to Java (Clay (1927, 1928)). The result shows that the further from equator, the higher CR intensity. Another exploration for the geographic variation was done by John Compton in the following five years. He basically sailed the ship from the Sydney (northern hemisphere) to Vancouver (the southern hemisphere) for various season during 1936 to 1937 back and forth (Compton & Turner (1937)). The Figure 2.1 demonstrates the latitude variation and the seasonality effects of the multiple trips from the experiment.

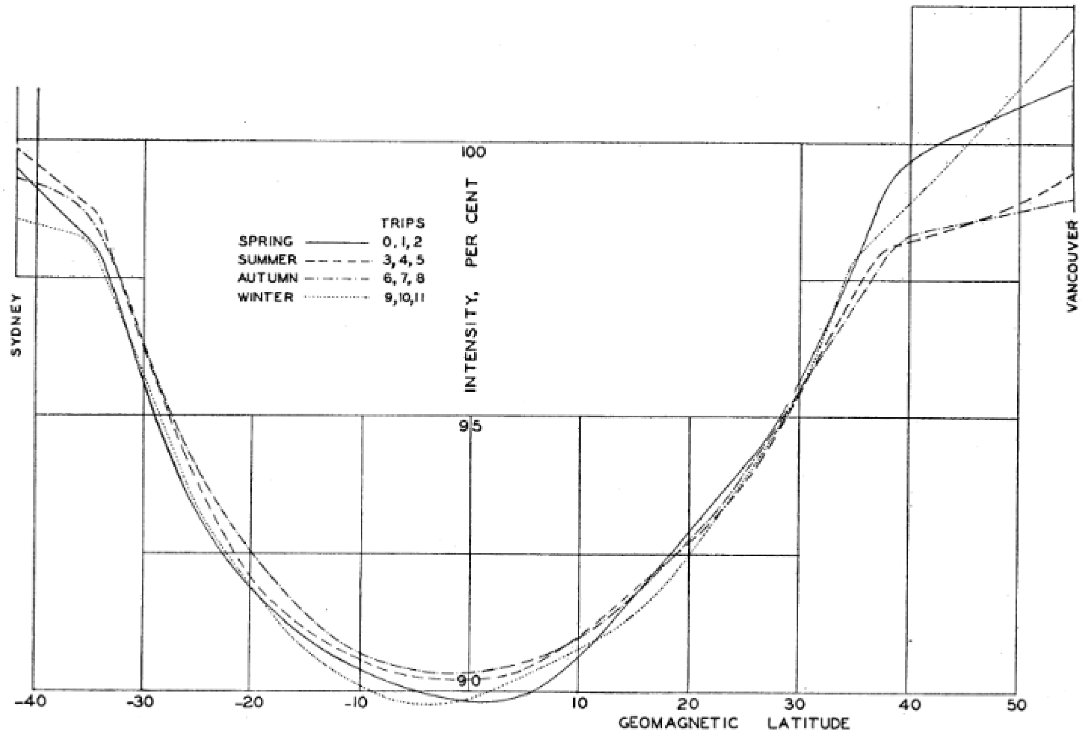

Figure 2.1: Latitude variation for various seasons (Compton & Turner (1937))

The first interpretation study from the discovery has been done by Carl Störmer. The explaination of the CR's altitude variation came from the trajectory of CR particles due to geomagnetic field (Störmer (1934)). In that period, the topic of geomagnetic field and the effects of CRs was quite famous. Another impactful study of the CRs trajectory and the relevant of Earth's magnetic field was conducted by Bruno Rossi for predicting an asymmetry of the East-West distribution of CR spectrum because the primary CRs does have a positive or negative charge then the cyclic moving direction of the particle was induced by Lorentz force where the direction of the Earth's magnetic field could be identified to determine the direction of the charged particles (Rossi & Greisen (1941)).

The ground based detector is a great option for detecting the CRs where it include primary and secondary CRs. However, investigating the primary CRs is a challenging topic for ground based detector especially for low energy particles. Another interesting option to inspect the asymmetry of East-West could be done by using space based detector that orbiting around the Earth's at some radius in the higher altitude and definitely it would face a lower atmospheric density which consider to be an interesting choice to study the CRs with a lower effects of atmospheric interaction.

In 2008, *Fermi* Large Area Telescope (LAT) has been launched to observed the γ-ray and the lightweight lepton particles which basically are electron and position.

2.1.2 Physical properties

The physical properties

2.1.3 γ-ray production

2.1.4 Earth's limb γ-ray production

2.2 *Fermi* Large Area Telescope (LAT)

2.2.1 Overview

2.2.2 Apparatus

2.2.3 Event reconstruction

CHAPTER III

LITERATURE REVIEW

CHAPTER IV
METHODOLOGY

4.1 Data selection

4.2 Flux extraction

4.3 Interaction Model

4.4 Optimization

4.5 Monte Carlo Simulation

4.6 Likelihood ratio test (LRT)

CHAPTER V
RESULTS AND DISCUSSION

5.1 Limb's angle correction

5.2 γ-ray measurement

5.3 Best fit result

5.4 Error determination

CHAPTER VI
CONCLUSION

example cite Curie (1923)

REFERENCES

1. Abdo, A. A., Ackermann, M., Ajello, M., Atwood, W. B., Baldini, L., Ballet, J., et al. (2009). Fermi large area telescope observations of the cosmic-ray induced γ-ray emission of the Earth's atmosphere. *Physical Review D*, 80(12), 122004.
2. Abraham, J., Abreu, P., Aglietta, M., Ahn, E., Allard, D., Allen, J., et al. (2010). Measurement of the energy spectrum of cosmic rays above 1018 ev using the pierre auger observatory. *Physics Letters B*, 685(4-5), 239–246.
3. Ackermann, M., Ajello, M., Albert, A., Allafort, A., Baldini, L., Barbiellini, G., et al. (2014). Inferred Cosmic-Ray Spectrum from Fermi Large Area Telescope γ-Ray Observations of Earth's Limb. *Physical Review Letters*, 112(15), 151103.
4. Ackermann, M., Ajello, M., Allafort, A., Atwood, W. B., Baldini, L., Barbiellini, G., et al. (2012). Measurement of Separate Cosmic-Ray Electron and Positron Spectra with the Fermi Large Area Telescope. *Physical Review Letters*, 108(1), 011103.
5. Adriani, O., Barbarino, G., Bazilevskaya, G., Bellotti, R., Boezio, M., Bogomolov, E., et al. (2009). An anomalous positron abundance in cosmic rays with energies 1.5–100 gev. *Nature*, 458(7238), 607–609.
6. Adriani, O., Barbarino, G., Bazilevskaya, G., Bellotti, R., Boezio, M., Bogomolov, E., et al. (2011). Pamela measurements of cosmic-ray proton and helium spectra. *Science*, 332(6025), 69–72.
7. Aguilar, M., Aisa, D., Alpat, B., Alvino, A., Ambrosi, G., Andeen, K., et al. (2015a). Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station. *Physical Review Letters*, 115(21), 211101.

8. Aguilar, M., Aisa, D., Alpat, B., Alvino, A., Ambrosi, G., Andeen, K., et al. (2015b). Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station. *Physical Review Letters*, 114(17), 171103.

9. Amsler, C., et al. (2008). Particle data group. *Phys. Lett. B*, 667(1).

10. Atwater, T. W., & Freier, P. S. (1986). Meson multiplicity versus energy in relativistic nucleus-nucleus collisions. *Physical review letters*, 56(13), 1350.

11. Atwood, W., Albert, A., Baldini, L., Tinivella, M., Bregeon, J., Pesce-Rollins, M., et al. (2013). Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential. *arXiv e-prints*, arXiv:1303.3514.

12. Atwood, W. B., Abdo, A. A., Ackermann, M., Althouse, W., Anderson, B., Axelsson, M., et al. (2009). The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission. *The Astrophysical Journal*, 697, 1071–1102.

13. Baldini, L. (2014). Space-based cosmic-ray and gamma-ray detectors: a review. *arXiv preprint arXiv:1407.7631.*

14. Becquerel, H. (1896). On the rays emitted by phosphorescence. *Compt. Rend. Hebd. Seances Acad. Sci.*, 122(8), 420–421.

15. Belolaptikov, I., Budnev, N., Sinegovsky, S., Padusenko, A., Wiebusch, C., Moroz, A., et al. (1997). The baikal underwater neutrino telescope: Design, performance and first results. Tech. rep., SCAN-9704016.

16. Bird, D., Corbato, S., Dai, H., Dawson, B., Elbert, J., Emerson, B., et al. (1994). The cosmic-ray energy spectrum observed by the fly's eye. *The Astrophysical Journal*, 424, 491–502.

17. Carlson, A., Hooper, J., & King, D. (1950). Lxiii. nuclear transmutations produced by cosmic-ray particles of great energy.-*Part V.* the neutral mesons. *Philosophical Magazine Series 7*, 41(318), 701–724.

18. Clay, J. (1927). Penetrating Radiation I. In Proceedings of the Royal Academy of Sciences Amsterdam. vol. 30, pp. 1115–1127.

19. Clay, J. (1928). Penetrating Radiation II. In Proceedings of the Royal Academy of Sciences Amsterdam. vol. 31, pp. 1091–1097.

20. Compton, A. H., & Turner, R. (1937). Cosmic rays on the pacific ocean. *Physical Review*, 52(8), 799.

21. Curie, M. (1923). Pierre Curie. Macmillan.

22. De Angelis, A. (2014). Atmospheric ionization and cosmic rays: studies and measurements before 1912. *Astroparticle Physics*, 53, 19–26.

23. Dorman, L. I., Fedchenko, S. G., Granitsky, L. V., & Rishe, G. A. (1970). Coupling and barometer coefficients for measurements of cosmic ray variations at altitudes of 260-400 mb. In International Cosmic Ray Conference. vol. 2, p. 233.

24. Fermi, E. (1949). On the origin of the cosmic radiation. *Physical review*, 75(8), 1169.

25. Fricke, R. G., & Schlegel, K. (2017). Julius elster and hans geitel-dioscuri of physics and pioneer investigators in atmospheric electricity. *History of Geo-and Space Sciences*, 8(1), 1.

26. Gaisser, T. K., Stanev, T., & Tilav, S. (2013). Cosmic ray energy spectrum from measurements of air showers. *Frontiers of Physics*, 8(6), 748–758.

27. Gerward, L. (1999). Paul villard and his discovery of gamma rays. *Physics in perspective*, 1(4), 367–383.

28. Gray, G. W. (1949). Cosmic rays. *Scientific American*, 180(3), 28–39.

29. Halzen, F., & Klein, S. R. (2010). Invited review article: Icecube: an instrument for neutrino astronomy. *Review of Scientific Instruments*, 81(8), 081101.

30. Hess, V. F. (1912). Über beobachtungen der durchdringenden strahlung bei sieben freiballonfahrten. *Phys. Z.*, 13, 1084–1091.

31. Kelner, S. R., Aharonian, F. A., & Bugayov, V. V. (2006). Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime. *Physical Review D*, 74(3), 034018.

32. Kirk, T. B., & Neddermeyer, S. H. (1968). Scattering of high-energy positive and negative muons on electrons. *Physical Review*, 171(5), 1412.

33. Kolhörster, W. (1934). Cosmic rays under 600 metres of water. *Nature*, 133(3359), 419–419.

34. Kraushaar, W., & Clark, G. (1962). Search for primary cosmic gamma rays with the satellite explorer xi. *Physical Review Letters*, 8(3), 106.

35. Kraushaar, W., Clark, G., Garmire, G., Helmken, H., Higbie, P., & Agogino, M. (1965). Explorer xi experiment on cosmic gamma rays. *The Astrophysical Journal*, 141, 845.

36. Kraushaar, W. L., Clark, G. W., Garmire, G. P., Borken, R., Higbie, P., Leong, V., & Thorsos, T. (1972). High-Energy Cosmic Gamma-Ray Observations from the OSO-3 Satellite. *The Astrophysical Journal*, 177, 341.

37. Lesur, V. (2006). Introducing localized constraints in global geomagnetic field modelling. *Earth, planets and space*, 58(4), 477–483.

38. Linsley, J. (1963). Evidence for a primary cosmic-ray particle with energy 10 20 ev. *Physical Review Letters*, 10(4), 146.

39. Millikan, R. A. (1932). Cosmic-ray ionization and electroscope-constants as a function of pressure. *Physical Review*, 39(3), 397.

40. Morris, D. J. (1984). Production of high-energy gamma rays by cosmic ray interactions in the atmosphere and lunar surface. *Journal of Geophysical Research*, 89, 10685–10696.

41. Morrison, P. (1958). On gamma-ray astronomy. *Il Nuovo Cimento (1955-1965)*, 7(6), 858–865.

42. Neddermeyer, S. H., & Anderson, C. D. (1937). Note on the nature of cosmic-ray particles. *Physical Review*, 51(10), 884.

43. Nuntiyakul, W., Evenson, P., Ruffolo, D., Sáiz, A., Bieber, J. W., Clem, J., et al. (2014). Latitude Survey Investigation of Galactic Cosmic Ray Solar Modulation during 1994-2007. *The Astrophysical Journal*, 795, 11.

44. Orth, C. D., & Buffington, A. (1976). Secondary cosmic-ray electrons and positrons from 1 to 100 gev in the upper atmosphere and interstellar space, and interpretation of a recent positron flux measurement. *The Astrophysical Journal*, 206, 312–332.

45. Petry, D. (2005). The Earth's Gamma-ray Albedo as observed by EGRET. In F. A. Aharonian, H. J. Völk, & D. Horns (Eds.), High Energy Gamma-Ray Astronomy. *American Institute of Physics Conference Series*, vol. 745, pp. 709–714.

46. Rochester, G., & Butler, C. (1953). The new unstable cosmic-ray particles. *Reports on Progress in Physics*, 16(1), 364.

47. Rossi, B. (1930). On the Magnetic Deflection of Cosmic Rays. *Physical Review*, 36, 606–606.

48. Rossi, B., & Greisen, K. (1941). Cosmic-ray theory. *Reviews of Modern Physics*, 13(4), 240.

49. Ruffolo, D., Sáiz, A., Mangeard, P.-S., Kamyan, N., Muangha, P., Nutaro, T., et al. (2016). Monitoring Short-term Cosmic-ray Spectral Variations Using Neutron Monitor Time-delay Measurements. *The Astrophysical Journal*, 817, 38.

50. Shea, M., Smart, D., & McCracken, K. (1965). A study of vertical cutoff rigidities using sixth degree simulations of the geomagnetic field. *Journal of Geophysical Research*, 70(17), 4117–4130.

51. Sigl, G. (2012). High energy neutrinos and cosmic rays. *arXiv preprint arXiv:1202.0466*.

52. Skobeltzyn, D. (1929). The Angular Distribution of Compton Recoil Electrons. *Nature*, 123(3098), 411–412.

53. Skobeltzyn, D. V. (1985). The early stage of cosmic ray particle research. In Early History of Cosmic Ray Studies, Springer. pp. 47–52.

54. Stecker, F. W. (1973). Simple Model for Scanning-angle Distribution of Planetary Albedo Gamma-rays. *Nature Physical Science*, 242, 59–60.

55. Stephens, S. A., & Badhwar, G. D. (1981). Production spectrum of gamma rays in interstellar space through neutral pion decay. *Astrophysics and Space Science*, 76, 213–233.

56. Störmer, C. (1934). Critical remarks on a paper by g. lemaître and ms vallarta on cosmic radiation. *Physical Review*, 45(11), 835.

57. Svensson, G. (1958). The cosmic ray photon and π^0-meson energy spectra at

29-30 km above sea-level. *Arkiv Fysik*, 13, 347.

58. Thébault, E., Finlay, C. C., Beggan, C. D., Alken, P., Aubert, J., Barrois, O., et al. (2015). International geomagnetic reference field: the 12th generation. *Earth, Planets and Space*, 67(1), 79.
59. Thompson, D. J., Simpson, G. A., & Ozel, M. E. (1981). SAS 2 observations of the earth albedo gamma radiation above 35 MeV. *Journal of Geophysical Research*, 86, 1265–1270.
60. Trenn, T. J. (1976). Rutherford on the alpha-beta-gamma classification of radioactive rays. *Isis*, 67(1), 61–75.
61. Tsyganenko, N. A. (1987). Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels. *Planetary and Space Science*, 35, 1347–1358.
62. Van Allen, J. A., & Frank, L. A. (1959). Radiation around the earth to a radial distance of 107,400 km. *Nature*, 183(4659), 430–434.
63. Van Oosterom, A., & Strackee, J. (1983). The solid angle of a plane triangle. *IEEE Transactions on Biomedical Engineering*, BME-30(2), 125–126.
64. Watson, A. (2000). Ultra-high-energy cosmic rays: the experimental situation. *Physics Reports*, 333, 309–327.
65. Wilson, C. T. R. (1921). Iii. investigations on lighting discharges and on the electric field of thunderstorms. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, 221(582-593), 73–115.
66. Yoshida, S., Hayashida, N., Honda, K., Honda, M., Imaizumi, S., Inoue, N., et al. (1994). Lateral distribution of charged particles in giant air showers above 1 eev observed by agasa. *Journal of Physics G: Nuclear and Particle Physics*, 20(4), 651.

APPENDICES

APPENDIX A
BLA

...

BIOGRAPHY

NAME	Mr. Patomporn Payoungkhamdee
DATE OF BIRTH	29 April 1996
PLACE OF BIRTH	Bangkok, Thailand
INSTITUTIONS ATTENDED	Mahidol University, 2014–2017
	Bachelor of Science (Physics)
	Mahidol University, 2018–2020
	Master of Science (Physics)
HOME ADDRESS	86/46 Moo. 7, Bangmuang, Muang,
	Samutprakan 10270 Thailand
E-MAIL	patomporn.pay@student.mahidol.ac.th