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Chung Park, pioneer of magnetosphere–ionosphere coupling research

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Abstract

Chung Park (1938–2003) was a true pioneer of magnetosphere–ionosphere coupling research. During a short career at Stanford University that began in 1970 and ended in 1981, he wrote seminal papers on several topics. Using ground-based whistler data, he was the first to demonstrate experimentally that day-side upward ion flow from the mid-latitude ionosphere was sufficient to maintain the night-time ionosphere. He made the only measurements to date of longitudinally localized drainage of significant quantities of plasmaspheric plasma into the underlying ionosphere during a period of enhanced convection activity. He pioneered in demonstrating the presence at ionospheric heights of geophysically important electric fields that originate in the troposphere in thunderstorm centers. He cooperated in a unique study of the guidance of whistler-mode waves by field-aligned density irregularities (ducts) in the magnetosphere. Park provided unique observational data on nonlinear wave–particle interaction processes such as: (i) the development of sidebands during the injection of whistler-mode waves from Siple, Antarctica, and (ii) the mysterious whistler precursor phenomenon. Today, in spite of the several decades that have elapsed since his work, Park's early findings remain cornerstones of our understanding of magnetosphere–ionosphere coupling processes. Some of his later studies of non-linear magnetospheric wave–particle interaction phenomena have stirred lively debate, and today remain relevant to a number of topics in space plasma wave research.

Keywords: Ionosphere–magnetosphere coupling; Whistler-mode probing of the magnetosphere; Plasmasphere; Night-time ionosphere; Whistler-mode propagation; Wave–particle interactions; Thundercloud electric fields in the ionosphere

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1. Introduction

In 1953, several years before the era of satellites, Owen Storey at Cambridge (Storey, 1953) used very low frequency (VLF) signals from lightning called 'whistlers' to demonstrate the existence of the protonosphere, a cloud of light ions extending thousands of kilometers upward from the Earth's oxygen-dominated ionosphere. Some 20 years later, Chung Park, again working with whistlers, provided the first clear evidence that the ionosphere and the region Storey had discovered were strongly coupled in terms of plasma interchange, to the extent that the protonosphere served as a reservoir for the night-time ionosphere (Park, 1970a).

Park began his work at a propitious time: in the 1960s, studies of the ionosphere had advanced rapidly as investigators drew upon ground data acquired during and after the International Geophysical Year

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(IGY) (1957–1958) and upon data acquired from the highly successful topside sounders that began operations in 1962. However, there was a serious drawback to continued progress, a lack of information about electric fields and coupling fluxes at the transition between the upper ionosphere and the overlying region. Park was an early leader in providing that information. (We note here that since 1966, the term 'plasmasphere' had come into use, representing a specific, variably extensive, inner part of the region that for some time continued to be called the 'protonosphere'.)

2. Graduate studies at Stanford University; the Whistler method

I first met Chung Park in the fall of 1966 at Byrd Station, Antarctica, where he was completing a year as a field engineer for our Stanford VLF research group, directed at the time by R.A. Helliwell. In 1967 Park entered Stanford as a graduate student in the Helliwell group and soon began work on the group's extensive library of whistler data. As did workers before him (e.g., Allcock, 1959; Smith and Carpenter, 1961; Carpenter and Smith, 1964; Helliwell, 1965; Dowden and Allcock, 1971), he sought to extend the power of the whistler method of probing the near-equatorial magnetosphere. Among his contributions were a technical handbook, one still in use today, in which he provided numerous graphs and aids for the analysis of individual whistler events, including discussion of sources of error (Park, 1972). He called attention to the fact that a whistler signal propagating on a geomagnetic-field aligned path spends 80% of its travel time within $\approx$30° of the magnetic equator and hence is particularly, sensitive to the plasma parameters along that roughly homogeneous portion of the path. He also stressed the use in whistler analysis of tube electron content, the total number of electrons in a tube of force extending from a cross section 1 cm^2 at 1000 km to the magnetospheric equator.

To supplement his growing knowledge of the plasmasphere-plasmatrough system, Park became a student of ionospheric structure and dynamics and of methods of radio probing of the ionosphere. By 1970 he was able to produce a landmark Ph.D. Thesis, entitled "A whistler study of the interchange of ionization between the ionosphere and the protonosphere" (Park, 1970b), as well as an associated journal publication (Park, 1970a).

3. Thesis: first measurements of the dayside upward flux into the protonosphere

At this time there were serious questions about the dayside upward flux of protons into the plasmasphere. There was widespread agreement that downward fluxes ranging from 5×10^7 to 3×10^8 el cm^{-2} s^{-1} were needed in order to sustain the decaying nighttime ionosphere (e.g., Hanson and Patterson, 1964; Geisler and Bowhill, 1965; Yonezawa, 1965). However, the maximum daytime upward flux attainable had been found by Hanson and Patterson (1964) and Geisler and Bowhill (1965) to be $\approx 1.5 \times 10^7$ el cm^{-2} s^{-1}, an order of magnitude less than the needed nighttime drainage flux. This low limit was attributed to the action of the so-called diffusive barrier, a vertical portion of the upper ionosphere through which protons must pass after originating at lower altitudes in the chemical equilibrium region through charge exchange of H with O^+. Within the diffusive barrier, defined as extending to an altitude at which protons become the dominant ion species, the upward progress of the protons would be inhibited by Coulomb collisions with the more numerous heavy ions. The predicted upward flux would not only fail to allow the protonosphere to serve as a reservoir for the nighttime ionosphere, but would also be insufficient to refill depleted regions outside a newly eroded plasmasphere within the few days during which whistler data had shown that substantial replenishment could occur (e.g., Corcuff et al., 1972).

The limiting flux calculations did involve several parameters that were not well known, and investigators Geisler and Bowhill (1965) and Hanson (private communication to Park) had stated that the actual flux might exceed their calculated values by an order of magnitude. Furthermore, Banks and Holzer (1969) had obtained limiting fluxes of $2\text{–}7 \times 10^8$ el cm^{-2} s^{-1} by using atmospheric models different from those used by the earlier investigators. The time was certainly ripe for the definitive measurements that Park was prepared to make.

Park selected for detailed examination data from an extended quiet period following a magnetic storm, with the aim to measure the changes with time in plasmasphere tube content over a range of mid-latitude L shells. As illustrated in Fig. 1, he was able to measure the changes from day to day in electron tube content between $L \simeq 3.5$ and 5 over an 8-day period of deep quieting following the

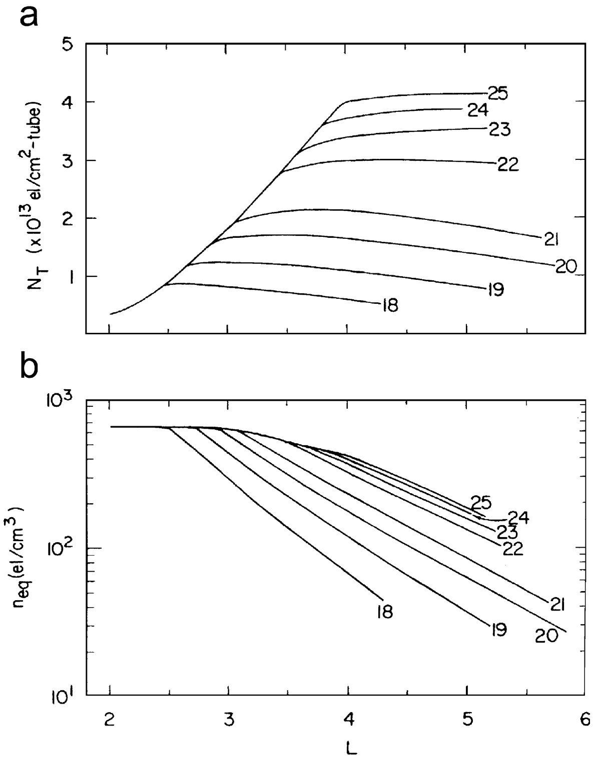

Fig. 1. (a) Nightly tube electron content and (b) equatorial density profiles during an 8-day recovery period. The numbers indicate UT days in June 1965. Branch points along the leftmost rising curve in (a) indicate the successive L-values where daytime filling and nighttime drainage were in balance on successive recovery days (from Park, 1974a).

magnetic storm of 15–16 June 1965. During one four-hour afternoon period, he was able to observe refilling on a continuous basis. Fig. 2 shows tube content along four discrete whistler paths between $L = 3.7$ and 3.9 during such a period on 18 June 1965. The quantity displayed is whistler travel time along a magnetospheric field-line path, measured at the whistler 'nose frequency' (frequency of minimum travel time). The whistler nose frequencies were found to vary only slightly with time, implying that the magnetic shells of the paths were roughly constant and that the increases in travel time were a direct measure of increases in tube electron content.

Fig. 3 shows a sequence of Park's measurements at $L \approx 4$ for both day and night from 18 to 22 June 1965. The dashed line, also from Park, is an empirical model based upon his estimate of an upward flux of $3 \times 10^8\,\mathrm{el\,cm^{-2}\,s^{-1}}$ when the 100-km level at both ends of the $L = 4$ path had been in sunlight, and a drainage flux of $1.8 \times 10^8\,\mathrm{el\,cm^{-2}\,s^{-1}}$ when in darkness.

Park began his summary of findings with the following statements:

"The observed daytime electron flux from the ionosphere into the protonosphere under quiet geomagnetic conditions is $2\text{–}4 \times 10^8\,\mathrm{el\,cm^{-2}\,s^{-1}}$. This flux is larger than the downward flux necessary to maintain the nocturnal ionosphere.

The observed downward electron flux at night under quiet geomagnetic conditions is $\approx 1.5 \times 10^8\,\mathrm{el\,cm^{-2}\,s^{-1}}$, an amount considered sufficient to maintain the nocturnal ionosphere."

Among Park's other conclusions was the following:

"The post-storm recovery of the plasmasphere takes place primarily by filling from the ionosphere." Given that this statement has become almost an article of faith in space physics, it may seem surprising to realize that until Park's work the refilling process had not been demonstrated by measurements and, as noted above, important theorists had not found it plausible.

Park was among the first to confront the differences between the ionosphere and the overlying region in terms of recovery following a magnetic storm. He found that while the ionosphere recovered from the 15–16 June 1965 storm in about three days, the protonosphere required about five days to reach the June, 1965 monthly median level. Furthermore, the protonosphere continued to fill during the eight exceptionally quiet days prior to a new disturbance on 25 June 1965, and "did not reach any saturation level." This was an early point of view that eventually became widely accepted, namely that the plasmasphere is a dynamic region that "is strongly affected during geomagnetic disturbances" and is "most of the time recovering from previous disturbances."

The extent to which Park's results have become cornerstones of our understanding today is illustrated on p. 336 of the monograph 'Ionospheres' by Schunk and Nagy (2000), where the authors state that "the downflowing H^+ ions charge exchange with O to produce O^+, and this process helps to maintain the nighttime F region." Furthermore, in agreement with Park's (1974a) finding about the time-dependent spatial division between an inner plasmasphere that is in equilibrium with the underlying ionosphere over a 24-h period and an outer plasmasphere that is still recovering from disturbance (see Fig. 1), they note that "the flux tubes at

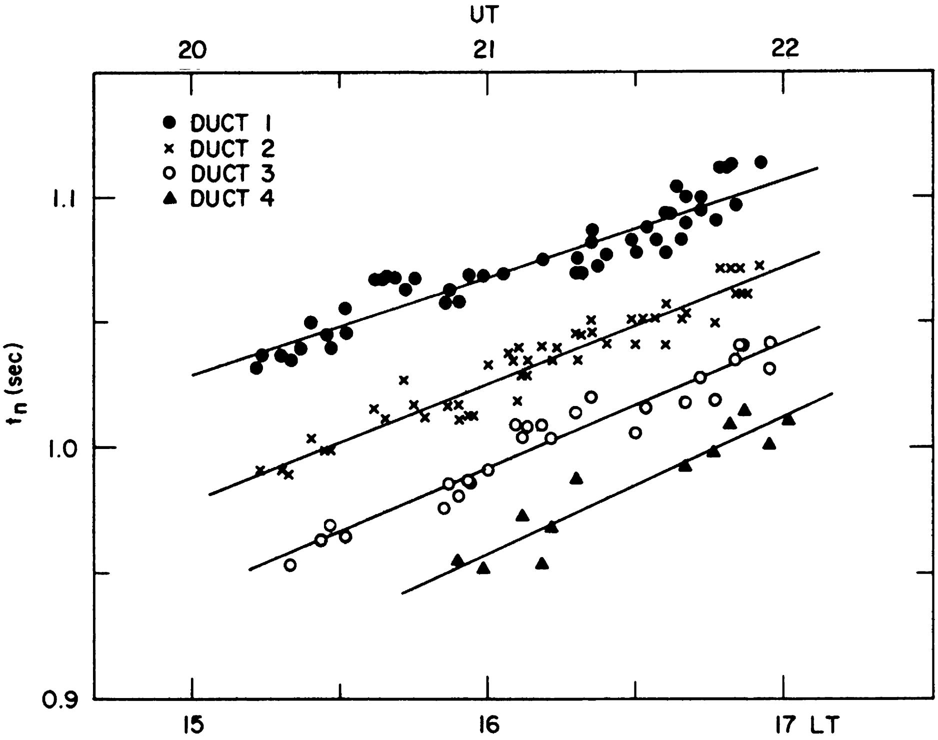

Fig. 2. Plot illustrating steady increases in tube electron content along four whistler paths during a several-hour period on 18 June 1965. The measured quantity is travel time along the magnetospheric path at the whistler nose frequency (from Park, 1970a).

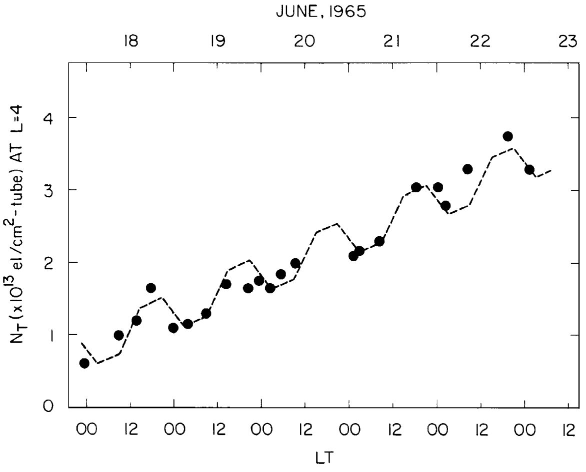

Fig. 3. Plot of measured tube electron content at $L = 4$ as a function of local time at Eights, Antarctica, showing the diurnal variation and the net day-to-day increase during the recovery period illustrated in Fig. 1. The dashed curve is a theoretical curve described in the text (from Park, 1970a).

low latitudes refill fairly quickly because their volumes are small…”, whereas “the flux tubes in the outer plasmasphere can take many days to refill….”

In his thesis, Park (1970b) estimated an overall loss of $\approx 3 \times 10^{31}$ electrons from the plasmasphere during the 15 June 1965 magnetic storm. Later, he pointed out that “the fate of such large amounts of plasma has important implications for the storm-time behavior of the ionosphere and the circulation of light neutral gases” (Park, 1973). In saying this, he recognized a broad area of work that would eventually receive much attention at conferences and in the literature (e.g., ISSI, 1997; Chen and Moore, 2006).

4. Later work

4.1. More studies of ionosphere–magnetosphere plasma interchange

As a graduate student, Park identified for the first time a class of electron density decreases that appear within the eroded plasmasphere during storm periods. In a case study he showed that the plasmasphere could be highly structured in longitude, with density varying from near quiet-time levels down to as much as factor of three below them within a range of about ±10° of the Eights

Fig. 4. Photo of Chung Park during the inaugural 1974 meeting at Yosemite (from video record of the proceedings made by Rick Chappell).

longitude (Park and Carpenter, 1970). While the global distribution of such structured decreases was not known, Park estimated that the number of electrons lost from the plasmasphere to the ionosphere through them was a significant fraction of the overall losses from the plasmasphere during a magnetic storm (Park, 1973).

In a related pair of studies involving both plasmasphere whistler data and multi-station ionosonde data, Park (1973, 1974a) found evidence that portions of the plasmasphere had been rapidly drained of plasma within a few hours during a substorm period, and that this drainage had been confined to a particular longitude sector. Furthermore, he found an increase in ionospheric density within the same sector and was able to infer downward fluxes into the affected low-altitude region of order $10^9\,\mathrm{el\,cm^{-2}\,s^{-1}}$ (Park, 1974b). Physical mechanisms for reducing the plasmasphere density by downward field-aligned flow had been advanced by other authors (e.g., Hanson, 1964). In his 1973 paper and at the inaugural Yosemite meeting in 1974 (see photo, Fig. 4), Park suggested that as a result of longitudinally structured cross-L inward drifts during substorms, the ionosphere at middle latitudes was lowered in a limited region and that the vertical pressure gradient of the H^+ distribution in the region of charge exchange with O^+ was thereby enhanced so as to stimulate downflow. Whatever the merits of Park's explanation, his work remains the only empirical study of which I am aware that demonstrates this first-order effect on the plasmasphere from the perspective of magnetosphere–ionosphere coupling.

4.2. More on plasma interchange and the effects of convection electric fields

Park helped to provide the first 'calibration' of the ULF technique being applied as a high-altitude mass density diagnostic by Lanzerotti and colleagues (Webb et al., 1977). Since that time ULF ground-based methods have continued to develop as probes of high altitude mass density and continue to benefit from intercalibrations with, for example, ground-based fixed-frequency VLF transmitter data and IMAGE satellite EUV and radio-sounder data (e.g., Clilverd et al., 2003).

In 1976, Park collaborated with Ching Meng in an empirical study (Park and Meng, 1976) of localized, relatively short-lived depressions in F-layer electron densities, arguing that the depressions were caused by changes in thermospheric composition during disturbed periods, changes that were initiated by Joule heating in the dayside polar cusp region.

Park was also attracted to theoretical modeling as a way of studying the interplay between forces acting on both the ionosphere and overlying regions. In a collaboration with Peter Banks it was found that at nighttime, plasma densities near the F2 layer peak depended sensitively on the plasma density of the plasmasphere and on the neutral hydrogen concentration in the thermosphere (Park and Banks, 1974). However, they found that in daytime, O^+ densities near the F2-layer peak were remarkably insensitive to plasma densities in the overlying magnetosphere (Park and Banks, 1975). The relevance of this work to contemporary modeling and data assimilation studies of ionospheric electron density is indicated in a paper by Zhang et al. (1999), who found agreement with the conclusions of Park and Banks on the importance of a nighttime downward ionization flux into the ionosphere.

4.3. Coupling effects involving catalytic effects on magnetospheric processes of thunderstorm electricity and ground-based sources of waves

The atmosphere, ionosphere, and magnetosphere are coupled through the interplay of thunderstorm electricity, lightning, ground-based transmitter signals, power grids, field-aligned density irregularities, and magnetospheric wave–particle interactions. Through a series of seminal works, Park helped to identify the places of these diverse phenomena in magnetospheric physics.

In several papers he tackled the problem of 'ducts,' field-aligned structures that allow whistlers recorded on the ground to serve as diagnostics of magnetospheric plasma structure and dynamics. In providing discrete propagation paths from hemisphere to hemisphere, ducts also appear to play a major role in the process discussed years ago in the seminal paper of Kennel and Petschek (1966) according to which whistler-mode wave activity sets an upper limit to the fluxes of energetic electrons in the Earth's radiation belts.

Two aspects of ducts were of special interest to Park: the process of their formation and their effectiveness in controlling the waves trapped within them. At the time of Park's work, indirect evidence for the existence of ducts was well established. Ducts had been postulated to involve field-aligned density irregularities, several-percent enhancements of ionization that internally trap wave energy and guide it between conjugate hemispheres (e.g., Smith, 1961; Helliwell, 1965; Angerami, 1970). However, in Park's time and even today, the density profiles of ducts and the mechanisms of their formation had not yet been well established, in part because of the elusiveness of ducts as objects of measurement in situ.

With this background, Park considered several questions, among them: how do ducts behave so as to permit the spreading of wave energy from an initially limited field-line region to a much larger one? Questions about the interplay between a magnetospheric field-line path and the ionospheric layers at its ends had been earlier suggested through evidence from whistlers of coupling between nearby whistler ducts at the time of ionospheric reflection (e.g., Morgan et al., 1959). Furthermore, ISIS satellite recordings of whistlers that followed a particular ducted path from the conjugate hemisphere had shown wide differences between the intervals of detection of those whistlers interpreted as downgoing and the much longer intervals for those interpreted as upgoing after reflection (Thomson and Dowden, 1977). In a collaboration with Bernhardt and Park (1977), the authors undertook to show numerically that as energy trapped in a duct approaches the ionosphere from above, an important fraction of it is reflected from the ionosphere and propagates back upward within nearby ducts, within the original duct, and also in a non-ducted mode (Bernhardt and Park, 1977). They identified the various geophysical conditions and altitudes at which ducting by the modeled ducts effectively ceases as the stronger ionospheric gradients take over from the weaker transverse density gradients of the ducts. Today the mechanism of magnetospheric whistler-mode ducting remains a subject of serious study. As in the past, questions continue to be raised about the role of fine structure in ducts (e.g., Lippmann et al., 1964; Lichtenberger et al., 1991) and new questions have been posed, for example about the size of the ionospheric area perturbed by energetic electrons that are precipitated by a ducted wave (e.g., Strangeways, 1999).

To what distance from a lightning source can magnetospheric ducts by excited? In collaboration with Phil Krider and colleagues and using data from an early version of the present country-wide lightning-detection network, Park showed that lightning could excite ducts with ionosphere endpoints as much as 2000 km poleward of the lightning location (Weidman et al., 1983). Since Park's day this type of experiment has evolved substantially in parallel with the proliferation of lightning detection networks. Rocket experiments have revealed significant upgoing wave fields in the ionosphere at distances of order 2000 km poleward from the causative flash locations (e.g., Holzworth et al., 1999). In related experiments, it has become possible to investigate the physics of so-called 'early/fast' perturbations of the ionosphere, in which a lightning source appears to have an 'immediate' influence on the overlying ionosphere (e.g., Corcuff, 1998; Haldoupis et al., 2004). Knowledge of lightning activity has helped to make possible analysis of an important new class of wave-induced scattering events in which a wave launched from lightning propagates in a non-ducted manner and thus perturbs a more extensive region of the ionosphere than does a ducted whistler (e.g., Lauben et al., 1999; Johnson et al., 1999).

Another question considered by Park was the possible role of thunderstorm electric fields in the formation of ducts. He suggested that if the horizontal electric field extending radially from a thundercloud charge center could be mapped upward to the ionosphere, that field would set the overlying plasma into circular motions (Park and Helliwell, 1971). These motions would give rise to fine structure, irrespective of the smoothness of the initial ionospheric density distribution. The fine structure could then diffuse upward to form field-aligned irregularities. Fig. 5 shows the calculated distortions in an originally smooth equatorial density profile roughly 2 h after the imposition of a model thunderstorm electric field. To this day

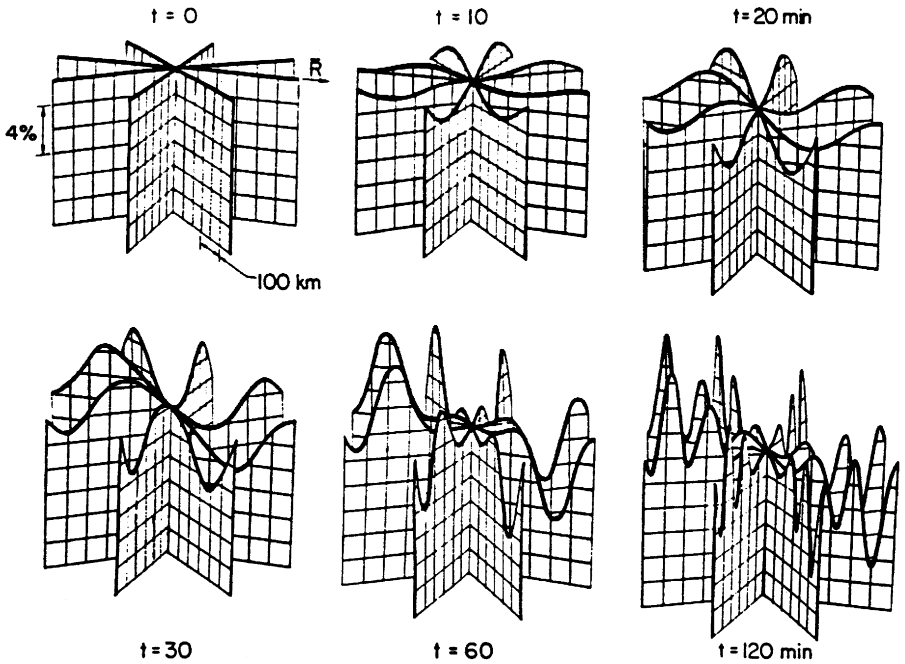

Fig. 5. Three dimensional models of an equatorial convection cell 600 km in diameter showing the development of density irregularities over a 2 h period following the imposition of a model electric field. The locally radial electric field is hypothesized to be mapped upward from a thunderstorm charge center (from Park and Helliwell, 1971). An arrow shows the radial direction.

there is no consensus on the mechanisms of magnetospheric duct formation, nor do we have a clear descriptive picture of the properties and distributions of ducts. However, recent IMAGE satellite work shows that ducts are more prevalent than previously realized, whether they are involved in whistler-mode or free-space X- and O-mode propagation. The RPI radio sounder has shown that when a pulse is transmitted at high altitudes within or near the plasmasphere, any discrete echoes received are predominantly the result of guided X- and O-mode propagation along geomagnetic-field-aligned paths to reflection points (e.g., Fung et al., 2003). This finding is consistent with and is also an extension of ducting observations from the ISIS-series topside sounders (e.g., Loftus et al., 1966; Muldrew and Hagg, 1969). Further evidence that the plasmasphere is regularly permeated by field-aligned density structure comes from RPI records indicating that pulses propagating transverse to the magnetic field are consistently scattered by irregularities ranging in scale sizes transverse (to **B**) from 200 m to >10 km (Carpenter et al., 2002).

Is the upward mapping of thunderstorm fields in fact efficient enough to affect the ionosphere? Here Park was joined by a student member of the Helliwell group from Thailand, Mongkol Dejnakarintra. The two pushed aside traditions according to which thunderstorm electricity was confined to the electrosphere, a spherical shell below the ionosphere with a conducting upper limit that precluded geophysically significant electrostatic or dynamic coupling to the ionosphere. They developed numerical models of the penetration to the ionosphere of both the electrostatic field associated with a thundercloud as well as the time-varying fields associated with lightning discharges (Park and Dejnakarintra, 1973; Dejnakarintra and Park, 1974). Significant field amplitudes at ionospheric heights were deduced, including fields large enough to support Park and Helliwell's duct formation hypothesis. The authors recognized that there was substantial uncertainty in their findings, based in large part upon uncertainty in their assumed conductivity models. Although they did not forecast the heating effects that were later found to occur in the medium, (e.g., Inan, 1990), they must be credited with taking pioneering steps in a field that has undergone spectacular growth since upward lightning from thunderclouds was first reported in the late 1980s (e.g., Rodger, 1999; Pasko et al., 2002; Su et al., 2003).

4.4. *Catalytic effects of weak coherent waves*

Park's interest was captured by the fact that a weak ground-level wave source such as a distant lightning flash or a low power transmitter could produce a strong signal along a magnetospheric path. This coupling effect became a basis for a number of papers that Park produced in the latter years of his tenure at Stanford. As a participant in the Stanford program of wave injection experiments from Siple Station, Antarctica (e.g., Helliwell and Katsufrakis, 1974, 1978), Park took a strong interest in wave–particle interactions involving weak coherent waves injected from the ground. His observations using records of amplified CW signals from Siple (Park, 1981) provided a detailed description of the sideband phenomenon, a description that has served as a challenge to theorists ever since (e.g., Nunn, 1986). Park noted that the frequency spacing of sidebands on Siple signals bore no simple relation to the amplitude of the carrier, and pointed out that such a relation was inconsistent with sideband theories in which sideband frequency reflected the oscillation of resonant particles trapped in the potential well of the carrier wave and thus was dependent upon the carrier amplitude.

Park paid particular attention to magnetospheric line radiation (MLR), multiple noise bands 20–30 Hz in width lasting for minutes at a time, exhibiting constant frequencies or at times drifting slowly in frequency. On dynamic spectrograms such lines often exhibited enhancements or triggering of new frequencies at intervals associated with the bounce period of waves along the field lines (Helliwell et al., 1975). Park sought corroborating evidence that MLR could originate in power grids, and argued that power-line harmonic radiation (PLHR) could be influential in triggering geophysically important VLF emission activity (e.g., Park, 1977). Various of his conclusions in this area have been disputed over the years, particularly on the subject of the levels and geophysical impact of PLHR in the magnetosphere (e.g., Tsurutani et al., 1979; Thorne and Tsurutani, 1979; Rodger et al., 2000). Current opinion seems to be that from a descriptive point of view, PLHR and MLR differ from one another in important ways (e.g., Paschal, 1988; Rodger et al., 2000; Nemèc et al., 2006). However, the possibility of a catalytic relation between the two under some circumstances remains an open question, one that is underscored by developing interest in anthropogenic effects in space and by observations such as those from the AUREOL 3 satellite, which showed frequency-drifting magnetospheric lines that were interpreted as having developed from PLHR through a gyroresonant whistler-mode instability (Parrot, 1994). During recent ground based studies, Manninen (2005) found evidence that MLR "is, initially, triggered by PLHR." The author found that "low-level PLHR can act as the "seed" for MLR, after which multiple wave processes occurring in MLR decouple from PLHR." Observations from the polar orbiting Demeter satellite show clear evidence of the propagation at 750 km altitude of whistler-mode waves at harmonics of both 50- and 60-Hz power systems, as well as evidence of associations of these waves with particular ground based sources of 50- or 60-Hz power (Nemèc et al., 2006).

The possible importance of power line radiation as a catalyst for energetic magnetospheric processes was discussed by Park and Helliwell in a paper on the whistler 'precursor' phenomenon that is occasionally found on the records of two hop whistlers (i.e., on spectrograms recorded in the hemisphere of the lightning source) (Park and Helliwell, 1977). Two examples from this paper appear in Fig. 6. In each case, a noise event precedes the whistler by an amount that is a significant fraction of the two-hop whistler delay. Park noticed that the apparent starting frequencies of the precursor emissions were at or close to the frequencies of local power-line harmonics, which (on these ground-station records) are indicated by narrow lines on the spectrograms. He postulated that during initial propagation of the whistler along its one-hop path, a beam of electrons was formed as a result of Landau resonance with the waves. Near the magnetic equator, the electrons then interacted in cyclotron resonance with components of weak coherent power line harmonic waves, giving rise to amplification of power-line-associated wave packets that were propagating in the direction opposite to that of the electron beam and toward the receiver end of the path. A measure of support for the Park and Helliwell ideas was supplied by Paschal (1988), who reported examples of whistler precursors in which the suggested role of power line harmonic radiation was played by a magnetospherically propagating two-tone signal at 3950 and 3980 Hz from the Siple, Antarctica VLF transmitter. In addition, Reinleitner et al. (1983) reported evidence that a strong whistler-mode chorus wave can give rise to an electron 'beam'.

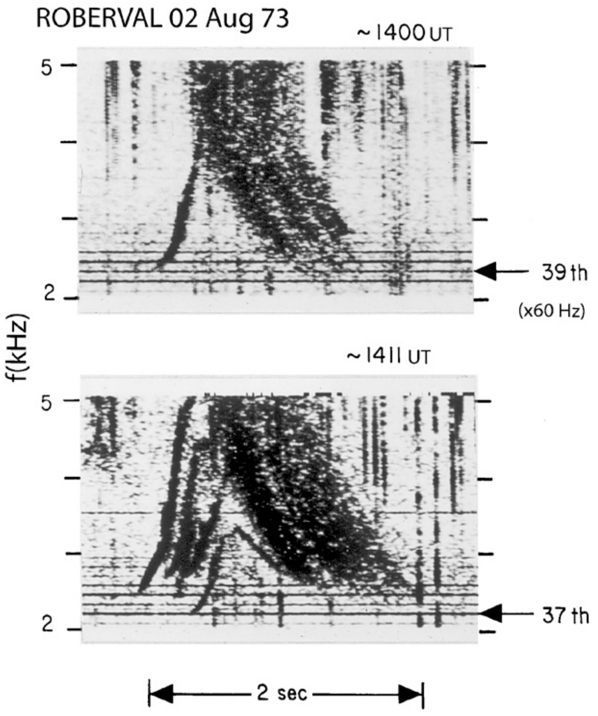

Fig. 6. Two examples of whistler precursors recorded at Roberval, Quebec in 1973. The two-hop whistlers, which originated in lightning in the northern hemisphere, are preceded by one or more discrete rising emissions. The narrow lines on the lower part of the records are identified as high odd-order harmonics of the local 60 Hz power system (from Park and Helliwell, 1977).

Nevertheless, the launching of precursors has proven difficult to connect to power line frequencies (e.g., Rietveld, 1980). This may be due in part to the low levels of PLHR in space and the fact that, as Park and Helliwell (1981) showed, magnetospheric line radiation and associated triggered emissions can develop as a consequence of repeated echoing of elementary wave packets back and forth along field-line paths. The packets, at a discrete frequency, are visually undetectable on the spectrographic records until they grow in amplitude through repeated passages through an interaction region. Today the whistler precursor phenomenon remains part of the ongoing challenge to understand the physics of line radiation in the magnetosphere.

5. Concluding remarks

Chung Park was both a visionary and an entrepreneur. A native of Korea, he acquired an exceptional command of English. His oral presentations and papers were models of clarity. His care and thoroughness in studying data were extraordinary.

When I look back on his all too brief research career, I am astonished at the variety of subjects that he tackled, both in terms of theory and experiment. His seminal findings on plasma interchange between the ionosphere and magnetosphere have become part of accepted wisdom on the subject. His work with a student on the static and dynamic effects on the ionosphere of thundercloud electricity foretold a remarkable end-of-the century explosion of work. His work on wave ducting and on the catalytic effects of weak injected whistler mode waves have been both influential and controversial, raising questions about the physics of phenomena such as magnetospheric line radiation that continue to the present day.

Chung Park left Stanford in 1981 for what became a successful career in business, but his work in the preceding 11 years occupies a special place in the history of our field. In spite of the passage of some 30 years, much of what Chung Park did remains relevant to the issues still before us in the area of magnetosphere–ionosphere coupling.

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