frontiers | Frontiers in Astronomy and Space Sciences

PERSPECTIVE
published: 08 August 2022
doi: 10.3389/fspas.2022.957776

A Story of Developing the Idea of Plasma-Sheet Flow Braking

*Kazuo Shiokawa**

Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan

This paper reports a story of developing the idea of Earthward ion flow braking in the near-Earth plasma sheet and its relationship with substorm onset processes. This idea and the data that support it are the basis for today's two competing models for substorms: the near-Earth neutral-line model and the current disruption model. The idea was developed when the author was staying at the Max Planck Institute for Extraterrestrial Physics (MPE) from July 1996 to June 1997. The story addresses the colleagues and mentors who had contributed to the development of this idea. The lessons learned from this story are also summarized for students and early-career scientists for their development of new scientific ideas.

Keywords: development of new idea, flow braking, plasma sheet, reconnection, magnetotail

Edited by:
Elena E. Grigorenko, Space Research Institute (RAS), Russia

Reviewed by:
Evgeny Panov, Austrian Academy of Sciences, Austria

***Correspondence:**
Kazuo Shiokawa
shiokawa@nagoya-u.jp

Specialty section:
This article was submitted to Space Physics, a section of the journal Frontiers in Astronomy and Space Sciences

Received: *31 May 2022*
Accepted: *13 June 2022*
Published: *08 August 2022*

Citation:
Shiokawa K (2022) A Story of Developing the Idea of Plasma-Sheet Flow Braking. Front. Astron. Space Sci. 9:957776. doi: 10.3389/fspas.2022.957776

INTRODUCTION

The study on the braking of high-speed ion flow in the near-Earth plasma sheet (Shiokawa et al., 1997) and a subsequent study on the relationship of flow braking with substorm onset processes (Shiokawa et al., 1998a) are one of the several important steps to understand plasma processes during substorms in the Earth's magnetosphere. These two works were carried out when the author was staying at the Max Planck Institute for Extraterrestrial Physics (MPE) from July 1996 to June 1997 as an overseas researcher supported by the Ministry of Education, Science, Sports, and Culture, Japan. In this short article, we would like to introduce a story of when we developed the idea of flow braking in MPE, in order to clarify how this idea was developed and to address the colleagues and mentors who had contributed to this idea. We hope this story is helpful for students and early-career scientists for their development of new scientific ideas.

MY BACKGROUND BEFORE STARTING THE MAGNETOSPHERE STUDY

I was graduated with a bachelor course (March 1988) and a graduate (master) course (March 1990) from Tohoku University, Japan, under the supervision of Prof. Hiroshi Fukunishi. After that, I joined the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, in April 1990, as a research assistant, working mainly with Associate Prof. Kiyohumi Yumoto, for optical and magnetic field measurements at ground stations during the Solar-Terrestrial Energy Program (STEP, 1990–1997) operated by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). I obtained a PhD in 1994 by combining the works in Tohoku University and STEL, on the topic of auroral electrons and ions using data from Antarctic rocket experiments and Defense Meteorological Satellite Program (DMSP) satellites (Shiokawa et al., 1990a; Shiokawa and Fukunishi, 1991; Shiokawa and Yumoto, 1993). In these works, we estimated the density and temperature of auroral electrons in the source magnetosphere by fitting the accelerated Maxwellian distribution function to the observed auroral electron spectra. I also developed a two-stream transportation code of auroral electrons to calculate electron spectra and auroral emissions in the thermosphere and ionosphere from input of precipitating electron distribution (Shiokawa and Fukunishi, 1990).

In 1996, I received an opportunity for an overseas researcher from the Ministry. In this opportunity, I could choose any overseas institution to stay for 1 year. There were two choices: one was to extend my research to the auroral energy dissipation in the thermosphere by using the electron transport code with Dr. Stan Solomon of the University of Colorado because I learned a lot from his study (Solomon et al., 1988) when I developed my auroral electron code. The other choice was to extend my research to the magnetosphere because my past research was focused on estimating the density and temperature of magnetospheric electrons using data from the ionosphere. We can directly compare the estimated density and temperature with those from direct measurements by magnetospheric satellites and possibly identify the source of auroras in the magnetosphere. I consulted Prof. Yosuke Kamide in STEL about these two possibilities, who had many experiences in international collaboration. Prof. Kamide introduced me to Dr. Wolfgang Baumjohann of MPE, as a possible host researcher on the magnetospheric study. Hence, I decided to stay at MPE with Dr. Baumjohann.

DEVELOPMENT OF THE FLOW BRAKING IDEA

I joined the MPE in July 1996. The magnetospheric satellite data I used for the analysis were the data from the Active Magnetospheric Particle Tracer Explorers/Ion Release Module (AMPTE/IRM) satellite. At the beginning of the study, Dr. Baumjohann suggested me to look into the three-dimensional distribution function of Earthward high-speed ion flow in the plasma sheet, in order to identify the evidence of magnetic reconnection in the magnetotail. This topic was extensively studied later by the Japanese Geotail satellite and made significant progress in understanding the magnetic reconnection processes (e.g., Nagai et al., 1998; Hoshino et al., 2001). Thus, Dr. Baumjohann had an excellent perspective on this direction prior to these extensive studies. However, I hesitated to move forward with this suggestion. I had been a co-investigator of the Geotail mission since 1990, and I knew that there were many excellent scientists who had studied magnetic reconnection. I thought that I should not take the same research direction with these smart scientists. Hence, I asked Dr. Baumjohann to give me time to look into the AMPTE/IRM dataset in detail as I am a beginner for magnetospheric physics. Dr. Baumjohann had already developed a well-organized database of the AMPTE/IRM particle and magnetic field and a Fortran code set to plot them (Baumjohann et al., 1988; Baumjohann et al. 1989; Baumjohann et al. 1990). This database and the code set were really easy for me to prepare various plots of magnetospheric plasma and field features and helped me to develop the idea of what happens in the magnetotail plasma sheet.

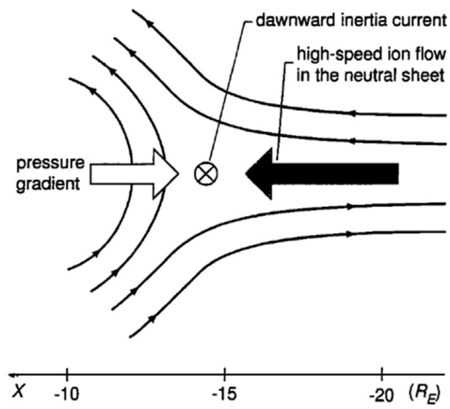

FIGURE 1 | Schematic picture of the proposed magnetic field configuration during Earthward high-speed ion flow (looking from dusk to dawn). The stopping point of the flow is the boundary between dipolar and tail-like magnetic fields which correspond to the inner edge of the neutral sheet. The boundary is formed by the downward inertia current that is caused by braking of the Earthward ion flow and by the pileup of northward magnetic flux carried by the flow (Shiokawa et al., 1997).

Looking into the AMPTE/IRM data, the occurrence rate of earthward flow decreased from ~4 to ~1% as the satellite moved closer to the Earth from 20 Re to 10 Re (**Figure 1A** of Shiokawa et al., 1997). Hence, the question as to how high-speed earthward ion flows stop arose. This question might arise because I was trying to avoid the reconnection topic. Also, I was not a good student of Tohoku University where lectures on magneto-hydro-dynamics (MHD) were made. Then, I started re-learning about MHD using a textbook by Nicholson (1983) and eventually understood that the flow must be stopped by tailward pressure gradient forces, because the plasma and magnetic pressures increase as the flow gets closer to the Earth. But the interesting point was that when the flow stops, there will be a downward inertia current that creates a clear boundary of dipole-like and tail-like magnetic field configuration, as shown in **Figure 1**. This boundary idea suddenly came up to me in the morning in bed, and I said to my wife, “I got a good idea” at 4 a.m. in the morning. This flow-braking process is similar to the process where solar wind hits Earth’s magnetosphere. Then, a magnetopause is formed with a clear boundary of magnetic field intensity due to the magnetopause current (inertia current). Using the AMPTE/IRM data, I confirmed that Earthward ion flows cannot propagate more than a few Re under the average tailward pressure gradient force in the plasma sheet (Figure 3A of Shiokawa et al., 1997).

I was really glad to obtain this idea and discussed it with the senior scientists in MPE, that is, Drs. Götz Paschmann, Manfred Scholer, Nova Scopke, and Rudolf A. Treumann (Dr. Baumjohann was on travel at that time). Dr. Treumann suggested me the possibility that the flow can diverge to dawn/duskward or north/southward, like a river water flow hitting a rock. So, I checked dawn/dusk and north/south velocities (Vy and Vz) in the AMPTE/IRM data and did not find any particular enhancement. But this suggestion helped my

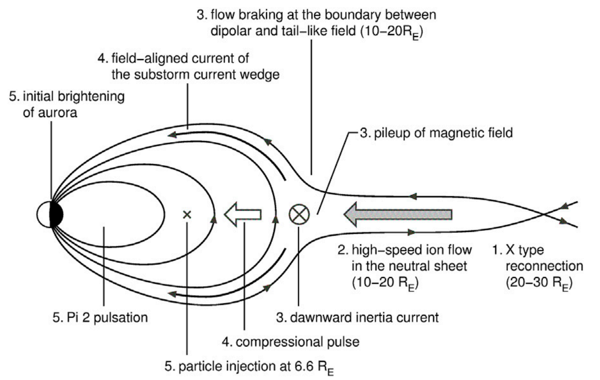

FIGURE 2 | Model proposed by Shiokawa et al. (1998a) for the current wedge formation during the initial stage of the substorm expansion phase. The number preceding each comment indicates the order of occurrence. The braking point of the Earthward flow moves tailward due to the pileup of magnetic field carried by the flow. This motion probably corresponds to the poleward expansion of aurora. The transition from tail-like field to dipolar field at the braking point is due to the downward inertia current. The substorm current wedge is formed at the braking point by the inertia current and the current due to flow shear. The fluctuation of field-aligned currents and the compressional pulses generated at the braking point can be the cause of the Pi2 pulsation in the inner magnetosphere.

understanding of the fluid behavior of magnetospheric plasma. Finally, I discussed the idea with Prof. Gerhard Haerendel, the director of MPE. After explaining my idea, he smiled at me and said to me, "Did you read my paper published in 1992?" Of course, I was lazy and did not search related past literature. He gave me Haerendel (1992) and said to me, "I wrote this paper when I got a heart attack. So this is my heart-attack paper." Haerendel (1992) theoretically discussed the processes of flow braking and its generation of inertia current. My data analysis eventually proved his idea using the AMPTE/IRM data. Haerendel (1992) also pointed out that this process can be a course of substorm current wedge. This paper led me to connect the flow braking idea with the substorm topic.

CONNECTION BETWEEN FLOW BRAKING AND SUBSTORM PROCESSES

After completing the flow-braking article (Shiokawa et al., 1997) in October 1996, it was rather straightforward for me to investigate the timing difference of Earthward flow and substorm onset processes. In that idea development, an excellent review of substorm controversy by McPherron (1995) was beneficial to me. Chapter 13.7 of this review article pointed out several difficulties of pre-existing substorm models to explain observation facts of substorm. For example, in the near-Earth neutral line model, the reconnection (flow reversal) was observed at 20–30 Re in the tail. On the other hand, the auroral breakup at the substorm onset occurs at low latitudes that map to the tail current sheet just outside of 6.6 Re. The flow braking idea can explain this discrepancy by providing an additional point between the reconnection site (20–30 Re) and Earth (1 Re). The flow braking point at ~10 Re can be a magnetospheric source of the auroral breakup at the substorm onset, as shown in **Figure 2** (Shiokawa et al., 1998a). The downward inertia current driven by flow braking can drive the substorm current wedge, as discussed by Haerendel (1992).

The Earthward ion flow with a speed of 400 km/s takes a few minutes to travel from the reconnection region (20–30 Re) to the flow braking region (10–20 Re). If we investigate the timing difference between the flow and auroral breakup, we can identify whether the flow (and reconnection) occurs before or after the auroral breakup. Thus, I collected substorm onset signatures in the ground and satellite data for a substorm-associated flow event on 1 March 1985, as observed by AMPTE/IRM. For this particular event, the onset of Earthward high-speed flow was observed 3 min before the onset of the global current wedge formation. From this observation, we concluded that the substorm current wedge was caused at the braking point of the Earthward high-speed flow during the initial stage of the substorm expansion phase and drew a schematic figure of the substorm onset sequence as shown in **Figure 2** (Shiokawa et al., 1998a, submitted on February 1997).

After this proposal of the substorm model by Shiokawa et al. (1998a), the onset mechanism models seemed to converge into the two major models, that is, the near-Earth neutral line (NENL) model (outside-in model, for e.g., Baker et al., 1996; Shiokawa et al., 1998a) and the current disruption model (inside-out model) (e.g., Lui, 2001). Then, the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission was proposed to identify the controversy of these models (Angelopoulos, 2008). The current understanding is that both models can work at a substorm onset, although which one is more significant is still unresolved (See Lui, 2015 versus Nagai and Shinohara, 2021 for the present state of the controversy). But I could not contribute much to these developments of new missions and subsequent substorm discussion. One of the reasons is that during my stay in MPE, STEL had obtained a new big budget from the Ministry to construct the Optical Mesosphere Thermosphere Imagers (OMTIs, Shiokawa et al., 1999) to measure airglow and aurora using multiple cameras and interferometers. I was responsible for this project, so I became really busy for ground-based multi-point measurements. The other reason may be that I tried to avoid the scientific topic that many smart scientists were studying.

After these two works in MPE, we (Shiokawa, Haerendel, and Baumjohann) also published one more article on azimuthal pressure gradient during substorms (Shiokawa et al., 1998b) to complete the substorm current budget because flow braking processes were clearly not sufficient to drive the total amount of field-aligned currents during substorms (Angelopoulos et al., 1994). In this work, I again tried to prove one of the many theoretical ideas of Haerendel (1990) using the AMPTE/IRM satellite data. My initial motivation to stay at MPE (magnetosphere-ionosphere coupling study) was finally published as Shiokawa et al. (2000) to compare the electron density and temperature estimated from ionospheric DMSP satellites with those directly measured by AMPTE/IRM and as Shiokawa et al. (2003) to show bi-directional field-aligned electrons observed by AMPTE/IRM possibly coming from the ionosphere and/or generated by magnetospheric Fermi acceleration.

DISCUSSION AND CONCLUSION

There were several lessons learned from my one-year stay at MPE which may be helpful for students and early-career scientists.

1. It is better to avoid taking the same research direction as other smart scientists.
2. It is better to take your class lectures more seriously when you are a student.
3. But, you can learn any time when you are interested in a topic. Maybe that is the best time to learn it.
4. It is better to choose an excellent team/institution when you go abroad for collaborative research. The team/institution should be slightly different from what you are currently doing to extend your research to wider fields.

The MPE team was the best team for me to start studying on the magnetospheric physics, that is, a well-organized database of AMPTE/IRM developed by Dr. Baumjohann and the AMPTE/IRM team and an excellent mentor Prof. Haerendel, who provided me background physics and indicated a new research direction. Actually, Dr. Vassilis Angelopoulos, who has been the principal investigator of the THEMIS mission, had also obtained his PhD in the study of bursty bulk flow in collaboration with MPE (e.g., Angelopoulos et al., 1992; Angelopoulos et al., 1994). These works were carried out just before my stay at MPE. MPE was an excellent institute where many active scientists from various countries joined and interacted with each other.

I sometimes remember the other possible choice to stay at the University of Colorado with Dr. Stan Solomon because my current research on ground-based measurements of airglow and aurora requires comparison with thermospheric modeling which Dr. Solomon developed. If I had had another chance to stay for 1 year abroad, I would have stayed at the University of Colorado to work with Dr. Solomon and his colleagues.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

KS contributed to the conception, design, and writing of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

The author’s research at MPE was supported by the Overseas Researcher Scholar (8-Wakate-70) of the Ministry of Education, Science, Sports and Culture, Japan.

ACKNOWLEDGMENTS

The author is grateful to the editorial board of the perspective article for the research topic “Generation-to-Generation Communications in Space Physics” for providing the opportunity to write the article. His work at MPE was supported by the Overseas Researcher Fund (Monbusho Zaigai Kenkyuin) of the Ministry of Education, Science, Sports and Culture, Japan. He also thanks all the MPE colleagues who supported him and made his stay in MPE enjoyable. Not only making the scientific research, but he also enjoyed playing soccer every Wednesday and Friday and sometimes playing tennis with Dr. Baumjohann. He joined a city table tennis club for which Thomas Bauer, his MPE colleague, introduced him, and made a lot of trips to Germany and other European countries every weekend with his wife, Miwa. The stay in Germany was really a memorable 1 year in his life.

REFERENCES

Angelopoulos, V., Baumjohann, W., Kennel, C. F., Coroniti, F. V., Kivelson, M. G., Pellat, R., et al. (1992). Bursty Bulk Flows in the Inner Central Plasma Sheet. *J. Geophys. Res.* 97, 4027–4039. doi:10.1029/91ja02701

Angelopoulos, V., Kennel, C. F., Coroniti, F. V., Pellat, R., Kivelson, M. G., Walker, R. J., et al. (1994). Statistical Characteristics of Bursty Bulk Flow Events. *J. Geophys. Res.* 99 (21), 21257–21280. doi:10.1029/94ja01263

Angelopoulos, V. (2008). The THEMIS Mission. *Space Sci. Rev.* 141, 5–34. doi:10.1007/s11214-008-9336-1

Baker, D. N., Pulkkinen, T. I., Angelopoulos, V., Baumjohann, W., and McPherron, R. L. (1996). Neural Line Model of Substorms: Past Results and Present View. *J. Geophys. Res.* 101 (12), 12,975–13,010. doi:10.1029/95ja03753

Baumjohann, W., Paschmann, G., and Cattell, C. A. (1989). Average Plasma Properties in the Central Plasma Sheet. *J. Geophys. Res.* 94, 6597–6606. doi:10.1029/ja094ia06p06597

Baumjohann, W., Paschmann, G., and Lühr, H. (1990). Characteristics of High-Speed Ion Flows in the Plasma Sheet. *J. Geophys. Res.* 95, 3801–3809. doi:10.1029/ja095ia04p03801

Baumjohann, W., Paschmann, G., Sckopke, N., Cattell, C. A., and Carlson, C. W. (1988). Average Ion Moments in the Plasma Sheet Boundary Layer. *J. Geophys. Res.* 93 (11), 11507–11520. doi:10.1029/ja093ia10p11507

Haerendel, G. (1992). “Disruption, Ballooning or Auroral Avalanche - on the Cause of Substorms,” in *Proc. Of the First International Conference on Substorms (ICS-1)* (Kiruna, Sweden: ESA), 417–420.

Haerendel, G. (1990). “Field-aligned Currents in the Earth’s Magnetosphere,” in *Physics of Magnetic Flux Ropes*. Editors C. T. Russell, E. R. Priest, and L. C. Lee (Washington, D. C: AGU), 58, 539–553. Geophys. Monogr.~Ser. doi:10.1029/gm058p0539

Hoshino, M., Mukai, T., Terasawa, T., and Shinohara, I. (2001). Suprathermal Electron Acceleration in Magnetic Reconnection. *J. Geophys. Res.* 106 (A11), 25979–25997. doi:10.1029/2001ja900052

Lui, A. T. Y. (2001). A Multiscale Model for Substorms. *Space Sci. Rev.* 95, 325–345. doi:10.1023/a:1005217304749

Lui, A. T. Y. (2015). “Magnetospheric Substorm Onset by Current Disruption Processes,” in *Auroral Dynamics and Space Weather: Understanding and Applications*. Editors Y. Zhang and L. J. Paxton (Washington, DC: American Geophysical Union). doi:10.1002/9781118978719.ch12

McPherron, R. L. (1995). “Magnetospheric Dynamics,” in *Introduction to Space Physics*. Editors M. G. Kivelson and C. T. Russell (Cambridge University Press), 400–458. doi:10.1017/9781139878296.014

Nagai, T., Fujimoto, M., Saito, Y., Machida, S., Terasawa, T., Nakamura, R., et al. (1998). Structure and Dynamics of Magnetic Reconnection for Substorm Onsets with Geotail Observations. *J. Geophys. Res.* 103 (97), 4419–4440. doi:10.1029/97ja02190

Nagai, T., and Shinohara, I. (2021). Dawn-dusk Confinement of Magnetotail Reconnection Site in the Near-Earth Magnetotail and its Implication for Depolarization and Substorm Current System. *J. Geophys. Res. Space Phys.* 126, e2021JA026691. doi:10.1029/2021ja029691

Nicholson, D. R. (1983). *Introduction to Plasma Theory*. New York: John Wiley & Sons.

Shiokawa, K., Baumjohann, W., and Haerendel, G. (1997). Braking of High-Speed Flows in the Near-Earth Tail. *Geophys. Res. Lett.* 24, 1179–1182. doi:10.1029/97gl01062

Shiokawa, K., Baumjohann, W., Haerendel, G., and Fukunishi, H. (2000). High- and Low-Altitude Observations of Adiabatic Parameters Associated with Auroral Electron Acceleration. *J. Geophys. Res.* 105, 2541–2550. doi:10.1029/1999ja900458

Shiokawa, K., Baumjohann, W., Haerendel, G., Paschmann, G., Fennell, J. F., Friis-Christensen, E., et al. (1998a). High-speed Ion Flow, Substorm Current Wedge, and Multiple Pi 2 Pulsations. *J. Geophys. Res.* 103, 4491–4507. doi:10.1029/97ja01680

Shiokawa, K., Baumjohann, W., and Paschmann, G. (2003). Bi-directional Electrons in the Near-Earth Plasma Sheet. *Ann. Geophys.* 21, 1497–1507. doi:10.5194/angeo-21-1497-2003

Shiokawa, K., and Fukunishi, H. (1990). "Dependences of Auroral 5577-A and 6300-A Emission Rates on Thermospheric Density Variations," in *Proc. NIPR Symposium on Coordinated Observations of the Ionosphere and the Magnetosphere in the Polar Regions* (Tokyo: National Institute of Polar Research NIPR), 3, 24–31.

Shiokawa, K., and Fukunishi, H. (1991). Global Characteristics of Field-Aligned Acceleration Processes Associated with Auroral Arcs. *J. Geomagn. geoelec* 43, 691–719. doi:10.5636/jgg.43.691

Shiokawa, K., Fukunishi, H., Yamagishi, H., Miyaoka, H., Fujii, R., and Tohyama, F. (1990a). Rocket Observation of the Magnetosphere-Ionosphere Coupling Processes in Quiet and Active Arcs. *J. Geophys. Res.* 95 (10), 10,679–10,686. doi:10.1029/ja095ia07p10679

Shiokawa, K., Haerendel, G., and Baumjohann, W. (1998b). Azimuthal Pressure Gradient as Driving Force of Substorm Currents. *Geophys. Res. Lett.* 25, 959–962. doi:10.1029/98gl00540

Shiokawa, K., and Yumoto, K. (1993). Global Characteristics of Particle Precipitation and Field-Aligned Electron Acceleration during Isolated Substorms. *J. Geophys. Res.* 98, 1359–1375. (Correction, J. Geophys. Res., 98, 9357-9362, 1993). doi:10.1029/92ja01092

Shiokawa, K., Katoh, Y., Satoh, M., Ejiri, M. K., Ogawa, T., Nakamura, T., et al. (1999). Development of Optical Mesosphere Thermosphere Imagers (OMTI). *Earth, Planets, and Space* 51, 887–896.

Solomon, S. C., Hays, P. B., and Abreu, V. J. (1988). The Auroral 6300 Å Emission: Observations and Modeling. *J. Geophys. Res.* 93 (A9), 9867–9882. doi:10.1029/JA093iA09p09867

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.