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Perspective Article for the Research Topic “Generation-to-Generation Communications in Space Physics” Find Fun and Joy in what You Do

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Reflections on career choices and career highlights, including scientific discovery, innovation, and friendships. Some advice to younger generations is offered.

Keywords: magnetosphere (magnetosphere-ionosphere interactions; plasma convection), ionosphere (2487 wave propagation), polar instrumentation, magnetospheric su, magnetic storm and substorm

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1 WHAT PATH TO TAKE?

As I think back, some of the first and best advice that I received was from my high school self as I was thinking about what I would do with my life. The advice was to pick something for a vocation that you really like, because you will be spending a large part of your life doing that. Along the same lines I remember talking only a few years ago with my colleague and good friend Eigil Friis-Christensen about our work and he said something like. “. . . .of course, why would you work on something if it was not fun”. Little did my high school self foresee my fortunate choices and resulting career in space physics. My path was not a planned route. Opportunities that were interesting presented themselves and I followed. I have enjoyed it and it has been fun—mostly. Of course, all paths are fraught with adversity somewhere along the way, but the wonderful friendships, fun and excitement in discovery have outweighed all of the difficulties.

As an undergraduate in physics, I was too distracted by the math that I did not really comprehend the physics as well as I should, I now believe in looking back. I was focused on learning equations rather than principles. I am not good at memorization, yet I tried to memorize equations for the types of problems, rather than building an equation to specify the conditions of the physics problem under consideration. It was not until graduate school that I matured enough to begin to learn the physics, and I believe that it was due to the style of teaching that I encountered at UCLA that enabled me to do this. Ferd Coroniti, for example would present problems, then work out an estimate of the details based on “back of the envelope” calculations. Each of these exercises presented the essential physics without obscuring it with complex equations. Paul Coleman’s course “Coleman Club” generally consisted of having each student go to the board and then try to work out a problem that he presented. His Socratic questioning and insights from the other students in the class were foundational in developing a deeper understanding of the physics of the systems under consideration. I enjoyed space science enormously because it was essentially 19th century physics (mostly electricity and magnetism) applied to new and interesting environments. Certainly there was the need for relativistic physics for some of the high energy environments, but it was not required for most of the basic magnetospheric physics that I was learning. My advisor, Bob McPherron was perhaps the most influential person in my education. His clear presentations of physics developed my intuitive understanding and then with time, my math abilities followed -- at least sufficient math ability to have a successful career as an experimental space physicist and data analyst—and to pass the exams. I also developed an appreciation for the breadth of science and it is my opinion that everyone has specific talents that they can apply to advance science. I am not a mathematical or theoretical genius, but I do have skills that can advance our understanding of magnetospheric physics, as do the many students that I have had the pleasure to mentor. Science is large and everyone can have a place and enjoy the excitement of scientific discovery.

At UCLA we had to pass three oral exams. The first was the field oral where a committee essentially asked questions until they found something that you did not know, then watched you try to figure it out. It was Coleman Club on steroids. That was the main hurdle. Following that was the qualifying exam where you presented your thesis topic and some preliminary work as well as a plan to complete the work, and then finally the dissertation defense. My preparation for the field oral was aided by working with other students who were also preparing, Howard Singer in particular. I also owe a great deal of appreciation to Chris Russell who generally came back to the lab after dinner to work late into the evening. He would often come down to where we were studying and begin to quiz us at the board with various problems. It was extremely good practice and also, for me, another learning experience where I developed a deeper understanding of the physics of the magnetosphere. Chris was a great mentor, and I have observed that his deep insight usually brought him to the successful side of resolving the various controversies that abounded in magnetospheric physics at the time. I also have to mention Ray Walker who also became a good friend and mentor.

It was an exciting time to be at UCLA during 1970—1980. Most of the discoveries (solar wind, radiation belts, plasmasphere, magnetotail, etc.,) had been made, and now was the period of trying to understand the dynamics of the systems. Several fundamental concepts were confirmed while I was a student and it was tremendously exciting to be at the cutting edge of this knowledge development. There is also joy in observing something or recognizing for the first time, "Oh, this is something new. I wonder what that is all about?" Of course, the magnetospheric substorm and substorm growth phase was central to being McPherron's student and being at UCLA. It was there that I observed that scientific argument does not always remain objective, but can become personal. That is a sad and unfortunate aspect of human behavior. It does not need to be this way, and I observed quite the opposite at the University of Michigan where different opinions on ring current development were appreciated and it was a happy and exciting effort to explore and determine the solution that best fit the observations. This was also the case for the development of the BATS-R-US space plasma simulation code which was a newly developed adaptive MHD code built from the ground up to work on massively parallel computers. BATS-R-US was the new kid on the block, and there were many challenges and criticisms leveled at the code. Each was taken seriously and explored and the results reported at the next scientific meeting. The result of this scrutiny is that the code is now considered one of the best and most flexible codes in the community.

2 THE PATH CHOSEN AND THE FUN FOLLOWS

It was a very exciting time to be at UCLA during the seventies. Large new ideas were developing through the close cooperative activities between great experimentalists like Bob McPherron and Chris Russell and theoreticians like Margaret Kivelson, Ferd Coroniti, and George Siscoe. In addition, the list of people who visited UCLA for extended periods was also impressive. A tight bond seemed to develop between UCLA and Imperial College and Jim Dungey and David Southwood were frequent visitors. The idea of magnetic merging between the interplanetary magnetic field and magnetosphere was being examined now closely since Dungey's 1961 paper described the cycle of energy flow. McPherron's growth phase ideas were developing along these lines with the southward turning of the interplanetary magnetic field (IMF) leading to dayside reconnection and the transport of flux to the tail and then the sudden release of the accumulated magnetic energy in the stretched field of the tail lobes during the expansion phase of the substorm initiated by a new near-Earth magnetic merging site. It was particularly exciting when an event study was completed that showed an inbound satellite on the dayside during a time when the IMF turned southward and the magnetopause was observed over and over as the satellite moved inward toward the Earth. Simultaneously during this observed magnetopause erosion, a satellite in the tail lobes observed an increase in the lobe field and high latitude ground observations showed an enhanced quiet time ionospheric convection system that supported the hypothesis of increased flow of energy from the dayside to the night side during this "growth phase" period (McPherron et al., 1973).

I remember another new exciting discovery made by a visiting scientist, Torbjorn Pytte. At that time, the idea of a magnetic storm was Sydney Chapman's view that a storm consisted of a continuous sequence of closely spaced substorms. Pytte studied several storm time sequences that were characterized by extended long periods of southward IMF, strong continuous auroral and magnetic activity, but seemed to lack the characteristic signatures of individual substorm expansions (Pytte et al., 1978). This research indicated that during a long sustained period of southward IMF the tail rate of merging could adjust to match the enhanced dayside merging rate and the entire magnetosphere would operate at an enhanced rate of convection without flux accumulation in the tail. These periods were called convection bays after the observed high latitude magnetic signatures from ground auroral zone magnetic observatories.

3 DISCOVERIES

It is a remarkable feeling to be part of a team that discovers something new. As a young scientist at my first job at Stanford, following graduate school I worked with John Wilcox and the solar group investigating sun-weather relationships. This was entirely new territory for me and I met some extremely interesting people engaged in this speculation that a statistical link could be found between solar variability and weather or climate variability. Among these was Jack Eddy, who is known for his studies of sun spots and the identification of the Maunder Minimum, a 70-year period of low auroral and geomagnetic activity associated with no sunspot activity. In 1987 Eddy was awarded the Arctowski Medal by the National Academy of Sciences for “studies in solar physics and solar-terrestrial relationships and specifically for his demonstration of the existence and nature of solar variations of long term and the consequences of these changes for climate and mankind.”

I worked with Wilcox for about 2 years investigating sun-weather relationships, but joined a new research group formed by Peter Banks when he moved to Stanford. With Peter, I was able to initiate a new research program focused on the day side of the Earth to examine the solar wind interaction with the Earth’s magnetic field more directly, and I was much more interested in this line of investigation. There, I was able to meet new friends, make new measurements for the first time at the intersection of the day-side magnetic field with the ionosphere and discover new phenomena. The focus on the day side of the Earth where the solar wind first encounters the magnetosphere was extremely exciting and learning to utilize the incoherent scatter radar recently relocated to Sondre Stromfjord, Greenland was like a fresh breeze in my sails. My previous graduate school research had been directed toward substorms and to the development of the ring current, where there are various intervening processes that occur between the solar wind coupling on the dayside and the transport of energy and momentum through the magnetosphere to the substorm or ring current phenomena being investigated. The observations in the dayside ionosphere were quite different because the reaction to a change in the solar wind IMF is seen immediately in the variability of the dayside ionospheric electric field and resulting ionospheric plasma convection (Banks et al., 1984; Clauer et al., 1984; Jorgensen et al., 1984; Clauer and Banks, 1986).

I enjoyed many years of research centered around the Sondrestrom radar, investigating the high latitude electric field and current systems. The west coast Greenland chain of magnetometer measurements provides a powerful tool when combined with the electric field measurements from the radar to examine the high latitude electrodynamics. The large scale DPY and DPZ current systems were examined as they developed in response to changes in the IMF By and Bz components (Banks et al., 1984; Clauer and Banks, 1986). The convection reversal boundary was examined and observed to have both stable and unstable wave-like motions that also were associated with magnetic waves (McHenry et al., 1990; Clauer 2003). It appears that as the dayside ionospheric flows increase, particularly in response to stronger IMF By component, the ionospheric convection reversal boundary shows wave-like behavior that is speculated to be the signature of a flow instability like the Kelvin-Helmholtz instability (Clauer and Ridley, 1995; Ridley and Clauer, 1996; Clauer et al., 1997). However, this flow instability is being generated within the magnetosphere between the tailward and return convection flow. I think that this is a new and exciting discovery that has not yet been explored fully.

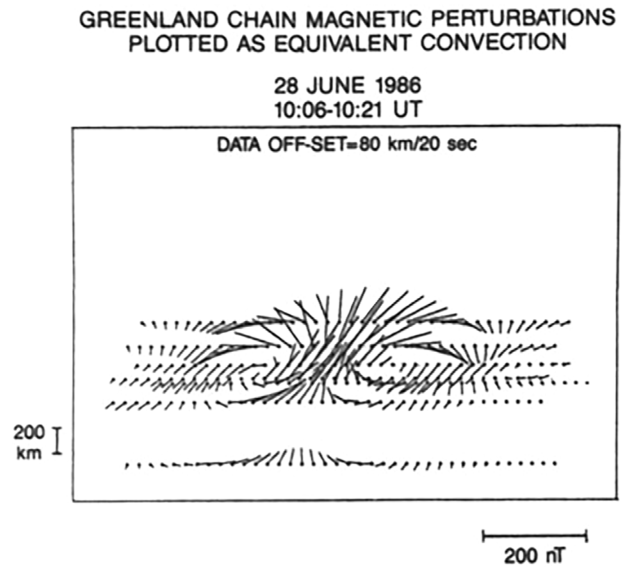

FIGURE 1 | Horizontal magnetic perturbation vectors rotated counter-clockwise and offset by a distance equivalent to 80 km/20 s shown on a geographic spatial coordinate system. (Friis-Christensen et al., 1988).

At the time that my student Mark McHenry and I were investigating the convection reversal boundary, Eigil Friis-Christensen came to Stanford to work with me for about 9 months with the idea to really examine some unusual magnetic impulse events observed in the Greenland magnetometer data. A great deal of attention has been devoted to these phenomena with the initial speculation that they might be the ionospheric signatures of flux transfer events described by Russell and Elphic (1979). Looking at the horizontal magnetic perturbation vectors, they appeared to point toward or away from a point that seemed to move across the Greenland magnetometer chain. Using the more extended array including the east coast stations showed that they were moving east or west roughly away from local noon. This did not support the flux transfer hypothesis in which the disturbance should move poleward or northward rather than in an east-west direction.

It was with the discovery of these magnetic impulse events that I learned the power and art of displaying the data in effective and creative ways. The idea to create a new display of the Greenland data was given to Eigil by Karl-Heinz Glassmeier during a boat ride at the Vancouver IUGG meeting. The horizontal vectors were rotated to be in the direction of the ionospheric F-region plasma convection (opposite to the Hall current direction), and then plotted on a single plot, but each set of measurements offset by a distance determined by the velocity at each measurement interval. The result shown in **Figure 1** was dramatic and made the cover of Geophysical Research Letters when we published (Friis-

Christensen et al., 1988). I was particularly amazed with near perfect organization of the display because it was produced by data and not the result of a model output.

The figure was an epiphany. At the center of each vortex must be a magnetic field-aligned current, in this case, downward in the left vortex and upward in the right (or leading) vortex with a corresponding horizontal ionospheric electric field outward or inward to the vortex center driving a corresponding circular Hall current that produced the magnetic perturbations. These field-aligned currents would map to the outer magnetosphere and were produced by waves on or near the magnetospheric boundary caused by sudden solar wind pressure pulses. These ideas were all later verified by further investigations by many investigators. The deformations in the magnetopause produced by the pressure changes propagated tailward and this was electrodynamically coupled to the ionosphere by field-aligned currents. What an exciting discovery of this direct electrodynamic linkage. These studies further enhanced our investigation of the ionospheric convection reversal boundary because when the reversal boundary became unstable with waves, a similar display of the magnetometer data showed a series of vortices produced by field-aligned currents inward and outward mapping the waves generated at the velocity shear in the outer magnetosphere to the ionosphere.

Since these were propagating structures across Greenland they were occasionally observed in the west coast magnetometers and then later in the east coast magnetometers, but not always. The impulses evolved and changed as they moved across Greenland and this was the motivation to deploy a temporary array of autonomous magnetometer stations near the center of Greenland on the Greenland Ice cap. This was really my start in developing and operating remote autonomous magnetometer arrays and it has been a fun and rewarding activity. It was exciting living in a tent at the Greenland summit and using snow mobile traverses to travel across the ice cap to set up the stations. One of my intense memories is returning to the summit station from a traverse and seeing my first ever mirage. The station was clear as ever but inverted upside down above the horizon where the station was actually sitting. I do not quite understand the optical atmospheric conditions to produce this, but it was remarkable. However, over the years, the array was tedious to maintain because the stations had to be visited each year to download data which was stored in local memory. After a sufficient period of operation, we closed the project and removed the stations from Greenland.

When I moved to Virginia Tech I had the opportunity to develop a new generation of remote measurement system that could be deployed in the Antarctic at extremely remote locations. These systems had to be able to operate unattended for many years and therefore required satellite communication links that were now available through the Iridium satellite network. This led to a new, more robust system that utilized instruments that met lower power requirements (Clauer et al., 2014). The fluxgate magnetometer was developed by Valery Korepanov at the Lviv Center of the Institute for Space Research in the Ukraine. It is an excellent low power instrument. We also added a low power induction magnetometer built by Marc Lessard at the University of New Hampshire, a new and innovative dual frequency GPS receiver developed by Geoff Crowley and his ASTRA research enterprise. The new system was also improved to allow installation without removing gloves. Nuts and bolts are no longer used to attach sections of the tower. Special push pins replaced the bolts, and the battery harness to connect the 16 batteries in parallel was built with snap connectors that could be installed simply and only in the correct way. I am quite proud of this project and achievement. At the time of this writing, the first station installed on the East Antarctic Plateau has been operating successfully for 14 years. The chain established on the East Antarctic Plateau is magnetically conjugate to the chain of magnetometers along the west coast of Greenland and enables the simultaneous measurement of high latitude phenomena in both hemispheres. The Antarctic stations are the next step taken to improve our understanding of the complete coupled system. Data from the Greenland and Antarctic chains are being utilized to investig and the impacts of the seasonal and field asymmetries that exist between hemispheres as they couple with the solar wind and each other.

What a wonderful group of people with whom I have been able to share my existence. All of us watching, examining and thinking about a particular aspect of the world around us, excited when we find some new feature or behavior and getting together to report and discuss our fascination and improve our understanding. It has been rewarding and exciting to be near the formation of new technologies that could be utilized to extend and improve our measurements and understanding.

I enjoy watching the world around me, particularly nature and animal behavior. I have spent many happy hours sitting with my wife Susan on a cliff on Santa Barbara Island off of Los Angeles, watching sea lions and elephant seals. I have enjoyed sitting on the porch of a hut next to a water hole on an African game reserve vacation watching all of the animal activity. And I have enjoyed a career of watching the solar wind interact with the Earth's magnetic field to produce some of the most wonderous phenomena like the aurora, geomagnetic variations, radiation belts and the ring current. Science has given me the tools to organize the observations to develop a deeper understanding and a community who delight and enjoy the discussion and debate over the meaning of our observations and ideas. Indeed, I did find a vocation that I liked and my advice and hope for everyone is that they, also, can find such a happy and fulfilling path in their life.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://mist.nianet.org.

AUTHOR CONTRIBUTIONS

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

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