

# Perspectives of Earth and Space Scientists



## RESEARCH ARTICLE

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## Tools for the Long Run

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### Key Points:

- Science understanding can take years or even a whole career to coalesce
- A career is driven by what you do with the opportunities that come your way
- Important contributions to science can be made through both research and supporting activities that enable research

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**Abstract** The first discovery of the space age was in the field of *space physics* and occurred with the Explorer 1 launch in 1958 and its observations of the radiation belts encircling Earth. *Space physics* remained a young science into 1981 when I started graduate school, so young that there were no comprehensive textbooks on the subject. It evolved quickly with missions such as Voyager, Interplanetary Monitoring Platform-8, Hawkeye, Active-Magnetospheric-Particle-Tracer-Experiment, and ISEE in the early years. The International Solar Terrestrial Physics mission focused part of solar and *space physics* into Sun-Earth-Connections (SECs) to understand the chain of events in the Sun-Earth system. Heliophysics was an extension and evolution of SEC, combining all of solar and *space physics*, maturing the whole and the individual parts into an established science.

**Plain Language Summary** This paper tells the story of how my career paralleled the evolution of *Space Physics* from an emerging field at the dawn of the space age to the comprehensive, complicated, connected system we know today.

## 1. Problems and Methods and Data

I joined Tom Armstrong's group at Kansas University in January 1981 just two months after Voyager-1 had its closest approach to Saturn, after launching in September 1977 and flying by Jupiter a year and a half later in March 1979, returning the very first close up pictures of the planets. Voyager-2 launched 16 days before Voyager-1 in August 1977 and passed by Jupiter in July 1979. Voyager-2 would go on to Saturn (August 1981), Uranus (January 1986) and Neptune (August 1989), flying by all the gas giants over the course of 10 years.

Not for another 175 years would the outer planets—Jupiter, Saturn, Uranus, and Neptune—be aligned such that a single spacecraft could glide by each of them in quick succession (Flandro, 1966). Never before were there dazzling up close pictures of the gas giants, nor measurements that would lead to understanding that all of the gas giants had magnetospheres, that Jupiter's was larger than the Sun and Uranus' was tipped 90° away from the others into the ecliptic plane.

Tom a.k.a. TPA was a co-Investigator on Voyager and supported both graduate and undergraduate students in processing and analyzing data from the Voyager Low Energy Charged Particle Instrument. Being a co-I he was well-supplied with glossy pictures of Jupiter and Saturn, with stickers and buttons and pins, all of which he passed on to his students. As a recruitment and retention strategy in those early days, it worked exceptionally well.

Voyager was his most exciting mission, but there was also the Interplanetary Monitoring Platform (IMP-8 or Explorer 50) and a spacecraft charging project with the NASA Lewis Research Center. He placed graduate students in each of the projects as a sequential stream. Students benefitted from the work of those before them and in turn contributed to those behind. TPA shepherded more than 50 PhD and MS students through their degrees in those and later projects.

1981 was still early days for *Space Physics*—we didn't have a comprehensive text book though there were a few topical books (e.g., Schulz & Lanzerotti, 1974). We used TPA's notes as our guide. We focused on data analysis and computer modeling. We talked about exotic topics like reconnection and shock physics—the excitement around the science was intoxicating; the science seemed as limitless as space itself.

I got pulled into the spacecraft charging project soon after coming onboard because two graduate students within the project were just completing their PhD projects. They overlapped with me for about 8 months and left behind a cylindrical particle-in-cell (PIC) simulation code applicable to plasma conditions in low earth orbit (LEO). We had access to a CRAY-1 computer from the United Telecom's Computer Service Group in Kansas City which



**Figure 1.** Mona Kessel and Tom Armstrong a.k.a. TPA at the University of Kansas, Lawrence, KS, in 1986.

allowed the PIC simulations to be run in about a day compared to the weeks it would have taken on the VAX 11–750 computer in TPA's group.

Although I worked on this project for a couple of years while taking graduate classes and even published in the *Journal of Applied Physics* (Brandon et al., 1984; Kessel et al., 1985), I was drawn to understanding the space environment itself, rather than effects of the environment on spacecraft. Understanding *space physics* was where the excitement was and where I wanted to be. At the time I didn't know or appreciate that each new research topic and method learned would contribute to an overall understanding that would take a career to coalesce.

I petitioned TPA for a new thesis project and he suggested particle energization at interplanetary shocks, following in the footsteps of Gloria Chen and Rob Decker. The data for this project came from IMP-8, a spacecraft launched in 1973 into a nearly circular orbit around Earth, spending slightly more than half its time in the solar wind. I identified interplanetary shocks by using *published* Sudden Storm Commencement times and then finding corresponding evidence for a shock in the IMP-8 data.

A significant jump in magnetic field, plasma density and plasma velocity between the upstream and downstream regions signified a shock. We assumed the shock was locally planar but needed to establish its orientation which boiled down to finding the shock normal direction and the angle between

that normal and the upstream magnetic field,  $\theta_{Bn}$ . I used three different methods: Vinas and Scudder (1985), Lepping and Argentiero (1971), and coplanarity; coding each method for my own use from the reports and papers describing the techniques.

In the process I found another instructive paper with a droll title that was an invaluable reference given the available data: *Interpretation of Inaccurate, Insufficient and Inconsistent Data* (Jackson, 1972). Magnetic field data were typically higher time resolution than plasma data because the latter were constructed from measurements taken during one or more complete spins of the spacecraft while the former were a series of single measurements. For the research I used 15.36-s resolution magnetic field data supplied by the NASA Goddard Space Flight Center (GSFC) Magnetic Field Experiment. The plasma density and velocity came from OMNI (essentially IMP-8) data at 5-min resolution. There were gaps in both of the data sets which had to be merged onto a common time line to find  $\theta_{Bn}$ .

Using the shock geometry determined from these observed parameters, I investigated whether shock drift acceleration was a viable method for energizing protons that encountered interplanetary shocks. Applied Physics Lab's Charged Particle Measurement Experiment (CPME) on IMP-8 provided the data, specifically the lowest energy proton channel, P1 (0.29–0.5 MeV). The detector had an aperture of 45° and returned data in eight conical sectors while spinning in the ecliptic plane and covering the full 360°.

Starting with particle trajectories calculated from the orientation of the CPME detector, a time-reversed computer simulation followed an ensemble of *test* particles through a single complete interaction with the shock in order to predict flux enhancements in the eight sectors of P1. In spite of the simplicity of the shock model used and the low resolution of the available data, I was able to roughly reproduce the observed angular distributions in sectors that interacted with *quasi-perpendicular* shocks,  $\theta_{Bn} > 45^\circ$  (Kessel, 1986, 1988).

PIC simulations, shock normal determinations, Monte Carlo techniques, particle-shock interaction simulations, coordinate system transformations—there was an arsenal of computer techniques and codes developed during graduate school. I also gleaned a basic understanding of *space physics* concepts and an appreciation for spacecraft data. Joe Giacalone came to KU in my last few months; he would be the next in line to study shock physics, followed by Juan Gomez half a dozen years later. After I cajoled TPA into letting me title my thesis “Gone with the *Solar Wind*,” I wore a black velvet period dress with a bustle and white gloves to defend it in 1986 (Figure 1).

At the Mullard Space Science Laboratory as a post-doc, the focus was on spacecraft hardware, instruments and missions from the European Space Agency, sometimes in collaboration with NASA. Alan Johnstone was the

head of the group and he was particularly good at framing mission concepts for success. His secrets were to put together technically convincing and politically persuasive teams and always have an elevator speech on hand to use when circumstances warranted, like standing next to someone from a funding agency.

Alan had proposed for and won the ion instrument on the United Kingdom Subsatellite (UKS) for the Active-Magnetospheric-Particle-Tracer-Experiment (AMPTE), a set of three spacecraft that had launched together on a NASA rocket in 1984. The primary mission was for the Ion Release Module, a German spacecraft, to release uncommonly found barium and lithium ions into near-Earth space that would be tracked by the other two spacecraft, UKS from the UK and the Charge Composition Explorer from NASA.

UKS only lasted 13 months but took plasma data at 5-s resolution, switching mode between the solar wind and the magnetosheath. Compared to the 5-min averaged data on IMP-8, the richness of the data set was impressive! The fundamental science possible with AMPTE surpassed that with IMP-8, but IMP-8 continued to chug along like the Energizer Bunny and provide a reliable monitor of the solar wind for 40 years.

Alan wanted to determine the accuracy of the ion measurements for UKS so we conducted an assessment applicable to electrostatic analyzers and microchannel plate detectors. We established a mathematical formalism for determining plasma parameters relating measured counts to geometrical factor, considering calibration techniques, MCP efficiency, detector energy and angular resolution as well as approximations in the mathematics. Of the three bulk parameters: density, velocity and temperature; velocity was best resolved (Kessel et al., 1989).

We carried the density assessment a step farther comparing the equivalent electron number density calculated from the ion instrument on UKS to the electron number densities calculated with the Sheffield University wave instrument on UKS and the passive sounder on ISEE-1, working with Les Woolliscroft and his group. For low and medium number density ( $\sim 3 \text{ cm}^{-3}$ ,  $\sim 7 \text{ cm}^{-3}$ ) the agreement was good (within 5%) but for higher number densities ( $\sim 20 \text{ cm}^{-3}$ ) the agreement was only within 15% (Kessel et al., 1991).

My research naturally shifted from the solar wind to the outer boundaries of Earth's magnetosphere with AMPTE UKS data. I was particularly interested in the bow shock that shares many basic characteristics with interplanetary shocks such as the existence of upstream and downstream regions, the ability to energize particles, and the importance of  $\theta_{\text{Bn}}$ . By contrast, interplanetary shocks are discontinuities traveling through the solar wind while the bow shock is a continual boundary that stands in the solar wind upstream from the magnetopause. The bow shock typically has a quasi-perpendicular side and a quasi-parallel side due to the angles between the conical bow shock boundary and the nominal Interplanetary Magnetic Field (IMF).

Steve Schwartz of Queen Mary College put together a science group using AMPTE UKS data to investigate the quasi-parallel side of Earth's bow shock, as a more challenging and less well studied phenomenon. This included the region upstream from the quasi-parallel side where ion and electron foreshocks are formed from particles reflected from the quasi-perpendicular side that interact with the incoming solar wind. Together we investigated phenomena such as active current sheets impacting the quasi-parallel bow shock and short-large-amplitude-magnetic-structures found in the vicinity (e.g., Kessel, 1991; Schwartz et al., 1988, 1992).

I expanded into research involving the magnetopause with AMPTE UKS, and got a crash course on reconnection. Alan wanted me to give his invited presentation on that topic at the third International School for Space Simulation (ISSS)—he had a conflicting meeting and could not attend ISSS. *Go to the south of France for 2 weeks in June (1987) at La Londe-les-Maures (first week) and Beaulieu (second week) and learn more about simulations? Sign me up!*

We had found a good example of a Flux Transfer Event in the UKS data at the dayside magnetopause and I presented it in the context of understanding gleaned from the ISEE-1 and -2 missions (Kessel et al., 1988). Steady-state reconnection had been established as an important process for the transfer of mass, momentum and energy from the solar wind into the magnetosphere, but at the time, only observations of the consequences of reconnection had been made. The relationship of steady-state reconnection to patchy reconnection (FTE's) remained an unanswered question.

I met Duncan Bryant at a science conference in the UK and he brought up a science hypothesis that would remain with me for the rest of my career. The conference was on magnetospheric processes and drivers and it was clear there was a lot we hadn't yet figured out. Duncan said that when we truly understood the workings of the magnetosphere, we should be able to describe it as a simple concept. It was an intriguing idea and it set me on an

educational journey to master the pieces on the way to deciphering the whole. That would require research within the magnetosphere as well as at the boundaries, but I wouldn't get there for another 10 years.

## 2. Contributions to Science

At the Goddard Space Flight Center in 1991, both my science research and involvement with missions expanded. The groundbreaking International Solar Terrestrial Physics mission (ISTP) was in an early stage of instrument development. NASA had joined with the European Space Agency (ESA) and the Institute of Space and Astronautical Science (ISAS) of Japan with each providing one or more spacecraft in critical regions. A major goal of ISTP was to understand the whole chain of events in the Sun-Earth system, what happened first, what happened second, what was a cause, what a consequence.

Both the ESA SOHO spacecraft and the NASA Wind spacecraft would be at the L1 point, the first taking continuous images of the Sun in several wavelengths and the second measuring in situ particles and fields in the solar wind. The NASA Polar spacecraft would orbit Earth over the poles, taking images of the aurora in order to characterize the energy deposited there. ISAS's Geotail spacecraft would be deep in Earth's geomagnetic tail to measure variations in the reservoir of solar particles. Several geostationary spacecraft would monitor the outer boundary of the radiation belts and a chain of ground-based stations across Canada would provide all sky images and variations in Earth's magnetic field.

The scope of the ISTP mission extended well beyond AMPTE and ISEE and Earth-orbiting single spacecraft missions because it had the potential to analyze the entire Sun-Earth system, sun to mud. The cooperation needed between spacecraft and ground-based assets and between the various international agencies was unprecedented for its time. ISTP would enable *coordinated* science across all of the distributed international assets.

ISTP adopted the Common Data Format (CDF) for their Key Parameter data, a trailblazing step in a discipline without data standards at the time. My role was from the National Space Science Data Center (NSSDC) that would also serve as the long-term archive. Bob McGuire recognized that just using CDF was insufficient; a set of metadata standards was also needed to enable the intercomparisons, allowing for common tools to be created and daily plots easily produced to search for and analyze events.

Bob and I created the ISTP Guidelines for CDF and I codified them in power point presentations and a 66-page document that originally formed Appendix A of the ISTP Key Parameter Generation Software Standards & Conventions (Mish, 1992) and was later updated and posted online ([spdf.gsfc.nasa.gov/istp\\_guide](https://pdf.gsfc.nasa.gov/istp_guide)). Bill Mish, Dick Schneider, Gerry Blackwell and I formed a traveling band that played all the universities and labs where ISTP instruments were being built or assets contributed, working with every instrument team to help them formulate their data processing software and make ISTP a success.

Geotail launched successfully in 1992. Wind followed in 1994. SOHO launched in 1995 and Polar in 1996. The pieces were in place. The first major event was a Coronal Mass Ejection from the Sun that impacted Earth, and was tracked cradle to grave from 6–11 January 1997. There was a two-fold benefit: the event gave scientists the first string-of-events data to start putting together the picture and it made a splash in the news since it possibly caused the loss of the AT&T Telestar communications satellite ([archive.pwg.gsfc.nasa.gov/istp/events](https://archive.pwg.gsfc.nasa.gov/istp/events)).

The event introduced Sun-Earth-Connection (SEC) science and emerging space weather to the general public in a spectacular way with international reporting, including on a premier U.S. source at the time: the CBS Evening News with Dan Rather. It was covered on radio. It was covered on the world-wide-web. It was printed by The Times, The Observer, New Scientist, and the Sunday Times in the UK; Le Soir and Liberation in France; Die Zeit in Germany, Izvestija and POISK in Russia; and la Repubblica in Italy; USA Today, Washington Post, New York Times, Baltimore Sun, Christian Science Monitor, Philadelphia Inquirer, Dallas Morning News, and Albuquerque Journal in the U.S.

Other events followed and ISTP was able to push SEC knowledge forward in a wide variety of areas such as parameterizing the geoeffectiveness of solar events, establishing global magnetotail structure and the location of the nightside reconnection line, identifying sources of magnetospheric plasmas, charting the development and decay of the ring current and global convection patterns, as well as providing inputs to and comparisons with magnetohydrodynamic computer models. ISTP set the stage for later collaborative missions.



Meanwhile, Jim Green, who was then the director of NSSDC, brought Hawkeye data from the University of Iowa into the data center. Hawkeye (Explorer 52, launched 1974) was a unique mission to investigate the northern polar region of the magnetosphere from  $21 R_E$  above (Polar was at  $\sim 9 R_E$ ). We converted the Hawkeye data into CDF and started analyzing it with modern tools, soon finding the first example of high-latitude reconnection with northward IMF.

The AMPTE reconnection event had occurred at low-latitude during an interval of southward IMF, adding to the evidence for one-half of Dungey's model of reconnection. The Hawkeye reconnection event corroborated the other half of Dungey's model during periods of northward IMF, showing that merging should be found poleward of the cusps in the high-latitude magnetopause (Dungey, 1963). Our example and analysis, being the first, made the cover of Geophysical Research Letters back when we only had print copies of journals (Kessel et al., 1996).

My research with ISTP data had concentrated on Geotail once its orbit moved closer to Earth ( $30 R_E$ ) and had multiple passes skimming either the bow shock or magnetopause, but I was looking to move on to research inside the magnetosphere. A paper by Mathie and Mann (2000) got me started. They showed that during periods of high-speed solar wind streams, Ultra Low Frequency (ULF) wave power in the Pc5 range at the Kilpisjärvi ground-based magnetometer increased and correlated with enhancements in  $>2$  MeV geosynchronous electron flux. They suggested that ULF pulsations might be the cause of the “killer” electrons in the inner magnetosphere.

I wondered about the source of the Pc5 wave power and started searching through solar wind data from Wind and Geotail. I found enhanced power in the solar wind at the leading edge of the high-speed streams. With help from Ian Mann, I was able to show that there was a clear correlation between Pc5 power inside and outside of Earth's magnetosphere between Wind, Geotail and Kilpisjärvi (Kessel et al., 2003).

The first few times I presented this research and a prior attempt at publication were met with skepticism—I was a newcomer to inner magnetospheric research and there were many things I did not know including the transfer mechanism. I kept working on it, presenting and publishing (Kessel, 2001, 2008; Kessel & Shao, 2005) and eventually the linkage gained traction and ULF research became a popular topic.

Frequently in my research, I would dig into a topic and at the end feel like I knew less than when I started—because I discovered how much more there was to learn. I was never going to get to a full understanding of the magnetosphere working by myself or with a few others. ISTP had shown the power of coordinated analysis. A comprehensive understanding was needed and I would soon be in a position to acquire that.

### 3. Opportunities and Closure

An unexpected benefit of being at NASA Headquarters, that I discovered soon after moving there in 2006, was the exposure to a broad spectrum of science. I began my tenure with the Living With a Star (LWS) program that was established in 2000 by the US Congress in order “to better study solar variability and understand its effect on humanity.” The LWS charter also included understanding basic natural processes and was a logical follow-on to ISTP, fitting neatly into Sun-Earth-Connections.

NASA HQ had been looking for a one-word term for the field of solar and *space physics* to go in the U.S. budget, expanding and replacing SEC; by 2006 they had settled on Heliophysics from the Greek Helios for the Sun and its environs and physika, the science of the natural world. The Heliophysics Division joined three other divisions—Astrophysics, Planetary Science and Earth Science—to form the Science Mission Directorate (SMD) at NASA HQ.

The LWS Science program (originally Targeted Research & Technology) had set up Focused Science Topics (FSTs) and put together teams to carry out research on these topics. One of my first tasks was to look across the existing FSTs at the breadth of the program and the progress being made by the teams to assess new directions. The FSTs covered all of the research regimes of Heliophysics: sun, heliosphere, magnetosphere, ionosphere and upper atmosphere; many FSTs were outside my expertise but I gained insights to their science and exposure to their communities through LWS.

Early FSTs included: topology and evolution of open magnetic field from photosphere to heliosphere; mechanism for solar wind heating and acceleration; shock acceleration of solar energetic particles by interplanetary coronal mass ejections; solar wind plasma entry and transport in the magnetosphere; formation and loss of new radiation

belts in the slot region; storm effects on the global electrodynamics and middle and low latitude ionosphere; response of thermospheric density and composition to solar and high latitude forcing ([lwstr.gsfc.nasa.gov](http://lwstr.gsfc.nasa.gov)).

After working with the LWS TR&T program, I moved to Geospace science which focused on the magnetosphere, ionosphere and upper atmosphere. The primary responsibility for this program and most other Research and Analysis (R&A) programs was to put together, manage and/or preside over review panels, make recommendations for selection and then monitor the selected awards. A side benefit was becoming cognizant of the latest and greatest research proposed across a few hundred review panels and thousands of awards, seeing what was the hot new topic, what was relevant within the scope of the latest Decadal Survey, and who was conducting what research; all of it contributed to a deeper understanding of Geospace science.

In addition to managing R&A, I was fortunate to be assigned as the Program Scientist (PS) for the second LWS mission, the Radiation Belt Storm Probes (RBSP), in 2008 just before the Preliminary Design Review (October 2008) and the Confirmation Review (January 2009). As PS, it was my responsibility to follow RBSP through development and testing to ensure no changes would be made that compromised the science. After launch and into their science phase, I would need to verify that mission success was achieved.

The Level One Mission success criteria had been established; RBSP had as its overall guiding objective “to provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun” (Kessel, 2012; Mauk et al., 2012). Here was my opportunity to dig into radiation belt science and gain a deeper understanding before launch.

The radiation belts were the first discovery of the space age with the launch of the first Explorer in 1958. James Van Allen and George Ludwig had built a Geiger counter to fly on Explorer 1 because Van Allen was interested in conducting a survey of cosmic ray intensity above the atmosphere and a satellite could provide much more data than the suborbital rockets he had been using, that lasted only a few minutes each. However, the Explorer 1 data were perplexing because there were places where the count rates dropped to zero; it made no sense that there were regions with no cosmic rays.

They launched Explorer 3 2 months later, shortly after Explorer 2 failed to launch, and confirmed the Explorer 1 finding. The answer to the puzzle came when Carl McIlwain tested their prototype Geiger tube and demonstrated that counts rates above 25,000 would register as zero. There were many more counts than expected and the counter saturated! Van Allen deduced that there was radiation, most likely electrons and protons, trapped in Earth's magnetic field. At a press conference, Van Allen was describing the trapped radiation as encircling Earth. When a reporter asked, “Do you mean like a belt?” the term stuck and the region became known as the Van Allen radiation belts. The discovery landed Van Allen on the cover of TIME magazine in May 1959.

A picture emerged of the radiation belts as two donut-shaped regions encircling Earth, an inner belt and an outer belt. The Combined Release and Radiation Effects Satellite and the Solar Anomalous and Magnetospheric Particle Explorer confirmed that basic picture. They showed that the inner belt was filled primarily with high-energy protons that could persist for decades. The outer belt, on the other hand, was composed of high-energy electrons that were highly volatile, ebbing and flowing with the absence and presence of solar storms.

Most satellites avoided the radiation belts and only encountered them during a strong solar storm when the inner belt, typically found from about 4 to 8 thousand miles above Earth's equator, could reach down as low as 125 miles above Earth's surface to LEO and the outer belt, usually from about 12 to 26 thousand miles, could extend out past 30 thousand miles encircling operating Geostationary satellites. RBSP instruments were designed to withstand the onslaught and succeeded remarkably well. After a successful launch and commissioning the mission was renamed the Van Allen Probes and began its discovery phase.

The picture of two belts with a slot region between was refined by the Van Allen Probes with a much finer gradation in the energy bands and a host of solar storms. Very early observations showed that the outer belt split into two belts, the inner of these persisting for weeks (Baker et al., 2013). Other observations showed that the extent of the outer radiation belt depended sensitively on electron energy; a slot region was evident for some energies, but at others, the outer belt was continuous (Reeves et al., 2016). Other early results resolved controversies or showed unexpected features (e.g., Mauk et al., 2014; Spence et al., 2016).

It is generally accepted now that the state of the radiation belts depends on competing processes of enhancement, transport, and loss. There is loss outward through the magnetopause and precipitation down into the atmosphere.

There is enhancement caused by inward radial transport and also by local acceleration. Ultra Low Frequency (ULF) waves, Electromagnetic Ion Cyclotron waves and Chorus waves all contribute to the state, causing loss or in some cases, enhancement. The Van Allen Probes eventually ran out of fuel and had to deorbit, but the data continued to be mined and analyzed.

Heliophysics had many other missions and I moved on. I served briefly as PS for the Magnetospheric Multiscale Mission (MMS), which provided a more in-depth knowledge of reconnection. The time resolution of its plasma data blew away all of the earlier instruments. The Fast Plasma Investigation—consisting of four dual electron spectrometers and four dual ion spectrometers—produced a three-dimensional picture of the ion plasma every 150 milliseconds and of the electron plasma every 30 milliseconds. Just like AMPTE had surpassed IMP-8, MMS was another leap forward. It was finally good enough resolution to see inside the electron diffusion region where the essence of reconnection resided.

Heliophysics science is dependent on many distributed assets because space is big and having spacecraft in critical positions is essential to interpreting the observations. ISTP had demonstrated that many years before. Missions that form essential parts of the Great Observatory continue to be supported such as three ISTP spacecraft, SOHO, Wind and Geotail, that are still in operation. Missions that continue to produce new science results or reach into new territory can be extended for many years.

Voyager, for example, celebrated its 40th anniversary in 2017 with a Gala at the Air and Space Museum in Washington, D.C. Gary Flandro talked about his role in Voyager at the Gala and also gave a NASA HQ seminar. As a young engineering post-doc at Cal Tech in the 1960s he searched for an auspicious alignment of the outer planets and came up with the Voyager Grand Tour. He helped convince critical people at JPL to invest in the project and Voyager was born. The two spacecraft are now in interstellar space.

With all the understanding gained over 40 plus years, especially of Earth's magnetosphere, its processes, drivers and boundary conditions, the pieces fell into place and it occurred to me what the simple concept Duncan was looking for could be. The magnetosphere could be described as a circulatory system of charged particles driven by electromagnetic fields and waves, analogous to the human body being a circulatory system of blood driven by the heart.

In both cases, these are simplistic descriptions of complex systems. Scientists are comfortable with and indeed require the complexity but a simple concept can engage non-scientists if an opportunity for discussion arises, for example, while waiting in line for coffee or concert tickets or stuck waiting to board a flight or get to the top floor on an elevator. There are other advantages to simple concepts whether you write them on paper, sketch them on canvas or speak them through a microphone: they can enthrall and inspire the next generation. Gary Flandro, for example, originally got his idea for the Voyager Grand Tour from a children's book.

## 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.

## Data Availability Statement

Data were not used, nor created for this research.

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