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Key Points:
- Outline of development of many aspects of basic field and particle interactions in magnetospheres
- Theories of linear and nonlinear magnetospheric MHD waves and wave-particle interactions
- MHD of giant planet magnetospheres and magnetosphere-moon interactions

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An Improbable Collaboration

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Abstract Fifty years of collaboration between the authors are reviewed. Common themes cover magnetospheric magnetohydrodynamic phenomena: MHD waves, wave-particle interactions, circulation, global modes and field line resonances in the terrestrial context, and magnetosphere-moon interactions, transport processes, instabilities, and global structure in the magnetospheres of giant planets. Over the period reviewed, instrumentation has improved, particularly in particle detectors, and interpretations that seemed radical when first suggested are now supported by measurements and seem commonplace.

Plain Language Summary The authors have worked together for almost 50 years. They met when the existence of the magnetosphere, the volume surrounding the Earth in space that is structured by its planetary magnetic field, had been established for only a decade. They have succeeded since then in showing that, in a field where new discoveries were regularly happening, there is a very useful role for people who, paying attention to the strengths and weaknesses of instrumentation, can move back and forth between theory, simple modeling, data analysis, and back to theory. Magnetohydrodynamics, a theoretical tool that simplifies the description of space plasmas by focusing on averaged responses, has been their key discipline, but some of their key contributions have elucidated the critical role of the energetic particles that depart from average behavior. Through a mix of theory, interpretation of observations, and even leading spacecraft instrument teams, the authors have contributed to understanding most aspects of the large-scale behavior of the magnetospheric systems at Earth, Jupiter, and Saturn.

1. Introduction

It must be exceptional for a scientific collaboration to have extended over nearly half a century, especially one that called for communication in pre-email days between colleagues separated by about 8,800 km. Against the odds, ours has thrived from the early 1970s to the present. Here we try to identify the evolution of our thinking against the background of a continuously changing knowledge of the magnetospheres of Earth and the outer planets. When we started working together, the earliest spacecraft exploration of the terrestrial environment had established the existence of the magnetopause, the bow shock, the radiation belts, and the magnetotail and determined the basic properties of the solar wind. However, there were large gaps in the understanding of how the system worked at macroscopic and microscopic levels. It was recognized that Jupiter had a magnetosphere, but it was not even known that Saturn did also.

When we met, UCLA and Imperial College were among the few academic institutions that recognized space plasma physics as an academic pursuit. David, trained as a mathematician and expert in theory, had recently completed a PhD at Imperial College in the still new field under the supervision of one of the giants of the field, James W. Dungey (see the history paper: Southwood, 2015). David's dissertation treated the theory and the first definitive observations with the Explorer 33 spacecraft of the Kelvin-Helmholtz instability on the magnetopause (Dungey & Southwood, 1970; Southwood, 1968). The dissertation also contained the first attempt at a theory explaining a class of steady magnetic pulsations seen at geosynchronous orbit (Cummings et al., 1969). The north-south symmetry of the signals made it unlikely they could be excited by any solar-wind-driven source but the thesis pointed out that the symmetry was just right for bounce resonant excitation by energetic particles.

Margaret, also a theorist, had obtained her PhD working on a theoretical problem remote from plasma physics (bremsstrahlung from ultrarelativistic electrons) under the direction of Julian Schwinger, a giant in the very different field of quantum electrodynamics. Ten years post-PhD, she stumbled into space physics by taking a job with Willard Libby's group at UCLA. Subsequently, she joined Paul Coleman's group to work with Tom Farley who asked her to analyze data from a charged particle instrument on the newly launched OGO-5 spacecraft, thereby launching her career as a magnetospheric physicist.

We both owe much to Paul Coleman who provided the geosynchronous magnetometer signals used in David's thesis. Paul, who had founded a space science group at UCLA a few years earlier, invited David to become a postdoctoral scholar at UCLA to help interpret geosynchronous spacecraft magnetic field data. Margaret and David crossed paths near the end of his stay at UCLA. They recognized some shared interests and complementary skills and began to discuss ideas for collaborative research. These discussions were interrupted by David's return to Imperial College, but fortunately, Margaret was successful in getting a Guggenheim fellowship that allowed her to spend the 1973–1974 academic year at Imperial College where the collaboration began in earnest. London was experiencing the disruptions of the 1974 oil crisis, and limitations on use of electricity darkened much of the city, including Imperial College, but we were fortunate to be working in a "laboratory" that was regarded as critical, so the lights did not go out on our endeavors. After returning to UCLA, Margaret applied to the National Science Foundation for funding to continue our theoretical magnetospheric studies. Bob Manka, the program officer for magnetospheric studies, made it clear that he took a risk in funding an unknown investigator. Although his trepidation was evident, he offered support that included trips for David to come to UCLA for a month each summer for a period of 3 years, support without which our collaboration would not have flourished; thereafter, the support was repeatedly renewed. UCLA colleagues became accustomed to hearing David's booming voice coming from Margaret's office, interrupted only occasionally by some quieter murmurs. They also became accustomed to receiving a new joint publication almost every year.

2. Particle and Energy Injection by a Time-Varying Global Magnetospheric Electric Field

Some scene-setting is appropriate in order to place our early work in context. In the decade before we started working together, the idea had emerged that the continuously flowing solar wind would confine the Earth's magnetic field within a cavity, the magnetosphere (Johnson, 1960). Subsequently, it was realized that momentum transfer across the boundary (Axford & Hines, 1961; Dungey, 1961) would not only strongly affect the shape of the cavity but also cause the solar wind to set up an internal magnetospheric circulation. Axford and Hines proposed that a viscous interaction at the boundary transfers momentum from the solar wind to the magnetospheric plasma. Dungey introduced the concept of magnetic reconnection between the terrestrial magnetic field and interplanetary field, a model in which momentum transfer is achieved in a more direct manner. As it happens, Axford rapidly became interested in the reconnection model (cf. Axford et al., 1965) while in parallel David, working with Dungey, studied the magnetopause K-H instability as a possible source of a viscous interaction.

In either case, a global magnetospheric circulation resulted. This implied that the terrestrial magnetosphere contains a large-scale electric field, $\mathbf{E} = -\mathbf{u} \times \mathbf{B}$, where $\mathbf{E}$ is the electric field, $\mathbf{u}$ is the flow velocity, and $\mathbf{B}$ is the background magnetic field. If the magnetosphere were a true magnetohydrodynamic (MHD) fluid, the electric field could be regarded as a secondary effect of the conducting fluid motion. However, the magnetosphere was collision-free and we thought that much could be gained by examining particle motions in the global magnetospheric electric field whatever the momentum transfer mechanism might be. Although the flow was induced by the antisolar flow of the solar wind, there had to be a return flow moving the plasma basically sunward deeper in the interior in the quasi-dipolar field regime of the magnetosphere. This field would determine the way in which particles in the tail of the energy distribution would be injected into the terrestrial system.

Although there were as yet no measurements of the electric field, it was straightforward to estimate that, due to the flow, the voltage across magnetosphere could be tens of kV. With a quasi-steady background electric field of this magnitude imposed across the magnetosphere from dawn to dusk, we realized that spacecraft-borne charged particle detectors with an energy range anywhere near the order of that imposed by the cross-system voltage would find that charged particle flux varied with the spacecraft distance from dusk. Using a MHD phenomenon as a basis for understanding the transport and acceleration of individual charged particles was a moderately revolutionary perspective. We would return to similar approaches frequently in the years to come.

Charged particle motion in a background magnetic and electric field using the concept of guiding center motion had been introduced by Alfvén in the early 1950s (Alfvén, 1950). In this picture, particle motion is broken down into a rapid gyration about a guiding center situated on the magnetic field and a slow drift of the guiding center at right angles to the field. A new apparent force is introduced as the magnetic moment of the particle gyration controls guiding center motion along the field, resulting in the magnetic mirror effect. A seminal paper by Northrop and Teller (1960) developed the concept further with particular application to motion in the magnetosphere. They used adiabatic invariants to break down the overall motion into three periodic motions. The three invariants were the magnetic moment, μ, associated with gyration about the field, the "longitudinal" invariant, J, associated with mirroring motion back and forth along the field and the flux invariant associated with the grad **B** and other slow drifts about the Earth. (The term longitudinal for J came from its use in the context of laboratory plasma devices. In the magnetosphere, it is associated with latitudinal motion.) Visualizing individual particle motion by combining the idea of motion conserving all or two of the invariants in the presence of a background electrostatic potential distribution in the magnetosphere would prove very productive.

The most important paper of this first phase of work was Kivelson and Southwood (1975a), a paper that elucidated the strong coupling between particle motion—simultaneously radially inward and Eastward (electrons) or Westward (positively charged ions)—and particle acceleration. Not only did we outline the use of adiabatic theory in the presence of a large-scale magnetospheric electric field but we also introduced use of the Liouville theorem to show what would happen to the energetic particle flux in the absence of collisions. We considered the effects of both a steady electric field and an impulsive increase, such as might be expected during a geomagnetic substorm. We then applied our ideas to the interpretation of a variety of published observations (Bogott & Mozer, 1974; DeForest & McIlwain, 1971; Frank, 1970; Konradi et al., 1973; Lezniak & Winckler, 1970; Pfitzer & Winckler, 1969) based on spacecraft measurements from the immediately previous years. In particular, the approach accounted for the local time dependence of increases of the flux of tens of keV protons during storm time intervals. Following several papers exploring additional aspects of this picture (Kivelson & Southwood, 1975b, 1975c; Southwood & Kivelson, 1975), we applied the basic ideas to the problem of the evolution of the ion cyclotron instability in the plasma convection system of the magnetosphere (Kaye et al., 1979).

3. Charged Particle Behavior in Low-Frequency Pulsations

David's interest in ultralow frequency (ULF) pulsations of the magnetic field was inspired by Jim Dungey who, as early as 1954, had proposed that magnetic pulsations in the frequency band observed by ground magnetometers (0.001 to 0.1 Hz) were the signatures of standing MHD waves in the magnetosphere (Dungey, 1954). By the mid-1970s Southwood had developed theories for magnetic signals detected in space and on the ground for sources both external to the magnetosphere (e.g., Southwood, 1974) and internal (e.g., Southwood, 1976). With Hughes he had developed a new theory for how signals penetrated the ionosphere and atmosphere (Hughes & Southwood, 1974, 1976). Internal magnetospheric sources for hydromagnetic waves were not due to a fluid MHD instability; waves were driven by a resonant interaction with drifting energetic particles, a process wherein the particles lose energy, diffusing both in energy and space. From the first (Southwood et al., 1969), it had been clear that large angular wavenumber, m, was a necessary feature of resonant generation, in contrast with other possible sources.

Studies of ULF waves initially relied exclusively on magnetic field data from space and ground, but the energetic charged particles that interact with the waves are also modulated in the ULF range and spacecraft data would allow us to investigate their response. Margaret had noted pulsations in the energetic particle flux measured by detectors on OGO-5 and other spacecraft but her initial interest in what she thought of as small wiggles on plots was minimal until she visited Imperial College in 1973–1974. There she found a group of scientists (not only David but also Jim Dungey, Jeff Hughes, and Chris Green) keenly focused on ULF pulsations registered by space and ground magnetometers and also met a short-term visitor from the Soviet Union, Valeria Troitskaya, who had pioneered the field of ULF studies in the USSR. She also was the first to champion the idea that ULF signals can serve as remote probes of magnetospheric properties.

The interest in ULF was contagious, so a few years later we began together to extend David's early work on ULF waves with a new focus on particle responses detectable in space. Boldly we entitled our first paper on the subject: "Charged particle behavior in low-frequency geomagnetic pulsations: 1. Transverse waves" (Southwood & Kivelson, 1981). A sagacious editor attempted to dissuade us from the implied commitment to additional publications on the topic, but we stood fast. A four part series of papers on the subject ensued.

Our choice of transverse waves as the introductory subject made it clear we wanted to move beyond looking at plasma behavior from a fluid perspective, as a theorist would know that MHD transverse waves are incompressible and do not change the particle pressure. A distinguishing aspect of our work on wave-particle interactions (as of our work on several other topics) was a desire to describe the properties of energetic particles in terms of quantities directly relevant to spacecraft instrumentation. Many of our results were presented in terms of directly measured quantities—energy and pitch angle—rather than the adiabatic invariants μ and J that are mathematically convenient but not directly measured.

We worried about the size of energy bins. One can, for example, find embedded in the largely theoretical treatment of our first paper on the subject, a section entitled "Comments on Detectors" in which we discuss the blurring effect of energy and pitch angle bins of finite range. Our wave-particle papers were written at a time when measurement of energetic particles were made in broad energy ranges that precluded refined identification of the resonant energy across which the phase jumped. In our analysis, we noted the limitations that this imposed on the ability to characterize wave effects. In recent years the data from the energetic particle instruments with narrow energy bins on the Van Allen probes have much more clearly demonstrated the particle responses that we described (Claudepierre et al., 2013).

Particle detectors on spacecraft measure particle flux, ideally as a function of energy and pitch angle. Waves induce particle motion and at the simplest level the flux changes can give direct information on the drift velocity associated with the electric field of the wave rather analogous to the Compton-Getting effect (Compton & Getting, 1935) in cosmic rays. However, the full picture is much more complex because the interaction between ULF waves and particles is energy and pitch angle dependent.

Particles whose bounce and drift relate closely to the wave properties can exchange energy with the waves and are referred to as resonant particles. With the assumption of axial symmetry, a wave with azimuthal structure of the form $e^{im\varphi}$ and angular frequency, ω, resonates with particles whose bounce (ω_b) and drift frequencies (ω_d), determined by the form of the background field and by the particle energy and pitch angle, satisfy

$$\omega = m\omega_d + N\omega_b \tag{1}$$

for integer m and N. If the distribution function is not a constant function of energy, particle fluxes at fixed energy oscillate in amplitude in response to the wave electric field. The signal is largest at the resonant energy/pitch angle; particles with energies just above and just below the resonant energy respond to the wave with phase shifts that differ by 180°. The response of a particle to an MHD wave depends not only on the particle's pitch angle and energy but also on the form of the wave structure along and across the flux tube and, consequently, details of the response of particles at different energies and pitch angles to low frequency waves can be diagnostic of interesting properties of the magnetosphere at locations remote from the observation point.

In the second paper of the series (Southwood & Kivelson, 1982), we illustrated graphically (Figure 1) how possible (geometrically simplified) structures of the perturbation electric field in a wave accelerate resonant particles as they bounce and drift through the perturbation field. In the figure, diagonal lines represent the drift/bounce trajectories of guiding centers of resonant particles as they move through (a) the fundamental mode wave or (b) a second harmonic wave. Bounce phase determines if particles gain (or lose) energy as they move through the standing wave structure. Positively charged particles on the solid trajectories gain energy in (a) and lose energy in (b). On dashed trajectories, energy on average does not change in (a) and decreases in (b). The assertion that a picture is worth a thousand words, or equivalently the substitution of images for equations may explain why this totally nonmathematical paper is the most frequently cited of the series.

The third paper (Kivelson & Southwood, 1983), hardly ever cited, dealt with measurements of particles in waves using a spinning spacecraft. It is a dense paper with a possibly off-putting title referring to spin

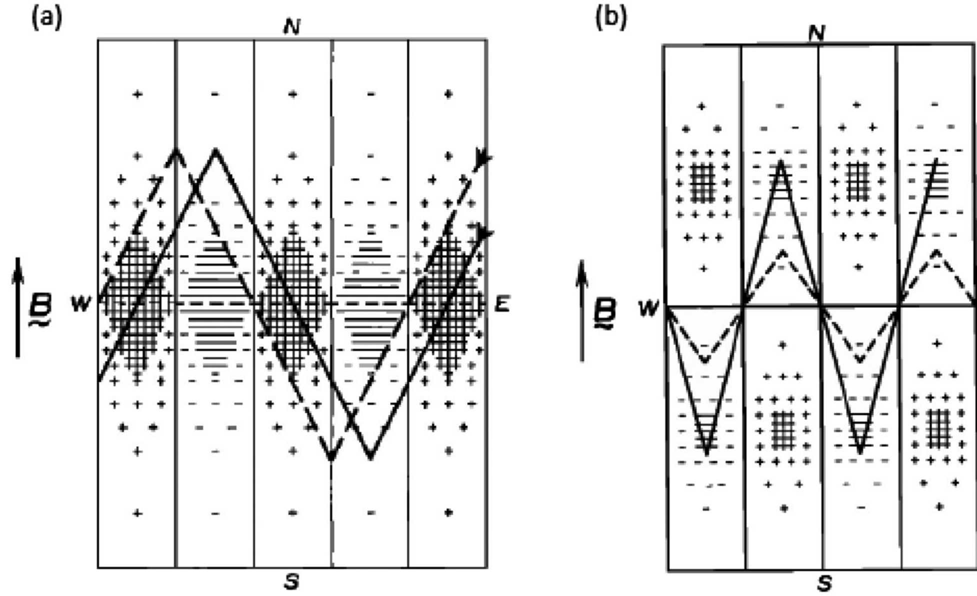

Figure 1. From Figures 1 and 3 of Southwood and Kivelson (1982). Schematics showing how resonant particles can change their energy as they bounce and drift (jagged straight lines show particle guiding center trajectories) through a standing wave structure. Field lines are shown as straight vertical lines bounded by uniform ionospheres in the north (N) and south (S). Plus and minus signs represent the sign of the wave electric field, and their density reflects intensity.

phase. Most spacecraft measuring fields and particles spin at a rate lower than the ion cyclotron frequency but greater than the most ULF frequencies. We showed that a detector on a spacecraft with spin axis aligned with the field can nonetheless detect velocity changes within a Larmor orbit as it rotates thus allowing detection of finite Larmor radius effects in waves. We also showed that the measurement in the rotating frame also allowed detection of acceleration/deceleration within gyration and thus determination of the wave electric field. Lastly, the case where the spacecraft spin axis made a large angle to the background field would allow detection of asymmetries in particle bounce motion along the field. We showed that the bounce resonant effect outlined in Figure 1 was present in particle data from the ISEE 1 spacecraft.

In the fourth and last paper of the series (Kivelson & Southwood, 1985a), we analyzed the interaction between energetic particles and compressional ULF waves, again demonstrating the importance of the structure of the wave perturbations along the field. As a result of the increase of mirror force with latitude, particles with relatively large pitch angles may be excluded from regions in which the wave perturbation increases the field magnitude. As in the case of transverse waves, the response of energetic particles depends on the wave frequency and the particle's bounce and drift frequencies. However, in compressional waves an additional characteristic frequency, ω^*, proportional to the ratio of derivatives of background distribution function with respect to L and to energy, becomes important. For Maxwellian particle distributions, ω^* is the diamagnetic drift frequency. For bouncing particles, the effect of a compressional wave on the distribution depends on its symmetry along the field and the relation of the wave frequency to the key frequencies ω_d, ω_b, and ω^*.

If a particle moves rapidly enough, that is, if $d/dt \cong \boldsymbol{v} \cdot \nabla \gg \partial/\partial t \sim \omega$ where $\boldsymbol{v}$ is the particle velocity, the changes related to its bounce motion in a nonuniform field may be much larger than the rate of change of the local field imposed by the wave. The total energy of the particle distribution remains unchanged, but the partition between parallel and perpendicular contributions of particle motion is modified by the wave during a bounce. The phenomenon is familiar in the mirror mode and we referred to it as the *mirror effect*. In the opposite extreme in which $\omega \sim \partial/\partial t \gg \boldsymbol{v} \cdot \nabla$, the particle energy does change, with the change appearing in the component of motion perpendicular to the field. We referred to this process as the *betatron effect*. For situations in which $\boldsymbol{v} \cdot \nabla$ and $\partial/\partial t$ are comparable, both effects may be important. This analysis was relevant to our later work on the mirror instability.

Today, there is no dispute about the fundamental importance of the ULF spectrum for understanding magnetospheric charged particle distributions. Happily, these early papers, from a time when the importance of ULF was far from accepted, are still being referenced with nearly 100 citations between January 2018 and April 2020.

4. Magnetospheric MHD Waves

Our first joint paper on MHD theory, inspired by work on MHD wave theory that had been undertaken by David as early as 1966, preceded the work discussed in the previous section. The research, led by student, Howard Singer (Singer et al., 1981), explored the standing Alfvén mode equations in a cold plasma for pure toroidal (low E-W angular wavenumber, m) and pure poloidal (large m) excitations in a realistic field geometry, using the newly produced Olson-Pfitzer magnetospheric field model. Previous solutions (e.g., Cummings et al., 1969) had been limited to a dipole background field. We presented generalized equations that could in principle allow such computations in nearly any background field. Our trick was to represent the background magnetic field using Euler potentials, α, β.

$$\mathbf{B} = \nabla\alpha \times \nabla\beta \tag{2}$$

α and β are constant along the field and can be used as the basis of a coordinate system that labels field lines. A small amount of manipulation led to a wave equation for incompressible Alfvén waves that were polarized either in the α or β direction. Assuming that signals were reflected at the feet of the field lines in the ionosphere and introducing for the background field one of the model fields that, based on spacecraft data, were beginning to gain acceptance, one could then compute eigenfrequencies for the lowest-frequency waves on field lines throughout the closed field region of the magnetosphere.

Eigenfrequencies for the lowest-frequency modes were found to differ substantially from estimates based on a dipole field. (The Singer et al. equations are at present being used to establish the resonant frequencies in Saturn's magnetosphere [Rusaitis et al., 2019] where not only is the field nondipolar but also the plasma density is highly confined near the equator.)

5. Pulsations: The Discovery of Global Modes

The Singer et al. (1981) calculations were idealized in that the signals were assumed to be incompressible. Where the background field and plasma are nonuniform, the transverse Alfvén mode is generally coupled to the compressional fast mode. Indeed, for a given frequency, incompressible Alfvén eigenmodes (i.e., modes with standing structure along the field) can exist only on isolated resonant magnetic shells. In general, in a nonuniform plasma at locations away from the resonant shells, the wave signal is compressible and so corresponds to the fast mode. David's work in the 1970s had concerned aspects of this problem where he demonstrated the general principles of field line resonance coupling in a nonuniform but idealized bounded system, the hydromagnetic box model (Southwood, 1974). With a source at a particular frequency, the compressional fast mode carries energy through the plasma to a resonant magnetic shell where the Alfvén mode eigenfrequency matches the fast mode frequency. The singular nature of the Alfvén mode means that there will be absorption of wave energy at the resonant shell. The localized transverse wave driven by the process is called a field line resonance. In practice, in the magnetosphere it is likely that the wave energy is dissipated in the ionosphere. Probably our most significant work on pulsation theory was presented in some papers in the eighties that built on the earlier theory by recognizing that the spectrum of the compressional signals might contain power at preferred frequencies set by the finite nature of the magnetospheric cavity. We thus introduced the concept of global mode ULF waves.

Our attention had been directed toward the global mode problem by some new spacecraft observations. While on a sabbatical visit to the Observatoire de Paris at Meudon, Margaret and colleagues had identified highly correlated compressional pulsations in electron density and field magnitude measurements from the ISEE-1 spacecraft. Noting that the period (~8 min) remained constant over a large range of radial distances (near equatorial and roughly $L = 5$ to 10), they proposed that the observed fluctuations arose from compressional waves standing in a plasma cavity bounded by the magnetopause and the plasmapause, a system that singled out a discrete spectrum of global mode waves (Kivelson et al., 1984). The analysis in that paper was theoretically flawed, but the concept appeared to be correct.

In fact, despite the success of the idea of field lines resonances in explaining many aspects of ULF pulsations, there had long been something of an elephant in the room: The global spectra of Alfvénic ULF pulsations tended to show peaks at particular frequencies (usually localized on magnetic shells). Why were these shells and frequencies preferred? If field line resonances were driven by a local absorption of energy from a standing fast mode whose frequencies were quantized by being trapped in a resonant outer magnetospheric cavity, the existence of discrete field line resonant frequencies was explained. However, the resonance itself meant that any such large-scale eigenmode would be damped by the field line resonance effect. A more consistent analysis was needed, and together we extended the use of a simple hydromagnetic box model (straight field lines bounded by uniform ionospheres at two ends as in Figure 1) with plasma density varying across the field to represent the change of the Alfvén speed with *L*-shell in the magnetosphere.

In Kivelson and Southwood (1985b) we used the model to prove that in a bounded nonuniform MHD system, the eigenmodes of the isotropic fast MHD mode would couple to the Alfvén mode in narrow magnetic shells where field line resonance conditions were met. Most importantly, we showed that the effect would mean that large-scale fast mode resonances would be inherently damped by the coupling. We gave a firm theoretical foundation based on analogy with previous work on radio wave propagation. The work was extended in Kivelson and Southwood (1986). This was an immense step forward as it made it clear that the magnetospheric cavity as a whole would favor excitation of discrete frequencies, despite the fact that energy would continuously drain into the field line resonance regions. Potentially broadband sources of energy, such as buffeting of the magnetopause by the solar wind or broadband Kelvin-Helmholtz instability generated waves, would not necessarily give rise to a featureless MHD spectrum in the magnetospheric cavity. Later work by Samson et al. (1992) proposed that the compressional waves that we were investigating were likely not to be bounded azimuthally (i.e., in local time) and consequently might be described as waveguide modes rather than cavity modes.

6. Jovian MHD Waves

While working with the box model, our interest turned toward what it might teach us about MHD mode coupling in the Jovian magnetosphere, the objective of the Galileo spacecraft (of which, more anon), whose launch was on hold following the Challenger disaster. The critical feature of the Jovian magnetosphere is the presence of a torus of ionized material originating from the moon, Io, and confined within a few R_J (R_J = 1 Jupiter radius) of the equator. This feature means that there are substantial density (and so Alfvén speed) gradients along the background field that threads through the torus. The nature of the coupling between compressional (fast) and transverse (Alfvén) modes and the effectiveness of excitation are significantly modified by the presence of such gradients. In particular, the structure along the field direction of the perturbations imposed by the compressible and incompressible wave modes differ significantly in the presence of a nonuniform density distribution (Southwood & Kivelson, 1986). The effectiveness of coupling of modes of the same order is reduced relative to the case with plasma density constant along the field, but cross feeding of energy from a particular fast mode harmonic to multiple modes of transverse oscillations becomes possible. Our model was later used by Khurana and Kivelson (1989) to interpret ULF waves observed at Jupiter, by Yates et al. (2016) to account for "1 hr" period waves observed at Saturn, and by Manners et al. (2018) to describe 10 to 60 min period waves at Jupiter.

7. Pulsations: A First Look at Nonlinearity

Southwood's early work on hydromagnetic wave theory and observations in the magnetosphere also involved the first studies of the excitation of waves through resonant interaction between the adiabatic motion of energetic particles in the magnetosphere and hydromagnetic waves. (A summary of his early work is given in Southwood, 1976.) Southwood et al. (1969) had shown that high angular wavenumber (i.e., short transverse wavelength) was a necessary feature of resonance from the theoretical perspective. Shortly after Coleman (1970) and also Barfield et al. (1972) noticed an odd feature of some ULF waves detected at synchronous orbit, namely that the compressional field component contained oscillations at the second harmonic of the frequency identified in the transverse component. The waves occurred when the magnetospheric ring

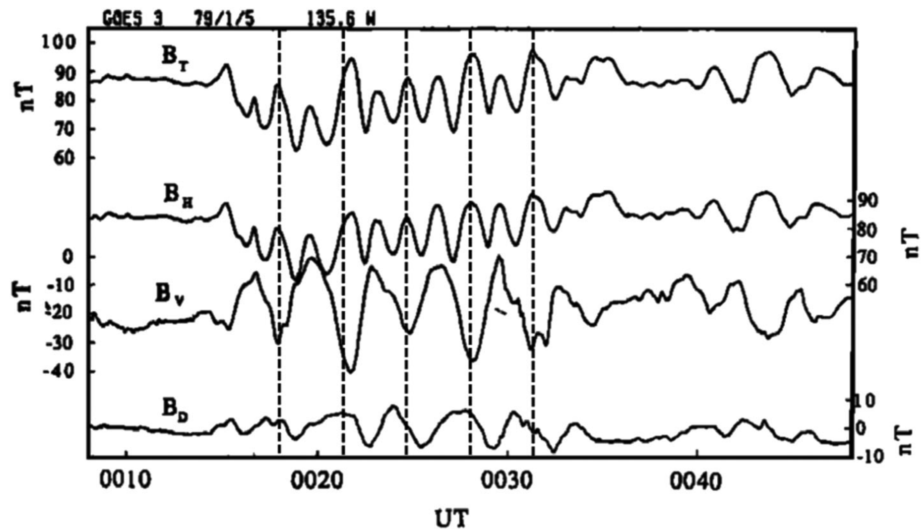

Figure 2. From Higuchi et al. (1986), an example of frequency doubling. Magnetic field fluctuations observed by GOES 3 on Jan. 5, 1979 are plotted in a VDH coordinate system (H antiparallel to the dipole axis, V radially outward, and D orthogonal to both). We have superimposed dashed lines uniformly spaced approximately at the troughs of the radial component, B_V, and note that they correspond closely to every second peak of the field magnitude perturbations (B_T).

current energetic particle population was enhanced—suggesting causality—but no connection was made with Southwood's theoretical work.

Subsequently, Higuchi et al. (1986), Engebretson et al. (1986), and Takahashi et al. (1990) provided further surveys of the phenomenon. Figure 2 shows an example from Higuchi et al. that shows clearly that the transverse field components oscillate at double the frequency of the compressional component. Other authors described the spectral effect seen in the compressional component as rectification (Coleman, 1970) or harmonic structure (e.g., Engebretson et al., 1986; Takahashi et al., 1990). The observations interested us but it was several years before we realized that the explanation lay with resonant particles (Southwood & Kivelson, 1997a). We chose to call the phenomenon frequency doubling, the change in nomenclature indicating our breakthrough in understanding. We linked the doubling effect detected in the compressional component directly to the waves being generated by resonating particles. The compressional component provides a magnetic pressure out of phase with the pressure in resonant bouncing ring current ions (ones with $|v_{||}/v_{\perp}| \gg 1$ at the equator) that satisfy Equation 1 with $m = 0$ and $N = 1$. Here the subscripts refer to the velocity components parallel and perpendicular to the field. The result showed that the waves were being excited by resonant transfer of energy from the resonating ions. Critical to our argument was the observation that, over complete bounce cycles, resonant particles would move inward or outward (thus gaining or losing energy) while they were bouncing. It was the net acceleration of the bouncing particles (and the corresponding change of thermal pressure) that modified the field magnitude and produced the periodic perturbations twice each wave cycle. This remains a remarkably clear example of the effects of charged ions on the perturbation fields of a wave. The resonant ion motion becomes organized asymmetrically about the equator. Ironically, at a far earlier time Dungey (1966) had speculated that such an effect might be observable, although he had in mind placing detectors pointing up and down the field near the equator to detect the effects. We ourselves had realized that the effect would be detectable where the spacecraft spin axis made a large angle with the field as noted earlier (Kivelson & Southwood, 1983). The paper is a rare example of a nonlinear theory that unambiguously points to bounce resonance as the source of observed magnetospheric pulsations and which is also coupled to observational evidence.

8. Mirror Mode Instability

Although our analysis of frequency doubling (Southwood & Kivelson, 1997a) identified unanticipated nonlinear effects arising from the behavior of subsets of particles in the plasma distribution, it was another strand of our work in the 1990s, similarly concerned with nonlinear behavior in compressional modes that attracted more attention. Two papers (Kivelson & Southwood, 1996; Southwood & Kivelson, 1993) on mirror mode waves built on our earlier work on particle behavior in compressional waves (Kivelson & Southwood, 1985a). Mirror mode waves appear in magnetometer data as quasiperiodic distinct oscillations in the field strength. The instability occurs at zero frequency in the plasma frame; the time-varying field detected on a spacecraft arises because quasi-static structures are carried over the spacecraft by the flow of the background plasma. Large amplitude waves are prevalent in planetary and cometary magnetosheaths and other high beta (plasma pressure > magnetic pressure) environments. The mirror instability was originally derived using MHD fluid theory (Vedenov et al., 1961), but we pointed out that, like the frequency doubling effect, a correct treatment requires that an MHD approach be combined with analysis based on kinetic theory (Southwood & Kivelson, 1993). Like the frequency-doubled waves, the mirror instability can be regarded as resonantly driven. However, in this case, the resonant particles are those with small parallel velocity along the background field and it is these that need the kinetic theory treatment. A special feature is that, in contrast with many resonantly driven instabilities that reduce gradients in velocity space or actual space through diffusive scattering of particles—making the plasma more uniform—the mirror instability saturates by making the plasma more nonuniform.

The dominant oscillation in mirror waves is in the field magnitude. However, although regular, the variation in field strength is often nonsinusoidal. Sometimes the field magnitude increases last longer than the depression within each cycle and sometimes the reverse (e.g., Joy et al., 2006). It is noticeable that the perturbation amplitudes remain fairly constant in time, neither rapidly growing nor decaying. This suggests that the waves are neither growing nor decaying. The original instability has saturated in a nonlinear state that is inherently spatially dependent.

Our second paper on the mirror mode (Kivelson & Southwood, 1996) describes the mechanism behind the nonlinear saturation process leading to the nonuniform spatial structure. The original instability depends on the anisotropy in the plasma pressure. For a bi-Maxwellian distribution with perpendicular pressure, $p_\perp$ and perpendicular and parallel temperatures, $T_\perp$ and $T_{||}$, the instability condition is

$$1 + \frac{2\mu_0 p_\perp}{B^2}\left(1 - \frac{T_\perp}{T_{||}}\right) < 0 \tag{3}$$

It is evident that not only does the perpendicular plasma pressure need to exceed the magnetic pressure, $B^2/2\mu_0$, but also there needs to be a temperature anisotropy, $T_\perp > T_{||}$.

Kivelson and Southwood (1996) show that the system stabilizes once the total perpendicular pressure (field plus particle) is balanced in the direction transverse to the background field and does not vary along the field direction. Two separate processes act to achieve this uniformity.

If the total perpendicular pressure is to be uniform in all directions, there must be higher perpendicular plasma pressure in regions where the field is depressed. Particles with low parallel velocity, confined in the low field region, contribute the excess pressure. The lower its parallel velocity, the deeper a particle becomes trapped in the weak field region in the wave structure through the mirror effect of the nonuniform field. When the structure is growing, these trapped particles are heated as they bounce back and forth in the increasingly localized magnetic minimum. On the other hand, the plasma population traveling along the field speeds up as it passes through the troughs in field and slows as it passes through the peaks in field. As Kivelson and Southwood (1996) describe, the plasma parallel velocity decreases in the peak field region while both density and perpendicular pressure increase in the weak field as the system evolves to the saturated state.

9. Plasma Interactions of the Jovian Moons and Other Small Bodies

Jupiter and its moons attracted scientific attention when observations by Burke and Franklin (1955) revealed that the Jupiter system was a source of strong radio frequency (decametric) emissions. Shortly after the discovery of the Earth's radiation belts, Drake and Hvatum (1959) proposed that decimetric radiation coming from Jupiter was synchrotron emission from electrons trapped in a Jovian radiation belt. Warwick (1963) and others inferred from the cutoff frequency of Jovian decametric radiation that Jupiter's dipole field has a magnitude of ~4 Gauss at the surface equator and Morris and Berge (1962) used decimetric emissions to identify the tilt of the dipole moment relative to the spin axis (9°), both very close to the correct values of Jupiter's tilted dipole field. In 1964, Bigg (1964) discovered that the intensity of Jovian decametric emissions varies with the orbital position of Io, a result seeming at the time more astrological than astrophysical.

Margaret, arriving at UCLA in 1967, was asked by Willard F. Libby to work with his PhD student, Robert G. Wilson, on analysis of the Io-related radiofrequency emissions. The process through which Io (Wilson, Warwick, Dulk, et al., 1968) (and even Europa; Wilson, Warwick, & Libby, 1968) modified the intensity of the radiation posed a challenge to theorists who, nonetheless, recognized that an interaction between Io and Jupiter's ionosphere required current to be flowing along magnetospheric field lines (Goldreich & Lynden-Bell, 1969; Marshall & Libby, 1967; Piddington & Drake, 1968). All invoked a MHD interaction between Io and magnetospheric plasma corotating with Jupiter but the process was poorly understood.

Opportunities for Margaret to learn more about outer planet magnetospheres arose in the early 1970s when the Pioneer 10 and 11 spacecraft flew by Jupiter and Saturn. Paul Coleman invited Margaret to become part of the team analyzing data from the magnetometers on these spacecraft. Some years later (1977), she became the Principal Investigator for the magnetometer investigation on the Jupiter Orbiter Probe spacecraft, soon to be renamed Galileo and destined to become the first spacecraft to be placed into orbit about Jupiter. Jupiter and its moons became even more central to our interests.

Our first joint work on the moons of Jupiter was inspired in part by a paper by Neubauer (1978) who had estimated plausible dipole field strengths of the Galilean moons (2,200 nT surface equatorial magnitude for Io and 200 nT for Ganymede) using a scaling law and limited knowledge of internal structure. The idea that any of Jupiter's moons might be magnetized suggested that they might have magnetospheres. The flow speed of that plasma toward the inner three Galilean moons is significantly smaller than the Alfvén speed. Intrigued by the thought that the sub-Alfvénic flow of Jovian plasma onto a magnetized moon would create an unusual interaction, we analyzed the process (Kivelson et al., 1979) arguing that it could account for "numerous puzzling features of the Jovian system." We considered extreme values of the orientation of the magnetic dipole moments. For a dipole moment aligned with Jupiter's dipole moment, we described the moon's magnetosphere as a "bubble with little asymmetry between upstream and downstream." Absent evidence of direct influence of the outer moons on Jovian radiation, we suggested that, if they were magnetized, their dipole moments would be aligned with Jupiter's. On the other hand, a strong interaction, for which there was clear evidence, would be expected at Io if its dipole moment were antiparallel to Jupiter's. Unlike Goldreich and Lynden-Bell (1969), we assumed that the Jovian field would move through Io's ionosphere. We imagined that the interaction would produce a magnetic cavity that might extend far downstream of Io (our estimate was 8° of longitude) and that the presence of a magnetic cocoon would explain how Io retains its ionosphere.

More data became available in 1979/1980 when the two Voyager spacecraft flew past Jupiter (the first step in their solar system odyssey that three decades later took them into the local interstellar medium). In particular, Voyager 1 passed directly below the innermost Galilean moon, Io, and detected a strong magnetic signature (Ness et al., 1979) as well as interesting energetic particle signatures (Krimigis et al., 1979) arising from the interaction of Jupiter's magnetospheric plasma with the moon. The new results led us to take a more serious look at the interaction of Jupiter's flowing plasma with Io (Southwood et al., 1980). Voyager 1 had flown through the Io flux tube about 20,000 km below the moon. In discussing the observed magnetic perturbations, we described the expected structure of the interaction region. Recognizing that the upstream field would bend as the flow slowed near Io's latitude but not above or below it, the disturbance then propagating along the field at the Alfvén speed while the field was convected downstream, we described the interaction as Alfvén wings (a term introduced by Drell et al., 1965, in relation to spacecraft in Earth's environment). Our paper appeared shortly after the publication of a more complete and very elegant treatment of the interaction by Neubauer (1980). Images that revealed an active volcano (Morabito et al., 1979) seemed to support the speculation that Io was partially molten, currently active, and might indeed be magnetized. We described what the interaction region would look like for such a situation, drawing an image for Io's environment (Figure 3) that resembles models of the interaction at Ganymede (which turned out to be the only magnetized moon).

Although our discussion of the interaction was framed in the language of MHD waves, we did not describe the full picture that arises when the plasma is sufficiently warm that the effects of the slow mode are also

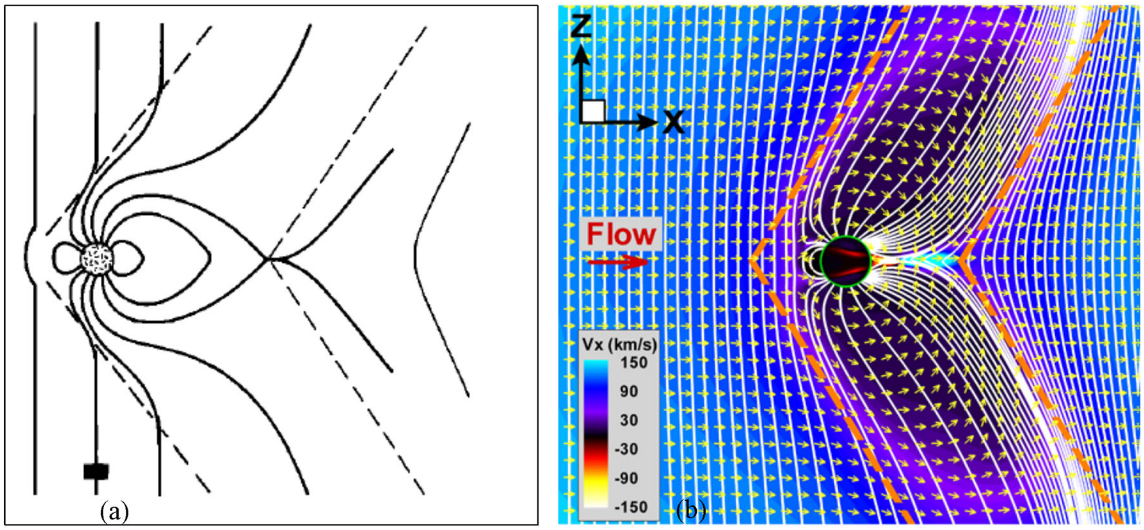

Figure 3. (a) From Figure 4b of Southwood et al. (1980), a schematic of field lines linked to a magnetized Io, shown in the plane of the flow and the field through Io's center. The dashed lines starting just upstream of Io identify the fronts referred to as Alfvén wings. (b) Figure 4a of Jia et al. (2009) showing field lines extracted from an MHD simulation of the interaction at Ganymede in the analogous plane and marking the Alfvén wings.

present. Some years later, Linker et al. (1988) simulated the interaction, showing that downstream of the Alfvén wing, a slow mode wing forms at an angle consistent with disturbances propagating along the field at the slow mode speed while being convected downstream at the background flow speed.

Years of intense effort and patient waiting were rewarded when the Galileo spacecraft entered the Jovian magnetosphere in late 1995. Flybys of the moons revealed unambiguously that Ganymede had a remarkably large planetary magnetic field (Kivelson et al., 1996; Southwood & Kivelson, 1997b). Flybys of Io were more difficult to interpret and for many years we found that we could explain our measurements with or without assuming that Io had a magnetic field (e.g., Khurana et al., 1997; Kivelson et al., 2001). It was only on Galileo's final passes by Io (August and October, 2001) that data were acquired at very low altitude in regions where plasma perturbations were not dominant, allowing us to conclude that there is no intrinsic magnetic field at Io.

The coup de grace for any proposal of Io internal field was delivered by the I31 pass in August 2001. The spacecraft was very close to periapsis and traveling close to azimuthally. The trajectory took it almost along the midplane of Io in its orbit and just over 0.1 R_{Io} (R_{Io} is Io's radius = 1821.6 km) above the surface at its closest point. Figure 4a shows the orbit in the *(X, Y)* plane in a local Io-centered system. The incident corotating plasma flow is in the $+X$ direction. The relative speed between Io and the corotating plasma is 57 km s^{-1}. The Z axis is parallel to the Jovian rotation axis and Y is positive toward Jupiter. The blue line shows that the spacecraft approaches from upstream and then spends an extended period in the wake. The spacecraft velocity relative to Io is 3.5 km s^{-1} and the 8 R_{IO} illustrated is covered in 2100 s (35 min).

Figure 4b shows the magnetic field perturbation data in Io-centered coordinates sampled at three samples/s by the spacecraft magnetometer plotted against spacecraft X position. The spacecraft position in Y and Z is shown below the X axis. A model Jovian magnetic field (Khurana, 1997) has been subtracted from the measured fields to provide an estimate of the perturbation due to Io. The traces ΔB_X (black), ΔB_Y (red), ΔB_Z (green) represent the perturbation field components (in nT) in the Io-centric system. ΔB_T (blue) is the difference between the model field magnitude and the observed field strength. At closest approach to Io, on Aug 06 04:59 when the spacecraft is at $X = 0$ and 197 km above the surface, the subtracted (model) field has components (225, −842, −1967) with magnitude 2,091 nT.

The field strength through the encounter is the strongest evidence that there no internal source of field. The blue (field magnitude) trace in Figure 4b is the smoothest trace showing an overall bipolar variation (~±150 nT). There is a field compression upstream that increases until the spacecraft moves to where it is above the moon (near $X = -1$). Here there is a fairly flat maximum and then the field magnitude

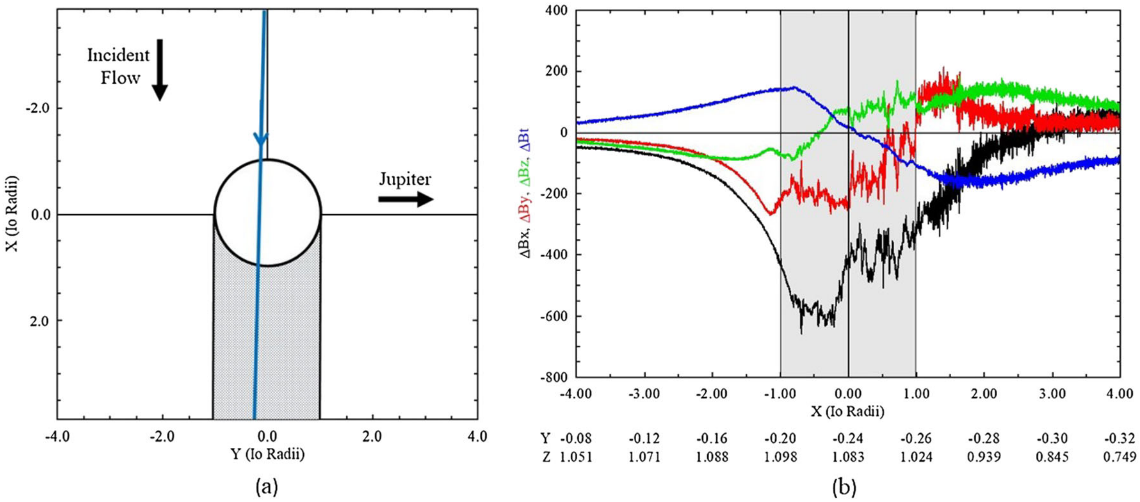

Figure 4. (a) The trajectory of Galileo on the I31 pass in the *X-Y* plane of an Io-centered coordinate system defined in the text. (b) The perturbation magnetic field from measurements of the Galileo magnetometer in the same coordinate system. Colors indicate field components in nT (*X*: black, *Y*: red, Z: green, magnitude: blue). Distances are in Io radii.

decreases before decreasing to zero close to $X = 0$ where the spacecraft is over the pole of the moon. The field rarefaction continues until $X = 2$ where the spacecraft is no longer over the moon and well into the wake region. Overflying Ganymede, which does have an internal field, one might detect a bipolar signal but it would ordered by the moon and (cf. a dipole source) there would be a corresponding peak in amplitude in a component at right angles.

The overall change ΔB_x is the largest perturbation overall. With total amplitude of ~600 nT, the large-scale perturbation is effectively unidirectional. The upstream undisturbed field B_x component is ~200 nT implying that the upstream field in the *X-Z* plane is tilted toward the flow direction by ~6°. Near the moon, the field is tilted by 16–17° in the opposite sense. The reversal in the vicinity of the moon, means that currents flowing through Io or its immediate environment are exerting a force in the direction of Io's motion. The perturbations are transmitted from Io by Alfvén waves, bending the flux tubes near Io to form Alfvén wings.

Upstream all components show a smooth increase until the spacecraft reaches approximately $X = -0.8\ R_{Io}$. Beyond that point ΔB_X and ΔB_Y and also to a lesser degree, ΔB_Z, vary more than ΔB_T on short time scales, implying that these signals (discussed in connection with the coupling of field-aligned current from Io to the Jovian ionosphere by Chust et al., 2005) are transverse to the background field. The onset appears quite rapid once the field line enters a regime where the local field passing through the spacecraft would connect to the moon itself. There is no evident front as the spacecraft changes regime. This means that there is no magnetopause separating a moon-associated regime from the unperturbed upstream plasma. The absence of any shear in the field means that, although the compression upstream is deflecting the flow and, with it, the frozen in field around the moon, the incident flux moves across the moon and presumably penetrates the moon. The sharp changes in the transverse field detected once the spacecraft is magnetically connected to the moon are symptomatic of field-aligned currents. The currents should close through the body of the moon (or a possible ionosphere).

In contrast with the upstream encounter in the regime where the field connects to the moon or its immediate environment, on the downstream portion of the pass, coincident with the spacecraft reaching $X = 1$ and entering the wake region, there are field shears in ΔB_X and ΔB_Y and also to a lesser degree, ΔB_Z. Thus, there is a thin current sheet marking the edge of the direct moon environment. In the wake, there is further transverse magnetic field activity on the shortest scales detectable. The signals commence at $X = 1$ and are visible in all three components but not the field magnitude. The spectrum peaks at 0.4 Hz; these are SO_2^+ ion cyclotron waves that have been previously reported on the flanks and in the downstream wake of Io (see, e.g., Russell et al., 2001).

Perhaps the most intriguing feature occurs in midpassage over the moon. At $X = 0$, there is a sharp change of more than 200 nT in ΔB_X close to $X = 0$ where the field would map near the pole of the moon. Subsequently,

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as the spacecraft moves toward the wake, there are large 100 nT oscillations in ΔB_X and ΔB_Y and smaller ΔB_Z changes (~50 nT). These appear coherent in all three components and represent purely transverse field changes as there is no sign in the blue field magnitude trace. The signals imply that the local plasma flow over the moon is being severely disrupted and is launching small-scale structures within the standing Alfvén wave system attached to the moon itself, corresponding to the filamentation of current discussed by Chust et al. (2005).

10. Order in Magnetosheath Flow

The magnetosheath, the region between the terrestrial bow shock and the magnetopause, is often thought of as turbulent and disordered. However, within the region, much or all of the submagnetosonic flow needs to be deflected around the magnetospheric obstacle downstream. Thus, although there may be apparent chaos, there will be order underlying it. Accordingly, in the 1990s, we brought ideas from some of our earlier work on plasma wave fronts set up by obstacles such as the Jovian moons or small bodies in the solar wind to bear on interpretation of features of the Earth's magnetosheath. Much as in our work on mirror modes (often present in the magnetosheath), we sought evidence of spatially ordered structural features in the magnetosheath flow.

The outer boundary of the sheath is the bow shock. If the flow of the solar wind were purely gas dynamic, that is, if the forces associated with the presence of the magnetic field were completely negligible, then the shock wave standing upstream of the magnetosphere would compress the supersonic upstream flow and divert the resulting downstream subsonic flow downstream around the obstacle represented by the magnetosphere. Along a streamline starting near noon, the density would increase with decreasing distance from the magnetopause and the inward pressure gradient that formed would divert the flow around the magnetospheric obstacle. As long as the obstacle is symmetric east-west and north-south, the flow maintains the same symmetries. The global peak in pressure in the sheath would be located at a stagnation point adjacent to the subsolar point of the obstacle.

Independent of the obstacle shape, the situation is more complicated if magnetic forces become important. The magnetic field direction becomes significant and can potentially disrupt the symmetry imposed by the obstacle shape. In 1976, Zwan and Wolf (1976) provided a theoretical illustration of how a magnetic field in the incident solar wind could change conclusions reached on the basis of gas dynamics. They considered a situation where the magnetic field was oriented north-south and described the motion of plasma on a flux tube whose midpoint was on a streamline directed toward the nose. As the tube moved toward the subsolar point, the magnetic field would increase and the cross section of the tube would decrease. The result would be to squeeze the flux tube near the subsolar point and plasma would then move along the tube away from the subsolar region. This effect would deplete plasma in the subsolar region, a result opposite to what simple gas dynamics predicted.

In 1990, Song et al. (1990) used spacecraft date to investigate the density variation on 26 passes of the ISEE 1 spacecraft in the magnetosheath near the subsolar point. They reported that the Zwan-Wolf effect (plasma depletion near the magnetopause) appeared clear on two passes but that on more than half of the passes there was a density enhancement with a decrease in field strength, in contradiction to the predictions of both gas dynamics and the Zwan-Wolf analysis.

We decided that it would be useful to describe the evolution of plasma and field properties across the magnetosheath in terms of the fundamental waves of an MHD system. In classical MHD, there are three wave modes: fast, Alfvén (sometimes called the intermediate mode) and slow. Fast and slow modes are compressional and, accordingly, can steepen to form shocks where flow energy is converted into thermal energy. The bow shock itself is a steepened fast mode wave. Passing through the shock, the flow decreases and the magnetic field is compressed. In Southwood and Kivelson (1992), we made two key points. Firstly, just behind the shock the speed of the flow, though subfast, may well exceed the slow mode speed (and also the Alfvén speed), so flow cannot be treated as quasi-incompressible. Depending on how the flow needs to be deflected in order to avoid the obstacle, either a slow or an Alfvén mode polarization will be needed. Accordingly, fronts in the overall flow associated with one or the other of the wave modes may form. However, only the slow mode can evolve into a shock as the Alfvén mode is incompressible.

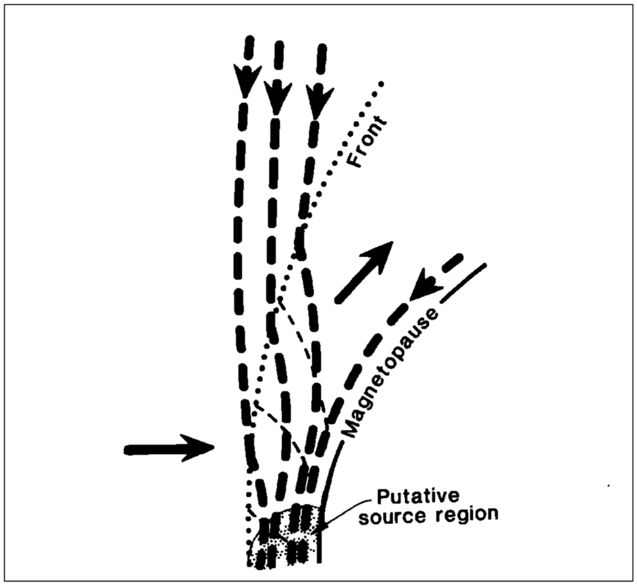

Figure 5. Schematic of field lines (heavy dashed lines), isobars of plasma pressure (light dashed curves), and a slow mode front (dotted curve) near the magnetopause for a northward interplanetary magnetic field from Southwood and Kivelson (1995), their Figure 4. The flow direction is shown with heavy arrows.

We considered how those other wave modes would structure the flow in regions downstream of the bow shock but upstream of the subsolar stagnation point. We argued that they would form standing fronts in the flow. Whether or not the slow mode front formed a shock (i.e., whether heat was locally added to the flow) was less important to us than characterizing the global structure of the upstream boundaries that limit the sunward propagation of intermediate and slow waves generated by the magnetopause obstacle. Critical to our simple approach was to assume that the plasma pressure ratio (β) was greater than 1, that is, large enough that the sound speed would be greater than the Alfvén speed. This is normally the case in the magnetosheath. The two slower modes then have close to the same phase velocity ($V_A \cos\theta$ where θ is the angle between the field and the front normal, $\hat{\mathbf{n}}$). The intermediate mode wave can bend the field and the flow in the same direction out of the plane of the field **B** and $\hat{\mathbf{n}}$. However, only the slow mode contributes to the front across which the flow bends in the plane containing **B** and $\hat{\mathbf{n}}$, a front across which the field magnitude decreases and the density increases. This meant that the flow diversion around the obstacle could be produced entirely by a slow/Alfvén front (consistent with observations from the ISEE 1, 2, and 3 spacecraft reported by Song et al., 1992). Compression (increase of plasma pressure) near the subsolar point (see Figure 5) would set up conditions for an expansion fan (along the flux tubes, associated with the fast mode) upstream of the front, implying drops of plasma density (depleted flux tubes) near the magnetopause away from the subsolar point. Hence, in this paper and a subsequent one (Southwood & Kivelson, 1995), we resolved the apparent contradiction posed originally by the conflicting predictions of the Zwan-Wolf theory and what the simplest slow mode notion predicted.

11. Outer Planet Magnetospheric Circulation: Interchange Motion

Although the properties of Jupiter's moons were not extensively investigated until the Galileo era (1995–2003), already in 1979, the Voyager 1 and 2 spacecraft had returned a bonanza of data for magnetospheric science. Volcanoes on Io fed a cloud of neutral material that, in turn, served as the ultimate source of a torus of heavy ions confined close to the magnetospheric equator with an inner boundary near the orbit of Io. Before Voyager, the Jovian magnetosphere had been regarded as either like the Earth's, with the solar wind the primary plasma source, or like a pulsar with a centrifugally driven wind of material from the ionosphere (see, e.g., Kennel & Coroniti, 1975). The significant role of Io as a plasma source deep in the equatorial inner magnetosphere had been unforeseen. With the presence of the Io plasma torus established, we recognized that transport might be described in terms of flux tube interchange, a concept discussed for Earth by Gold (1959) in the paper that introduces the term "magnetosphere."

Gold (1959) was working when it was believed that plasma trapped in the magnetosphere originated in high field regions (i.e., near Earth). The discovery of the continuous Io plasma source deep in the Jovian magnetosphere, but well beyond regions where gravity was the dominant inertial force, meant that there must be a centrifugally driven transport of ionized material outward to be lost eventually into the interplanetary medium. Deep in the magnetosphere the magnetic field pressure dominates overall pressure and then the energetically preferred motions are those that do not change the magnetic field, interchange motions. When the inward gradient of plasma density is large enough, the motion will occur spontaneously. This is interchange instability. If the system is left to evolve with the plasma source remaining steady it will do so until the density gradient matches the critical gradient. (Cheng, 1985; Melrose, 1967; Southwood & Kivelson, 1987, 1989; Summers & Siscoe, 1985).

Interchange is an MHD process and so outward transport of entire flux tubes transports not only plasma, but also magnetic flux. Outward flux transport must be balanced by inward motion of flux tubes returning from

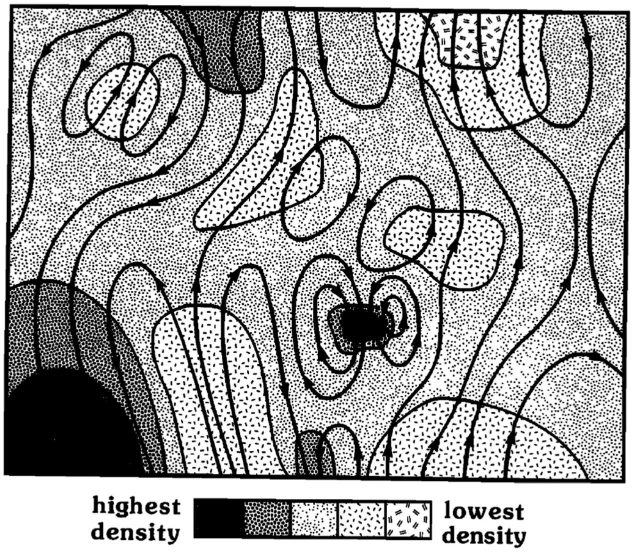

Figure 6. From Southwood and Kivelson (1989), their Figure 4. Schematic "snapshot" of the equatorial cross section of a portion of the Io plasma torus showing varying flux tube content (gray scale) and flow directions. The distributions in space and in scale size is assumed random. However, flux tubes with high plasma content will, over long times, show net outward motion whereas flux tubes with low plasma content will show net inward motion. Magnetospheric flux tubes are anchored in Jupiter's ionosphere and, although magnetospheric conditions determine whether tubes move inward or outward, the speed of the process depends inversely on the ionospheric conductance.

wherever plasma loss occurs. The inward-moving flux tubes would be depleted in low-energy heavy ion plasma but might contain energetic plasma typical of the middle magnetosphere.

The spatial scale of the interchange was uncertain. The transport could, in principle, occur on a global scale, much as the convection-driven interchange flow in the terrestrial magnetosphere returns plasma from the magnetotail to the dayside magnetopause. Equivalent at Jupiter would be a two-cell convection pattern (Hill et al., 1981) with large azimuthal scales of inward-moving and outward-moving plasma. However, the observed near monotonic fall-off of flux tube content with radial distance seemed inconsistent with that assumption. Alternatively, transport could occur in localized small-scale motions, possibly of the sort illustrated in Figure 6 from Southwood and Kivelson (1989). In this picture, random fluctuations of flux tube plasma content lead to apparently random displacements of full and empty flux tubes, but, on average, those with high flux tube content move out. If the average rate of outward transport of dense flux tubes was slow and the inward transport of low-density flux tubes was rapid, the spatial scale of the depleted flux tubes could be quite small; very rapid changes of plasma density would be detected intermittently. This picture is inconsistent with the conclusions of Richardson and McNutt (1987) who found no evidence that adjacent flux tubes of significantly varying density were present in the Io plasma torus on the Voyager 1 flyby of Jupiter. They based their conclusion on analysis of 93 min of plasma measurements (time resolution of 0.24 s and spatial resolution of about 20 km) between 9 and 7 R_J acquired on the inbound leg on which they found no density fluctuations of 10% or greater. Untroubled by this evidence, we continued to analyze the interchange process assuming that the failure to find significant density changes in previous analysis proved not that depleted flux tubes are absent, but that they are highly intermittent. We were gratified when Galileo data acquired in the Io torus identified rapidly varying flux tube content (average duration of 26 s) on its inbound pass near Io (Kivelson et al., 1997; Thorne et al., 1997). A few years later, Russell et al. (2000) investigated all of the high time resolution data collected by the Galileo mission and found that depletions are observed only "about 0.25% of the observing time in the region of the Io torus," thus justifying our assumption.

Our theoretical analysis based on MHD was not capable of establishing the scale of the overturning flux tubes but we argued that coherence over large azimuthal distances was unlikely. We described constraints on the potentially stabilizing effect on plasma outflow of a positive radial gradient of particle pressure (ring current impoundment) near the outer edge of the dense torus (Siscoe et al., 1981). In the MHD treatment, the growth rate of the instability increases with the wave number of the convecting flux bundles. For large enough wave number, the length scale of perturbations decreases to the order of the gyroradius of energetic ions and they would no longer be bound to the field. We used this to set a rough upper limit to the wave number (k) of the interchange growth rate (i.e., $k \geq 2\pi/\rho_{\mathrm{gyro}}$) where ρ_{gyro} is the gyroradius of a ring current ion. Structures of scale smaller than this lower bound would not be slowed in their radial motion. Thus one could understand the small spatial scale of inward-moving flux tubes as determined by the scale of the fastest-growing structures able to contain ring current ions.

Far from the planet the plasma pressure and the dynamic pressure associated with the centrifugal effects in a fast-rotating magnetosphere become comparable to the magnetic pressure. We will return to this issue in the global circulation section.

12. Magnetometer Results From the Galileo Spacecraft

Although we started our careers as theorists and spent our formative years analyzing data, we both eventually found ourselves leading major instrument teams on NASA missions. As previously noted, in the late 1970's Margaret became the Principal Investigator for the Galileo (Jupiter Orbiter) magnetometer and a decade later David became the Principal Investigator for the Cassini (Saturn Orbiter) magnetometer—of which more anon. Both missions turned out to be stunning successes.

Galileo was launched on the space shuttle Atlantis on 18 October 1989, but, because of limitations imposed on the launch vehicle following the tragic loss of Challenger, the originally anticipated 2 year voyage to Jupiter had transformed into a 6 year cruise that called for multiple gravitational assists from Venus and Earth. Although our primary objective was to learn about Jupiter's magnetosphere and its large moons, we found that measurements acquired on the way to Jupiter provided opportunities to examine the interactions of small bodies (the asteroids Gaspra and Ida) with the solar wind (Kivelson et al., 1995a; Wang et al., 1995) and to identify how the orientation of the interplanetary magnetic field controls the shape of the bow shocks downstream of Venus (Kivelson et al., 1991) and Earth (Kivelson et al., 1995b).

During the long cruise phase the failure of the high gain antenna, whose power was needed to transmit our data at a fraction of a second time resolution, was confirmed. Repairs in space may happen for an instrument on a satellite in low Earth orbit (i.e., the Hubble Space Telescope), but not for one en route to an outer planet. The antenna remained nonfunctional but some brilliant coding by Tal Brady of the Jet Propulsion Laboratory (Clow, 2013) and Joe Means of UCLA enabled us to retrieve highly compressed data transmitted by a small supplementary antenna. We were able to measure the magnetic field of Jupiter's magnetosphere at very low time resolution throughout most orbits. The new system also enabled us to acquire data at our original cadence for roughly 1 hr around each satellite encounter and store it on a tape recorder for delayed transmission.

Galileo's tour at Jupiter confirmed us as data analysts, eagerly awaiting the latest downloads. It still gratifies us to think about how much we were able to learn from a constrained data set. In particular, using the information acquired over multiple years in orbit about Jupiter, we described aspects of solar wind control of the magnetosphere, put together arguments regarding the global dynamics of the system, and characterized important features of the Galilean moons based on how they interacted with magnetospheric plasma.

13. A Two Spacecraft Study at Jupiter

Our joint involvements in Galileo and Cassini missions offered one special opportunity. The structure of Jupiter's magnetosphere is imposed in large part by the rapid rotation of the magnetospheric plasma, but it seemed likely that the solar wind not only shaped and confined the magnetosphere but also played a role in the dynamics of the system. However, the lack of a solar wind monitor upstream of Jupiter or Saturn made it hard to assess the contributions to magnetospheric dynamics arising from interactions with the solar wind. Therefore, we were particularly intrigued by the interval from October 2000 to March 2001 when the Cassini spacecraft flew by Jupiter en route to Saturn, with the Galileo Orbiter still acquiring data in Jupiter's magnetosphere. David's magnetometer became a solar wind monitor and provided the information needed to understand the changes that Margaret's magnetometer was observing in the outer region of the magnetosphere. The spacecraft orbits are illustrated in Figure 7 (from Kivelson & Southwood, 2003). Cassini's path goes past the dusk flank of the magnetosphere, whereas Galileo is in an eccentric planetary orbit whose axis is close to the dusk meridian.

On day 342 of 2000, the Cassini spacecraft recorded an interplanetary shock far upstream of Jupiter. Some 15 hr later at Galileo's location on the dawn flank, a compression driven by an interplanetary shock displaced the magnetopause and the Jovian bow shock inward. For some time following this displacement and after moving into the solar wind, Galileo intermittently found itself either in the magnetosheath, that is, beyond the magnetopause but still planetward of the bow shock, or in the solar wind, that is, outside the bow shock. Cassini magnetometer data showed no evidence of significant variations of field magnitude in the day following the shock's passage, but there were clear field rotations. We found that the displacements of the Jovian bow shock—time delayed to correspond to the propagation of the rotated field from Cassini's location to the bow shock—correlated with changes in the north-south orientation of the interplanetary magnetic field detected by Cassini behind the shock. At Earth, the position of the magnetopause depends on the north-south component of the interplanetary magnetic field. When there is a southward component in the external field, the magnetopause moves planetward due to erosion of flux by magnetic reconnection. The reduced size of the magnetosphere causes the bow shock as well to move planetward. Jupiter's dipole is oppositely directed to Earth's and the data showed that northward turnings (facilitating reconnection

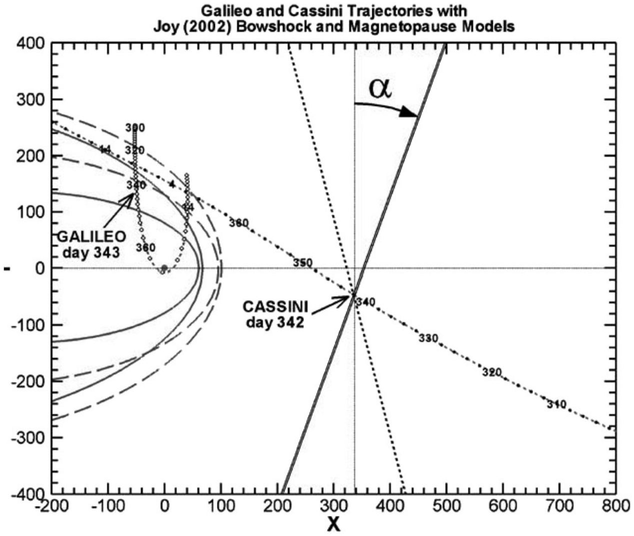

Figure 7. Original caption from Kivelson and Southwood (2003): Trajectories of Galileo and Cassini in December 2000 and January 2001 during the Cassini flyby of Jupiter. Labels on the trajectories provide the day of year in 2000 (numbers in the 300 s) or 2001 (numbers less than 100). On the Cassini (Galileo) trajectory, black dots (open circles) are separated by 2 days. The approximate positions of Galileo and Cassini during the interval discussed in this paper are indicated. Because the boundaries move in response to solar wind dynamic pressure changes, the positions of the bow shock (dashed curves) and magnetopause (solid curves) are plotted for both the compressed and the expanded magnetosphere using statistically determined locations reported by Joy et al. (2002).

near the nose of Jupiter's magnetopause) corresponded to inward motion of the shock over Galileo and southward turnings corresponded to outward shock motion. The fractional change of size of the magnetosphere was small, but the small variation detected provided the first evidence that reconnection affects the global configuration of Jupiter's magnetosphere and thus also contributes to the internal circulation of the system.

14. Effects of Solar Wind Dynamic Pressure

Ironically, shortly before we found the evidence just described that the orientation of the interplanetary magnetic field affects the magnetosphere by changing its scale, we had published a theoretical paper (Southwood & Kivelson, 2001) exploring the possibility that it is changing dynamic pressure of the solar wind rather than the orientation of its field that is most important for understanding temporal variations within Jupiter's magnetosphere. Our proposal recognized the importance of rotational stresses in the magnetospheres of Jupiter and Saturn. In both systems, the planetary rotation period is short compared with the time for solar wind to flow past the planet, quite different from the situation at Earth. In addition, both magnetospheres are loaded with heavy ion plasma, confined principally near the magnetic equator, from sources associated with moons. At Jupiter, the existence of a heavy ion plasma localized near the equator had already been fully established before Galileo's arrival. A heavy ion plasma whose source is geysers on the Saturnian moon, Enceladus, was discovered only some years later with the first hints of the existence of a plasma source revealed in magnetic perturbations recorded by the Cassini magnetometer (Dougherty et al., 2006). As described earlier, as long as sources are active, ionized material diffuses outward, eventually to be lost into interplanetary space. Were the plasma to move outward conserving angular momentum, its angular velocity would decrease. This does not happen because, in parallel with the outward diffusion, a global current system provides angular momentum from the planetary atmosphere/ionosphere (Hill et al., 1981). Electron precipitation associated with the upward field-aligned portions of the currents are a primary cause of the Jovian main auroral oval and of the characteristic decametric radiofrequency emissions previously discussed.

Field-aligned currents also drive much of the aurora seen at Earth; in the terrestrial case, these currents arise through solar wind-magnetosphere-ionosphere interaction and not through rotation. At Earth, a shock in the solar wind almost certainly increases auroral activity. We posed ourselves the question whether this would be the case in magnetospheres where the primary driver of the aurora is planetary rotation. Regarding the primary effect of the arrival of an interplanetary shock at the planetary magnetosphere as a reduction of the magnetospheric volume, we pointed out that the equatorial plasma would be displaced inward, closer to the planet and thus closer to the axis of rotation. The demand for transport of angular momentum from Jupiter's ionosphere would diminish and the stress in the magnetic field and associated field-aligned current would decrease. Accordingly, we proposed that the response of a fast-rotating magnetosphere like Jupiter's to an interplanetary shock should be a reduction of auroral activity. In contrast, a solar wind rarefaction would lead to an expansion of the outward diffusing plasma sheet and thus to increased magnetic stress between ionosphere and magnetosphere, intensified field-aligned currents and thus enhanced aurora. The counterintuitive idea that enhanced solar wind pressure might reduce the brightness of the Jovian aurora was put forward at about the same time by Cowley and Bunce (2001). The originally surprising idea that enhanced solar wind pressure might reduce the intensity of the Jovian aurora is also supported by simulations (Yates et al., 2012).

Our proposal focused on the magnetospheric processes that drive the main aurora and applied most directly to its dayside arc. We failed to take account of the fact that Jupiter's aurora is complex and that there appear to be multiple sources of auroral activity that might be difficult to disentangle. Our suggestion was contested with evidence that contradicted our prediction. Gurnett et al. (2002), for example, found that the interplanetary shock observed by Cassini on day 342 of 2000 (see Figure 7) produced an increase in the intensity of Jovian hectometric radiation (closely associated with auroral activity) and of extreme ultraviolet emissions. Prangé et al. (2004) reported that a (forward) shock propagating through the solar system triggered enhanced auroral emissions consecutively at Earth, Jupiter, and Saturn. Clarke et al. (2009) found a relationship between solar wind conditions and auroral emissions but also observed changes of intensity independent of the solar wind. Hess et al. (2012, 2014) concluded that "the relation of Jupiter's auroral emission to solar wind pressure is complex." One source of complexity is the uncertainty of the shock arrival time and the fact that forward shocks are typically followed by reverse shocks typically by a day or two, often within the uncertainty of the prediction of arrival time.

Observations suggested that our argument was either wrong or incomplete. We realize now that our description of the response of the dayside aurora may be valid but that the response may differ on the night side. We still believe that when a shock hits the magnetosphere, it compresses the dayside cavity and reduces its volume. The plasma on the dayside in the equatorial region must then move planetward as we originally envisioned. The shrinkage of the dayside cavity would reduce the stress between the ionosphere and the magnetosphere and the currents in the system would weaken as would any associated auroral activity. However, the response of magnetospheric plasma to a traveling shock may differ on the night side. In that local time sector, the compression imposes an antisolar traveling compression on the magnetotail that may well displace the equatorial plasma downtail and away from the planet, stressing the stretched field lines and thus generating currents and increasing nightside auroral activity. It seems likely that the increase of auroral activity observed in association with interplanetary shocks comes predominantly from parts of the aurora that map to the magnetotail.

Hess et al. (2014) characterize not merely global brightening or dimming, of the aurora but also identify the local time sector where the changes occur, and they do find different responses at different local times. They find that fast reverse shocks drive emissions at dawn and dusk, consistent with our predictions. Fast forward shocks, on the other hand, trigger emissions in the dusk sector but not the dawn sector. They suggest that the cushion region (which lies beyond the nearly corotating portion of the dayside magnetosphere in the morning sector) absorbs the magnetospheric compression imposed by the shock, leaving much of the magnetospheric plasma unaffected in this sector. It is not clear how they account for the dusk side emissions, but they may arise through the magnetotail response just described. Furthermore, once it is accepted that part of the solar wind-Jovian interaction is associated with magnetic reconnection as indicated by the change of magnetopause location with the orientation of the interplanetary magnetic field (Kivelson & Southwood, 2003), there will be elements of the overall global field-aligned currents that are attributable to an Earth-like interaction. Such effects should be more evident on the night side, whereas the reduction in stress would be dominant on the dayside. Overall an asymmetric change in the aurora, a dayside reduction and a nightside enhancement, could result. We hope that future observations will establish more clearly the locus of auroral brightening associated with interplanetary shocks.

15. Global Circulation, Ion Acceleration, and Plasma Loss

Kivelson and Southwood (2005) marked a return to looking at plasma circulation within the Jovian magnetosphere. Written after the Galileo mission ended, the paper aimed to provide a conceptual framework for understanding the significance of all available plasma and field observations at Jupiter. Our work expanded on ideas introduced by Vasyliūnas (1983), which described features of the overall plasma circulation pattern (see Figure 8a) in a rotationally dominated magnetosphere. Our intention, as the annotations in Figure 8b show, was to fill out the picture by discussing the dominant physical processes affecting the plasma near the equatorial plane in different local time sectors.

Large local time variation in the Jovian system was known to be substantial. Galileo had acquired data in Jupiter's equatorial region from dawn through the night sector, ending near noon. Pioneer, Voyager, and Ulysses flyby data had provided data in the equatorial region near midmorning. Prior to the 2016 arrival of the Juno spacecraft in polar orbit, little data had been acquired away from the equator. Nonetheless, Ulysses probed regions near 35° southern latitude in the dusk sector on its outbound orbit and Pioneer 11's outbound orbit took it to relatively high positive latitudes near noon.

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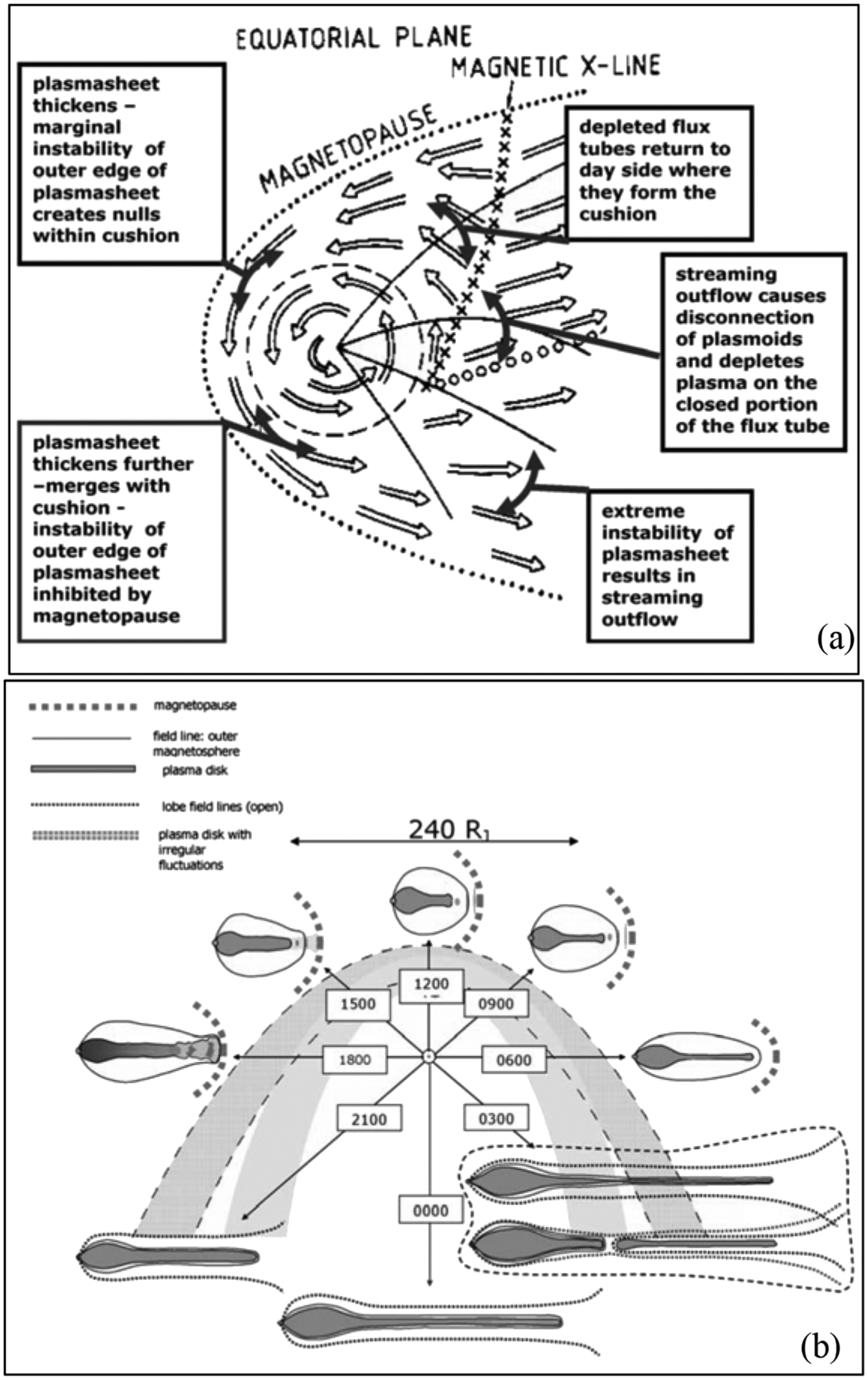

Figure 8. (a) The equatorial plane of Jupiter's magnetosphere as represented by Vasyliūnas (1983). Labels indicate the interpretation of the dynamics in the schematic in terms of the processes discussed in Kivelson and Southwood (2005). (b) From Kivelson and Southwood (2005), their Figure 7. Background: cut of equatorial magnetosphere showing nominal locations of the bow shock and the magnetopause. Sketches linked to arrows that represent cuts at different local times provide schematic meridional views of an outermost field line, the magnetopause (dotted), and the plasma sheet (dark gray). For meridians that do not intersect the magnetopause, dotted lines are lobe field lines.

The large dawn-dusk asymmetry in the field and accordingly, in the plasma distribution was our starting point. Near dawn, the plasma sheet is thin (~2–4 R_J thick) and above and below the magnetic field is close to radial. In contrast, on the dusk side Galileo found the field dominated by its north-south component even 10 R_J away from the centrifugal equator (see Figure 24-20 in Khurana et al., 2004). Moreover, the particle data obtained on the Ulysses outbound afternoon pass showed that the plasma sheet was more than 20 R_J thick (Lanzerotti et al., 1993).

Figure 8b illustrates the local time dependence of the field and the equatorial plasma conditions that we envisaged. As a flux tube rotates around the planet it undergoes a cyclic process. Starting on the night side, we argued that, as flux tubes rotate across the magnetotail, an outflow of material down tail causes the thinning of the plasma sheet. Eventually as the tube moves eastward flux tubes break, indicated in Vasyliūnas's sketch by the line of crosses representing reconnection at a magnetic X-line. A large fraction of flux tube plasma content becomes magnetically detached from the planet and will escape downtail. Outward diffusion of ionized material from the Io torus will eventually replenish the plasma lost down tail over the rest of the cycle.

In the early morning sector, the depleted tube shortens and moves toward the dayside. Tubes are still stretched but the depletion means the sheet is now thin. Indeed, at the largest radial distances near dawn, quasi-dipolar flux tubes on which the equatorial plasma is tenuous enough not to distort the magnetic field form what is referred to as the cushion region (a term introduced by V. M Vasyliūnas). This region extends from the distinct outer edge of the plasma sheet where magnetic field tension can just keep material in motion about the planet out to the magnetopause. From time to time, due to changes in pressure balance, plasma will break off from the outer edge of the sheet in blobs in the cushion region giving rise to the magnetic nulls first reported during the Ulysses Jupiter flyby (Southwood et al., 1993).

As the plasma rotates to noon and beyond, two features of the data change. The plasma sheet thickens but also the cushion region disappears. The thickening occurs in the afternoon because the rotating flux tubes move outward because of the flaring of the magnetopause. Particles on the flux tube are, on average, displaced to ever larger radial distances and experience centrifugal acceleration increasing the parallel plasma pressure. The relation to plasma heating and associated thickening of the plasma sheet is investigated quantitatively in papers by Vogt et al. (2014) and Kivelson (2015). Pitch angle scattering (probably mediated by the fire hose instability) converts the increased parallel pressure into perpendicular pressure. The increased perpendicular pressure, in turn, leads to the more dipolar form of the field in the postnoon sector. The absence of the depleted tubes of the cushion region remains to be fully elucidated.

Once past dusk, the newly heated and loaded flux tubes rotate into the expanding volume of the planetary magnetotail stretching the field once again. Centrifugal acceleration along the quasi-radial field drive outflow and, as we described above, eventually material breaks off and escapes down tail. In Vasyliūnas's sketch (Figure 8a) the onset of magnetic reconnection is shown as starting near midnight but our sketch (Figure 8) shows reconnection occurring initially close to the duskside magnetopause where the most extended flux tubes should be found. In Figure 9 we suggest that the plasma bubbles released by reconnection retain azimuthal velocity and drift across the tail. The newly emptied flux tubes retract and possibly refill with outward-diffusing plasma, but also continue to rotate, stretch again, and possibly break off an additional plasma bubble.

The picture outlined has been influential but there remain questions to resolve. Why do the highly depleted tubes of the cushion region exist at all? In the morning sector, although occasionally blobs of sheet plasma are found in the region, there is no sign of empty tubes moving inward in the outer sheet region and yet there is no cushion in the afternoon sector. Centrifugal acceleration is invoked in the afternoon heating process but little thought has been given to its effect on the low-energy plasma of ionospheric origin on the same flux tubes. Finally, given our 2003 evidence that the interplanetary magnetic field north-south sense does affect the Jovian magnetosphere, one should consider the possibility of reconnection with the interplanetary magnetic field as a mechanism for limiting the cushion region to the morning sector.

16. Magnetometer Results From the Cassini Spacecraft

Our most recent collaborations have taken advantage of the rich data set on Saturn's magnetosphere provided by the Cassini mission. The Cassini spacecraft, carrying David's magnetometer, was launched from

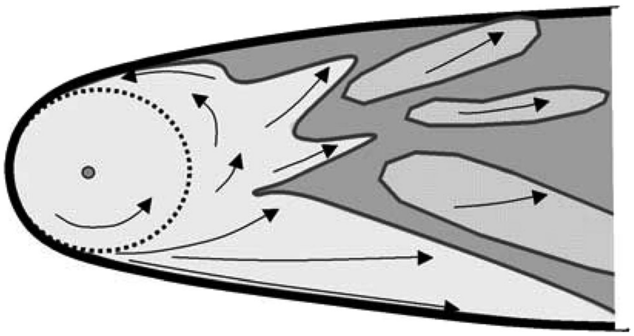

Figure 9. Schematic view of multiple plasma bubbles arising from reconnection in the magnetotail. This diagram suggests that following reconnection, the plasma continues to drift toward the morning side magnetopause, while the reconnected portion of the flux tube retracts radially but the flux tube subsequently may start stretching downtail and shed new plasma bubbles. From Kivelson and Southwood (2005), their Figure 4b.

Cape Canaveral on 15 October 1997. Following a nearly 7 year journey, it was placed into Saturn orbit on 1 July 2004, at which point, David, by that time Science Director at the European Space Agency, stepped down from being the Principal Investigator for the magnetometer leaving the leadership of the team in the capable hands of his Imperial College colleague, Michele Dougherty.

David's first contribution to magnetospheric studies at Saturn began while Cassini was still en route to its destination at Saturn. Fluctuations of the magnetic field at a period close to the planetary rotation period (thought, at the time, to be 10 hr 39 min 24 s) had been identified in the pre-Cassini magnetometer data of Pioneer 11 and Voyager 1 and 2 by Espinosa and Dougherty (2000, 2001). David joined Espinosa and Dougherty as coauthor of two additional papers that analyzed the fluctuating signals more extensively. Espinosa et al. (2003a) demonstrated unambiguously that the source of the mysterious perturbations could not be internal to Saturn even though the observed period was close to that of planetary rotation. They showed that perturbations were nearly in-phase on the inbound pass (near noon) and the outbound pass (near dawn) of Pioneer 11, and that the magnetopause position in the dawn sector was modulated in-phase with the radial component of the perturbation magnetic field. Espinosa et al. (2003b) showed that the magnetic perturbations were consistent with a rotating source of compressional waves at or near the surface of the planet, the so-called "camshaft model."

Once Cassini arrived at Saturn, new data on periodicities over time frames long compared to the time of a single flyby made it possible to characterize their properties more extensively. In Southwood and Kivelson (2007) we showed that inside of 10–15 R_s near the equator, the transverse magnetic perturbations were well approximated as the signature of a uniform field rotating at a rate close to the period of modulation of the power of Saturn Kilometric Radiation (SKR) as established, for example, by Kurth et al. (2007). Although the periods of the magnetic perturbations were found to be very close to those associated with SKR power, the latter was not a rotating signal, instead being preferentially emitted from the southern morning sector (Galopeau et al., 1995).

Perturbations of the azimuthal component of the magnetic field, B_φ, imposed by rotational drag are routinely observed at large distances at both Jupiter and Saturn. Rotational drag arises when the rotation rate of equatorial plasma is slower than that of the ionosphere. A typical mechanism that creates such a difference is outward diffusion of plasma, such as previously discussed for the Io plasma torus at Jupiter or outward of Enceladus at Saturn. Constancy of angular momentum requires that the angular velocity of the plasma decrease with outward displacement. This effect imposes azimuthal field perturbations with a node at the equator and a phase change of approximately 180° across the equator. The periodic azimuthal field perturbations observed within 10–15 R_S did not change phase across the equator, but, rather were consistent with flux tubes being dragged by the ionosphere in one hemisphere, which imposes a tilt in a direction independent of latitude and, thus, produces a finite B_φ at the equator. We identified the signature of azimuthal momentum propagating along the background field direction with the direction of transport reversing once per cycle. The form of the magnetic perturbation led us to postulate an interhemispheric current system with properties represented schematically in Figure 10. The left side of the image shows interhemispheric currents varying sinusoidally in intensity as $e^{im\varphi}$ with an $m = 1$ symmetry and flowing on a dipolar magnetic surface at $L = 15$. The image on the right is an equatorial plane view of the approximate form of the perturbation magnetic field generated by the currents in the left hand image. If the currents are set into rotation about Saturn's spin axis, the effect is to create a rotating uniform field within the current-carrying shell and an equatorial dipole field outside the shell. This perturbation field would add to the permanent field of Saturn, creating a tilted dipole moment that rotated around the spin axis.

We speculated on mechanisms that could account for the observations. Others (Goldreich & Farmer, 2007; Gurnett et al., 2007) had suggested that the periodic signature could be attributed to rotating convective flows in the equatorial plane. However, the equatorial plasma rotates at a period substantially longer than

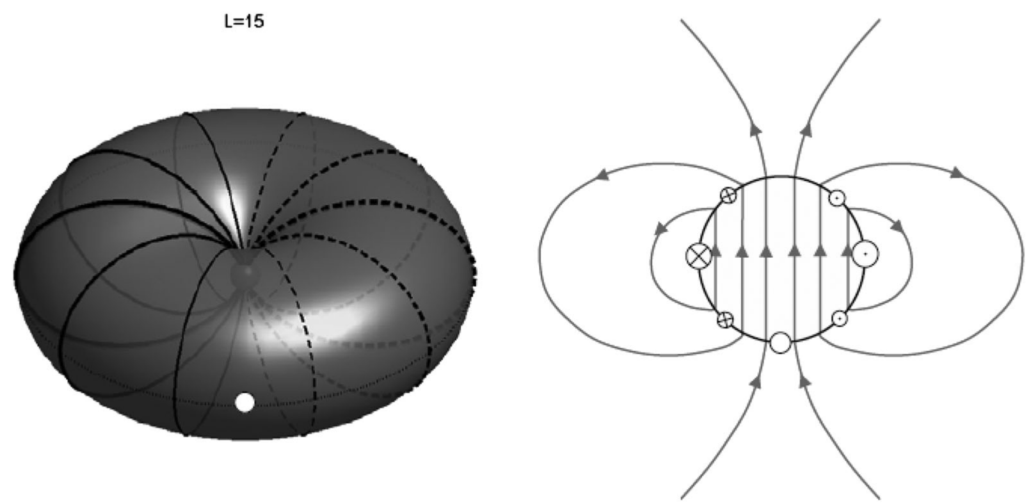

Figure 10. From Southwood and Kivelson (2007). Original caption: (left) Schematic shell of $L = 15$ dipolar field lines on which currents flow into and out of the northern ionosphere. If the current strength varied sinusoidally with longitude, as indicated by varying thickness of the lines representing the current, but flowed on a spherical surface, the perturbation field within the shell would be uniform. In order to produce the observed uniform field within a nonspherical surface, additional current loops must be present on the surface. (right) In a cut through the equatorial plane, field lines arising from the field-aligned currents at $L = 15$ shown in the left hand diagram. The field is uniform in the area inside the shell at $L = 15$ (here shown on a different scale) and dipolar outside of that boundary. The white dots in the two images are at the same location on the boundary.

the SKR period which makes it unlikely that the flow is driven in equatorial regions. As well, the absence of a node of B_φ at the equator is an additional challenge to identifying magnetospheric flow as a source of the periodicity. Thus, it seemed to us that the field-aligned current must be driven from the ionosphere, and that it was likely that the summer hemisphere ionosphere, with larger conductivity, would be the source, but we did not identify a mechanism that would drive currents with an $m = 1$ symmetry.

In 2009, we returned to the camshaft problem (Southwood & Kivelson, 2009) with a new question in mind. Convinced that it should be possible to explain the modulation of SKR and the rotating cam currents with a single mechanism, we decided to try to understand the link. The essence of a cam is an asymmetry that drives a disturbance once per rotation period, and we sought to identify an asymmetry of Saturn's system that would explain how field-aligned currents rotating around the planet on flux tubes that crossed the equator inside of 15 R_S might enhance SKR power principally in the morning sector. By plotting magnetometer data from 2005 and 2006 (southern summer at Saturn) against a phase based on the SKR period but corrected for spacecraft location in local time, we confirmed that the cam currents rotate at the SKR period and that, at the time of peak SKR power, the cam currents flow upward from the south in the morning sector. We found also that the SKR power peaked as the most intense cam current flowing upward from the south rotated through the morning sector. In the auroral zone, intense upward field-aligned currents are typically associated with downward field-aligned acceleration of electrons. It is those accelerated electrons that produce the SKR emissions so it became clear that the morning peak SKR arose from the intensification of field-aligned current as the cam current supplemented some preexisting field-aligned current. We still needed to understand the source of the preexisting current and why the morning sector was more active than the afternoon sector.

We noted that, at both Jupiter and Saturn, beyond the dipole-dominated regions the orientation of the field lines above the plasma sheet is not dawn-dusk symmetric. Field lines are more strongly swept back near dawn than near dusk. Sweepback in the high-latitude morningside southern hemisphere implies a positive B_φ perturbation on field lines entering the ionosphere at southern latitudes higher than ~72°. This requires current to flow upward from the low-latitude boundary of the swept-back field (near 72–75° latitude). The upward current would then peak each time the upward cam current rotated into the morning sector. The dominance of the southern source of SKR was accounted for by solar illumination which would imply higher conductivity in the south than in the north. We predicted the switch to northern hemisphere dominance as the Saturn season changed, and that switch did occur, although with a considerable delay after equinox (Gurnett et al., 2010) We remained puzzled about the source of the cam currents but continued to view it as likely that they arose at the ionospheric end of the flux tubes.

Our interest in Saturn and Jupiter-related questions has continued since we published our last joint paper, but that interest has been pursued with other colleagues. Margaret and coauthors Xianzhe Jia and Tamas Gombosi (Jia et al., 2012; Jia & Kivelson, 2016) proposed that the periodic phenomena in Saturn's magnetosphere are driven by a pair of ionospheric vortices centered at high latitude that rotate at the SKR period. The vortices generate periodic perturbations that propagate throughout the magnetosphere, as demonstrated by a MHD simulation that reproduces quantitatively the critical features of the magnetospheric response. The ionospheric vortices require that momentum be delivered from a source in the upper atmosphere whose origin remains unspecified. Kivelson and Jia (2014) using additional simulations showed that the rotating vortices in the ionosphere generate not only the Alfvénic disturbances that carry the field-aligned currents first identified as the source of periodic disturbances but also serve as a source of compressional waves that propagate outward causing periodic north-south displacement of the tail current sheet and of the magnetopause. The largest displacements of the magnetopause were found to be localized in the morning sector where they had been observed earlier by Espinosa et al. (2003b). Regrettably, the simulation paper failed to acknowledge that earlier discovery of magnetopause displacement.

David and coauthor Stan Cowley (Southwood & Cowley, 2014) addressed the problem of closure of the cam currents, focusing on the properties of the polar regions both north and south and emphasizing the importance of the fact that the dominant field-aligned currents flow at the open-closed field line boundary. The field-aligned currents are generated in a dynamo region in one polar cap; transverse currents flow across that polar cap but also on closed field lines within the magnetosphere causing the field-aligned currents to attenuate as they flow toward the opposite pole and through the ionosphere in the opposite polar cap. The transverse currents contribute to generating the compressional features discussed by Kivelson and Jia (2014).

With Emanuel Chané (Southwood & Chané, 2016), David examined the balance between the transport and loss of the heavy ion plasma whose source is Io (at Jupiter) and that of the solar wind plasma introduced into the ionosphere by dayside reconnection. They consider how the distinct Vasyliūnas cycle and Dungey cycle relate. They argue that plasma of solar wind origin enters the magnetosphere on the morning side, circulates at high invariant latitudes through the dusk hemisphere and is largely lost as it rotates through the night sector while the Vasyliūnas cycle acts at lower invariant latitudes and through the morning sector.

17. Postscript

As we conclude this review of our many joint papers, we find that some seem to have been helpful in clarifying the physics underlying phenomena observed at Earth and the giant planets, while being humbled by noting that others headed in the wrong direction (especially those proposing that Io might have an internal magnetic field). Rereading some of the theoretical papers, we recognize that many of them are heavily tutorial, relying on interpretations based on fundamental principles that govern physical systems with a minimum number of equations to support our arguments. We hope that our readers viewed them as illuminating.

Over the years, we filled journals with our writings. How did the process work? Most years, we started new papers during one of David's summer visits. Finding a topic for a new start required a great deal of back and forth discussion. Once we decided on a subject, we would scramble to understand what was going on in whatever process we had decided to work on. For theoretical papers, we sometimes had to refresh our knowledge of basic math. For our work on the global mode, we revived our expertise in working with Mathieu functions and reminded ourselves of the treatment of singularities in a solution. For other papers —such as our work on the periodic pulsations at Saturn—we needed to grab the latest data and use the graphical features of Splash (a UCLA interactive graphical and analysis tool: see PDS3 Software at https://pds-ppi.igpp.ucla.edu/software/index.jsp) to reveal what in the data was relevant to the problem at hand. Then we started to write. David usually did a first draft of the bulk of the material, with Margaret handling some subsections or figures. We usually managed to complete a rough draft about 5 hr before David's return flight to London or Paris. The rewrite was turned over to Margaret, but not until after she had driven David to the airport in Los Angeles, followed him to check-in, joined him for dinner and engaged in an intense conversation about possible directions for next summer's paper. Finishing touches, submission, revision, etc. were handled remotely, and in the early, preinternet days, slowly. Odd to say, final discussion was often carried out with longhand letters. But we did make use of technology as it evolved. We started with the earliest versions of Word but had an assistant type in the equations with an IBM Selectric Typewriter. Then Margaret's colleague, Ron Shreve, provided us with a program of his own devising that could create Greek letters and mathematical symbols and we were able to write the equations ourselves. The next step involved a commercial program, "Publisher," that few used and fewer recall. It required input in a form similar to today's LateX and was coupled with a "what you see is what you get" companion page. The computer versions of papers written with this tool are no longer accessible to us because Publisher has long been obsolete.

Our joint work linked our institutions. David spent a year as a Regents Professor at UCLA. Margaret often visited Imperial College (or ESA) for short but highly interactive intervals. We look back with pleasure at the meetings at which we reported our work, the many friends we shared, and the fun we had working together. This paper has given us a chance to collaborate once again and we are grateful to Larry Kepko for providing this opportunity.

Data Availability Statement

The data used in this work are readily available from the NASA Planetary Data System (https://pds-ppi.igpp.ucla.edu/search/view/?f=no&id=pds://PPI/GO-J-MAG-3-RDR-HIGHRES-V1.0/DATA/SATELLITES/IO/ORB32_IO_IPHIO&o=1).

Acknowledgments

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