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Reflections by Bengt Ulf Östen Sonnerup

Bengt Sonnerup* *

Dartmouth College, Hanover, NH, United States

First, I will tell readers about memories of my graduate student days at Cornell. I will highlight some of my experiences there, and what I learned, and didn't learn from them. Then I will then discuss a few of the research topics I have been working on over the years, including data interpretation and the tools for it, with special emphasis on the magnetopause. Aspects of MHD shocks and other structures, including boundary layers, are among those topics. I will mention a few people with whom I have worked closely and a few famous individuals, who influenced me in a significant way. The presentation contains material of potential interest to new, as well as more seasoned workers in the field. It will not always be in time order.

Keywords: reconnection, upstream facing waves, shock waves, Hall effect, magnetopause

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****Correspondence:***
Bengt Sonnerup
bengt.u.o.sonnerup@dartmouth.edu

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1 AT CORNELL

My studies at the Graduate School of Aerospace Engineering at Cornell began in 1958. It was there that I first encountered magnetohydrodynamics and space plasma physics. The Aerospace faculty at that time, including my advisor W. R. Sears, had become intensely interested in MHD and were active in building the mathematical and experimental foundations of that discipline. I was swept up by their enthusiasm and have remained active in the field ever since, working on a variety of problems, a particular emphasis of mine being the outer boundary of Earth's magnetic field, the magnetopause. Over many years, I have tried, with variable success, to use basic plasma physics to explain spacecraft observations of the magnetopause, as well as of interplanetary boundaries and other structures.

As a graduate student, I was mostly working on terrestrial applications such as MHD power generation, because, at the time, hardly any *in-situ* spacecraft measurements were available. At a conference somewhere in Japan, Jim McCune, one of my teachers in the Aerospace School, was asked where the Cornell group's work on MHD wing theory could find applications. His reported response was: "Oh somewhere in outer space." A good prediction, it turns out.

One of the things I came to fully appreciate and love was the sublime beauty and tight intertwining of mathematics and physics.

A stark memory from graduate school was the PhD qualifying exam. At Cornell it was entirely oral. My committee consisted of my advisor, Bill Sears together with mathematics professor R. Agnew, and famous astrophysicist, Edwin E. Salpeter. Things went wrong right from the start. As always, Agnew brought along his dog, a large Collie. Salpeter commented that the dog must be very smart after attending all those math classes. To this Sears responded that he knew about dogs and that they were stupid. He quickly realized that Agnew became insulted and tried to improve the situation by saying "now I have insulted his dog and he will flunk my candidate." It probably did not help, and it augmented my sense of doom. The next disaster followed in short order. Salpeter started to ask me questions about the Mössbauer effect, for which the Nobel prize had just been awarded. But he led me through the discussion in a friendly manner. Afterwards, I asked him why he had asked such a question of a low-level mechanical engineer. His response was: "I had already decided to pass you so I thought I could have a bit of fun." But I myself had difficulty appreciating the fun of it. Since then, I have come to feel that faculty should challenge their students but be careful to not torment them.

Here is another memory: Theodore von Kàrmàn, of vortex street fame, was the mentor of Bill Sears at Cal Tech. This world-famous Hungarian had been invited to spend the Spring term of 1960 at the Aero-School and we, the graduate students were lined up to be introduced to him, one by one. Von Kàrmàn was 79 at the time and rather deaf. When it was my turn, I said something respectful and polite. He paid no attention but said to Sears in a loud voice: "What language does he speak?" The response was quick: "Same as you, broken English." (At Caltech von Kàrmàn had confounded his students by using the European pronunciation of chaos, which sounds like cows.)

In my last year at Cornell, I was a postdoc with Austrian physicist Tommy Gold, who had been hired as director of the new Arecibo Observatory, the brainchild of EE professor William Gordon. One of the EE graduate students at Cornell, who helped design the Arecibo antenna feed, was a friend of mine, Thomas Laaspere, who then arranged for me to come to Dartmouth, where he, and Millett Morgan (of whistler fame) served as my mentors.

Tommy Gold was fun and friendly, and a great alpine skier who, quite erroneously, claimed that cross country skiing was a dying sport. But he was right in his very early prediction of Earth's bow shock. And I am very grateful that, in 1962, he arranged a job for me at Hannes Alfvén's laboratory at KTH in Stockholm.

As it turned out, I left KTH for Dartmouth after only a couple of years. Hannes and I had irreconcilable disagreements over the reality and importance of magnetic reconnection. On my end, I had become convinced that Tommy Gold's comment was correct: "Reconnection must happen, and at a substantial rate, otherwise the interplanetary magnetic field would become hopelessly entangled." I don't think Hannes ever came to agree with that.

It was at Cornell that I first met Ian Axford and developed awe for his work with Colin Axford and Hines (1961) on the global plasma circulation and currents in the magnetosphere. I did not meet Carl Sagan, who was almost never on campus, and not Vladimir Nabokov, who gave lectures about the writing of Lolita, to overflow audiences.

My MS thesis at Cornell was concerned with Hall effects in MHD flow past a wavy wall. It became my first publication (Sonnerup, 1961). To my knowledge it has seldom, if ever, been cited but was a precursor to my later work on the Hall effect in magnetic reconnection (Sonnerup, 1979).

There were memorable papers by Sears and coworkers (1961, 1964), in which they demonstrated the possibility of upstream-facing standing waves in compressible MHD. Many features of such flows remain unexplored, both theoretically and in spacecraft observations. With the high precision and time resolution provided by MMS, the search for such forward facing waves could be a rewarding one. More details will be given in **Section 4**.

But first, I want to make a brief jump back in time to my high school days in the forties in Malmö, Sweden. There, a very special mathematics teacher taught his students something important, in addition to mathematics. He would ask us to solve geometry problems on the blackboard. If you just stood there doing nothing, he would get upset, where he stood right behind you. At the peril of a sharp rap on the posterior from his pointer, he would urge you to do something, for example, draw a help line. It might not solve the problem but thinking about why it didn't was, he knew, an effective way to figure out a useful next move. His approach has been a great help to me, not only in geometry but in all sorts of problems encountered in life. The message from him was clear: Get on with that first step.

2 MHD SHOCK WAVES

My interest in shock waves was spurred by two facts. The first of these was the paper by Petschek (1964), in which the concept of standing waves associated with reconnection at the magnetopause was first proposed. It was followed by a, now mostly forgotten, but perfectly beautiful, comprehensive, article on MHD waves by Kantrowitz and Petschek (1966). There was also the seminal work of Levy et al. (1964) on magnetopause reconnection in the limit of zero magnetospheric plasma pressure.

The second fact was the arrival in 1988 of Lin-Ni Hau as my postdoctoral coworker. Her studies of MHD shock structures, including Hall effects (Hau and Sonnerup, 1989, 1990), are beautiful, even unique. In her work, ordinary gas-dynamic shocks allow abrupt transfer of the MHD shock structure from a supersonic upstream portion, located on one Riemann sheet, to subsonic conditions on a downstream sheet. Samples of her shock work can be found in **Figure 1B**. She is now a renowned professor at the National Central University in Taiwan.

3 DATA INTERPRETATION

My first encounter with spacecraft data, occurred in collaboration with Larry Cahill, who was then at the UNH in Durham. We used his magnetic field data from Explorer 12 to try to determine the sign and magnitude of the field component perpendicular to the magnetopause. The use of model normal vectors failed completely, which led us to seek for a direction in which that component was as constant as the data would permit. The resulting analysis process became known as magnetic variance analysis or MVAB (Sonnerup et al., 2010). This method is still in common use. But it has proved very difficult to obtain reliable results, a curse caused by eigenvalue degeneracy in combination with the very small value of the field component along the normal.

What my work with Cahill did was to get me deeply involved in developing and using data analysis methods. By far, my most extensive collaboration has been with Goetz Paschmann at the Max-Planck Institute for Extraterrestrial Physics (MPE) in Garching. Our collaboration tended to work this way: Goetz would look at a large data base and identify features that were mysterious and promised to give new insights. I would suggest

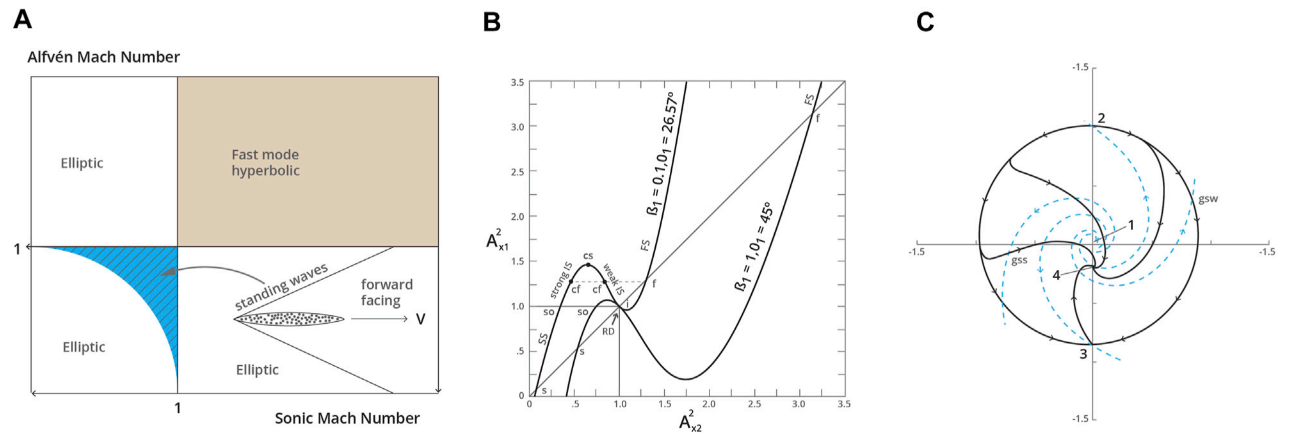

FIGURE 1 | Standing waves and shocks in MHD: **(A)** Standing upstream-facing slow mode waves in blue shaded region; **(B)** Slow, intermediate, and fast shock wave jump properties from upstream (1) to downstream (2) conditions; angle θ_1, is between shock normal and upstream magnetic field **(C)** Example of predicted magnetic hodogram for a shock structure.

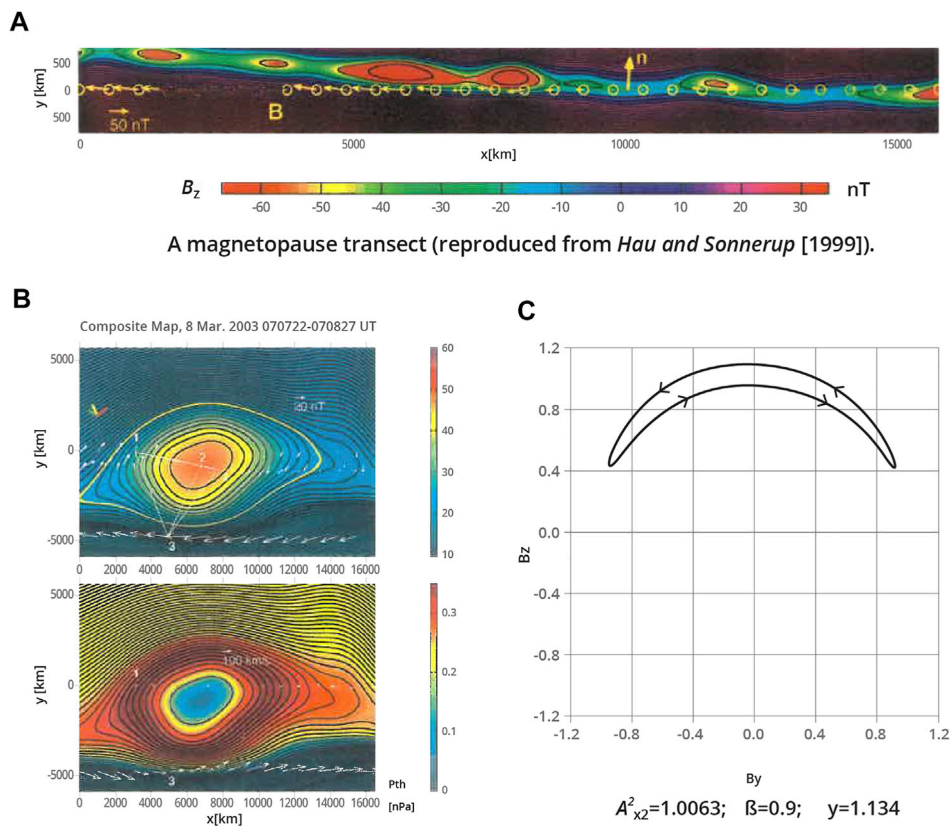

FIGURE 2 | Reconstruction: **(A)** Nearly tangential discontinuity behavior seen by AMPTE at the magnetopause; **(B)** Field and plasma pressure in a "Flux transfer" event. **(C)** Back and forth motion of the field in arc-polarized waves.

various interpretations and then try to do some mathematical analysis to quantify them. Our cooperation started in 1979 and has been extremely fruitful until the present, with some allowance for my old age failings. What I want to highlight is that having a skillful coworker is a tremendous boon. I have been in great luck about that, with students as well as seasoned scientists.

I only had a small number of graduate students here at Dartmouth; among them were Tai Phan, Sasha Khrabrov, Dave Walthour, and Qiang Hu. All have done theoretically based data interpretation work of exceptional quality.

My most influential collaboration here at Dartmouth was with Lin-Ni Hau. One of the most successful projects was the development and use of software to reconstruct field structures, observed during the flight pass of a spacecraft through them or near them. The method was originally based on the Grad Shafranov equation, as discussed by Sonnerup and Guo (1996). Examples of such reconstructions at the magnetopause are shown in **Figures 2A,B**. It has been greatly generalized since then and now involves direct integration of various versions of the ion and electron equations of motion. Applications involving electron dynamics are given by Sonnerup et al. (2016) and by Hasegawa et al. (2017).

In joint work (Sonnerup et al., 2010), Stein, Goetz, and I presented theoretical analysis of ark-polarized structures in the solar wind, such as observed by Bruce Tsurutani, and others. Our analysis incorporated plasma compressibility as well as electron and ion inertia. As shown in **Figure 2C**, it accounts for the back-and-forth motion of the field seen in such structures.

At MPE, I also had wonderful collaboration with Iannis Papamastorakis, leading to new findings about the convection electric field. With Stein Haaland and a group of others, I also participated in a comparison of results from single- and multi-spacecraft measurements concerning magnetopause orientation, motion, and thickness.

4 THE WAVY WALL PROBLEM

The first problem I was exposed to at Cornell was the analysis of waves generated by MHD flow past an impenetrable wavy wall. Such flows remain incompletely studied, both theoretically and observationally. **Figure 1A** shows a diagram of the Alfvén-Mach number M_A, here denoted simply by A, versus ordinary sonic Mach number, $M_s = M$ for such flows, developed by Sears and coworkers [see for example, the papers by McCune and Resler (1960) and Sears (1961)]. The region of interest is shaded blue in **Figure 1A**. In this diagram of A versus M, it is bounded by the two lines $A = 1$ and $M = 1$, and a circular arc from $A = 1, M = 0$ to $A = 0, M = 1$. In that small region upstream-facing, rather than downstream-facing, standing waves are predicted. To my knowledge, such remarkable and unexpected wave orientations have yet to be observed. With the high precision and time resolution provided by MMS, the hunt for them should be a rewarding one. Old age slows us all down, but I am still tempted to join the hunt.

5 MORE COWORKERS

Over the years, I have had good and useful working relations with many researchers. Included are some of my former and present colleagues at Dartmouth, especially Richard Denton. He taught me the extreme importance of asking persistent probing questions. My engineering colleague, Bill Lotko, whose understanding of, and ability to mathematically describe, the entire dynamic magnetospheric system were indispensable in our collaboration. In the sixties, I also worked on magnetic field annihilation with solar physicist Eric Priest.

I have worked with a group of scientists at the Mission Research Corporation, with a branch located in Nashua, NH and headed by Willard W. White. The group included George Siscoe, Nelson Maynard, Keith Siebert, Dan Weimer and others. George Siscoe, who passed away in April of 2022, was an inspiring teacher and mentor of students. He was a soft-spoken intellectual leader, whose work will have lasting impact on our field. He was a gentle soul and a dear friend.

At MPE, I primarily worked with Goetz Paschmann. But I also collaborated, with and befriended, Norbert Schkopke, Wolfgang Baumjohann and Rumi Nakamura, Chuck Carlson (visiting from Berkeley), and many others. At ISSI, it was great to interact with its founder, Johannes Geiss, and co-director, Rudi von Steiger, and with many science visitors to the Institute, some of them well-established or famous, like Rudolf Treumann, others being in earlier stages of their careers.

Among the many people I met at MPE, there were two individuals in addition to Paschmann, who had a strong, albeit more indirect, influence on my development as a scientist.

The first was Reimar Lüst, the founder of MPE. He went on to become president of the entire Max-Planck Society, then director general of ESA. He was the founder and president of the private Jakobs Universität in Bremen. He later became president of the Alexander von Humboldt Foundation, which funded my 9-month stay in Garching and in Bern in 2001–2002.

He second was Gerhard Haerendel. He was a director at MPE and enabled my many visits to the institute. Later, he served as the Dean of Faculty at the Jakobs Universität, before returning to Garching and retirement. Gerhard and I shared a love of Mozart's opera The Magic Flute.

Among the scientists I interacted with were many who are still active, working with data from Cluster, MMS, and other missions. One notable among those individuals is Chris Russell. Here is an old but acute memory I have of him. He was a coauthor on the MPE paper (Paschmann et al., 1979) about the first *in-situ* observations, "the smoking gun evidence", of reconnection at the magnetopause. When we sent him a draft, his prompt, salt-of-the-earth, response was: "This paper starts with a roar and ends with a whimper." Of course, we then did work to remove the whimper part. A bit later on, the MPE based team pursued the reconnection topic in further detail (Sonnerup et al., 1981).

6 CLOSING REMARK

I have had good relations with most people I interacted with in science, even during my period as JGR editor (1981–84). But at that time, as well as both earlier and later, I also encountered people exhibiting what I refer to as the "barracuda syndrome," ranging from simple passive-reactive to outright aggressive behavior, which included an unsuccessful effort to get me fired. But being editor also has many attractive features: It is a great service to the research community, and the editor learns a great deal about the wide activities and personalities of workers in the field. If the opportunity arises, my advice is to give it serious thought.

This account of my thoughts and reflections about space physics would be incomplete without mention of Vytenis Vasyliunas, whose awe-inspiring insights into global heliospheric physics remain difficult to match, and whose organ concerts in church were high points at many science meetings.

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

The author confirms being the sole contributor of this work and has approved it for publication.

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