Chapter 7
Jim Dungey's Contributions to Magnetospheric ULF Waves and Field Line Resonances

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Abstract Jim Dungey introduced the concept of geomagnetic field line resonances in an obscure report published when he was a post-doc in 1954. This paper first describes how Dungey arrived at the idea of an Outer Atmospheric Cavity filled with a cold hydrogen plasma within which the dynamics were controlled by hydromagnetics and Alfvén waves, and how he showed that this cavity would support field line resonances. How Dungey's idea provided a ready explanation for the sinusoidal nature of magnetospheric ULF waves and led to the development of the rich field of ULF wave research are then briefly sketched.

7.1 Resonating Field Lines and Micropulsations

The idea that geomagnetic field lines might be capable of supporting a standing wave or resonance was first put forward by Jim Dungey in 1954 in an obscure report that is packed with important new ideas (Dungey 1954). This report was written during Jim's year as a post-doc at Penn State. The previous year Owen Storey (1953) had published his theory of whistler dispersion that depended on geomagnetic field lines being populated by a plasma (or at least electrons, ions then being required for charge neutrality) along their entire length. Storey used observations of whistler wave dispersion together with his new theory to deduce electron densities in the "outer atmosphere" as it was then called. Jim combined this new idea together with the established concept of the Chapman-Ferraro cavity (Chapman and Ferraro 1931a, b, 1932, 1933) to conceive of a large plasma-filled outer atmospheric cavity, which today we call the magnetosphere, within which hydromagnetics and Alfvén waves would control the dynamics.

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D. Southwood et al. (eds.), *Magnetospheric Plasma Physics: The Impact of Jim Dungey's Research*, Astrophysics and Space Science Proceedings 41,
DOI 10.1007/978-3-319-18359-6_7

Jim pictured the cavity filled with a hydrogen plasma in diffusive equilibrium with the upper F-region ionosphere, something like our modern concept of the plasmasphere, that filled flux tubes out to the outer boundary of the cavity, at least at low latitudes. The properties of the interplanetary medium were unknown and subject to considerable guesswork, but whatever they were, Jim realized that there would be a thin boundary containing a current that separated the outer atmospheric cavity and interplanetary space. Within this geomagnetic cavity, Jim calculated, magnetic energy density would be far greater than plasma thermal energy density. Using this approximation, the cold plasma approximation, he derived the equations for hydromagnetic waves in a rotationally symmetric magnetic field, such as a dipole, and found two modes corresponding roughly to the shear and fast modes in a uniform plasma which are coupled. He then went on to show that in the limits of both no azimuthal phase variation and very rapid azimuthal phase variation the modes decouple leading to the basic theory of field line resonances now found in textbooks (the first appearance being Dungey 1968, eqs. 22–26). Figure 7.1 illustrates these resonances. Jim understood that to first approximation the Earth and ionosphere would together act as a very good conductor, reflecting incident waves with little loss and effectively tying the ends of the field lines as the electric field must be very small. Given this boundary condition, a wave mode that is guided along the magnetic field, such as the shear Alfvén mode, will set up resonant oscillations or eigenmodes on a field line. The poloidal mode, illustrated on the right in Fig. 7.1, has field lines oscillating in the meridian plane and occurs for rapid azimuthal phase variation. In the toroidal mode which occurs for no azimuthal phase variation, field lines are displaced azimuthally, so that the whole magnetic shell oscillates. Table 7.1, taken from Jim's (Dungey 1954) report, shows his estimates of the fundamental resonant period of a field line versus the geomagnetic latitude of its foot-point. Given the almost wild guesses Jim had to make, these estimates are in remarkably good agreement with the values we would calculate and observe today.

In 1954 observations of magnetospheric ULF waves, or micropulsations as they were then called, were rudimentary. However Jim realized that his resonant field lines might well explain why these geomagnetic variations have a much more sinusoidal character than any other geomagnetic disturbance. As we will see below it took another 20 years for this to be clearly established observationally.

In another section of the 1954 report Jim proposed that Kelvin-Helmholtz waves excited on the outer boundary of the geomagnetic cavity might be a source of these waves, and derived an initial theory for this instability (see also Dungey 1955). However so little was known about the interplanetary medium, that he thought that the Earth's orbital velocity (30 km s^{-1}) through a stationary interplanetary gas rather than the solar wind might be the cause of the velocity shear.

The rather obscure Penn State report, parts of which were republished some years later as part of a contribution Jim wrote based on summer school lectures he presented (Dungey 1963a), laid the foundations for the theory of magnetospheric ULF waves and the whole subdiscipline that emerged. Jim continued to be active in this field for the rest of his career, making contributions to both wave excitation by wave particle interactions and to the effect of the ionosphere on ULF waves, which is the subject of the next section.

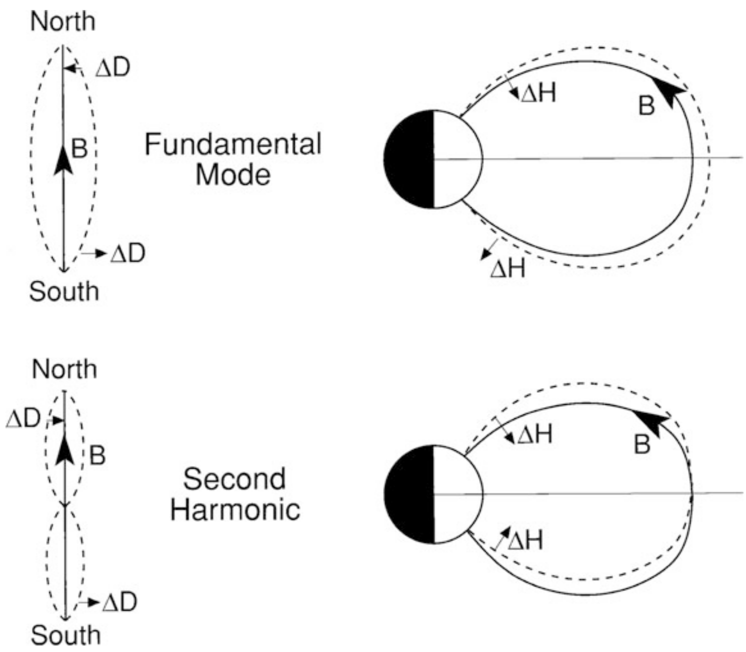

Fig. 7.1 Cartoons showing the oscillation of a geomagnetic field line in the fundamental (*top*) and second harmonic (*bottom*) of the toroidal mode (*left*) and poloidal mode (*right*). On the *left* we look towards the earth with the field line stretched out from north to south. The field line motion and the magnetic perturbations are both in the east-west or azimuthal direction (ΔD). On the *right* the field line is displaced within a meridian plane so both the motion and magnetic perturbations are in the radial direction (ΔH) (after Hughes 1994)

Table 7.1 Resonant period versus latitude

λ_0	τ
45°	10 s
55°	54 s
65°	11 min
70°	55 min

From Dungey (1954)

7.2 The Effect of the Ionosphere

Until the late 1960s, when spacecraft magnetometers in geostationary orbit began to observe them in space, the only way to observe a magnetospheric ULF wave was with a ground-based magnetometer. And for a long time after that ground-based observations provided the only way to observe the spatial variation of a ULF wave. As a result the ionosphere plays two important functions in the study of ULF waves: it provides the boundary condition at the ends of a resonating field line as

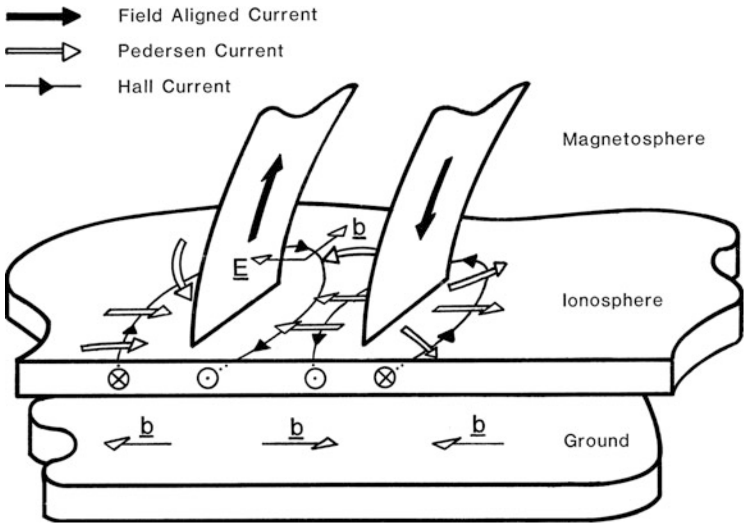

Fig. 7.2 A schematic representation of how the field aligned currents associated with a field line resonance close in the ionosphere via Pedersen currents. As these currents are solenoidal they create little or no magnetic perturbation on the ground provided the ionospheric conductivity is uniform. The magnetic perturbation observed on the ground is the result of the Hall currents that close on themselves within the ionosphere (after Southwood and Hughes 1983)

recognized by Jim in the 1954 Penn State Report, and it also modifies the wave signal before it is detected at ground level.

From the outset Jim realized that the solid earth, neutral atmosphere and ionosphere must be thought of as a whole system when considering their effect on resonating field lines. ULF waves which typically have periods of tens of seconds have wavelengths in free space and in the magnetosphere that are far larger than the height of the ionosphere, making this entire boundary effectively a thin sheet. In 1963 Jim published a short paper pointing this out and showing the importance of including the horizontal variation of the signal in the problem (Dungey 1963b). But he realized that the problem wasn't fully solved, and after I joined his group as a graduate student in 1971 he suggested that I work on it as part of my thesis project.

Although he understood that the anisotropic conductivity of the ionosphere would couple wave modes, Jim did not explore this effect in his 1963 paper. It turned out that the anisotropic conductivity when combined with a horizontal variation in the signal was the critical effect. If the ionosphere were simply a Pedersen conductor the field aligned currents of the transverse Alfvén wave would simply close via Pedersen currents in a solenoidal pattern, effectively screening the ULF wave magnetic signal from the ground (see Fig. 7.2). But the Hall conductivity creates another current that closes on itself (provided that the conductivity is spatially uniform) causing a different magnetic variation on the ground that is rotated through a right angle from the magnetospheric wave above

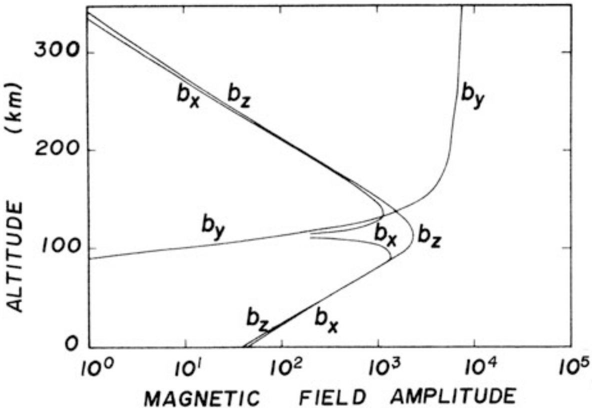

Fig. 7.3 The altitude variation of the components of the magnetic field of a monochromatic Alfvén wave incident on the ionosphere. See text for detailed explanation (after Hughes and Southwood 1976)

the ionosphere (Hughes 1974; Hughes and Southwood 1974). This effect is illustrated more quantitatively in Fig. 7.3, which is the result of a numerical integration of the wave equations through a realistic earth-atmosphere-ionosphere conductivity structure. The wave is monochromatic and has a horizontal variation, $k_\perp$, in the x-direction. The Alfvén mode in the magnetosphere is polarized with the magnetic perturbation, **b**, perpendicular to **k**, so in the y-direction. However, below the ionosphere where the non-conducting atmosphere precludes any vertical current, $(\text{curl } \mathbf{b})_z = 0$ so the magnetic perturbation has to be parallel to **k**, i.e., in the x-direction. The direction of the wave magnetic field changes in a thin region just above 100 km altitude. This is where the conductivity peaks in the E-region ionosphere and hence where the major currents flow.

It is characteristic of Jim that his name does not appear on the publications describing this work even though he provided much of the impetus and motivation behind it. He tended to have his students publish by themselves or just with other collaborators, which means that it is easy to underestimate his contributions to the development of magnetospheric physics when simply looking at the published record.

This ionospheric rotation of the wave polarization helped make sense of the ground-based observations coming from the magnetometers in Canada and elsewhere. By the end of the decade observations from the new ionospheric radars provided the first solid evidence of field line resonance structures at the foot of the field lines in the ionosphere (e.g., Walker et al. 1979). The radars observed the latitudinal variation of the wave amplitude and phase that had been predicted theoretically by Southwood (1974) and Chen and Hasagawa (1974) earlier in the decade.

Direct confirmation of the ionospheric rotation proved observationally challenging, and was further complicated by the fact that when spatial variation in the ionospheric conductivity is included, the rotation, though significant, may not be by exactly a right angle. A recent observation by Ponomarenko and Waters (2013) using rapidly sampled beams from two coherent scatter ionospheric radars, one located in Tasmania and the other in New Zealand, that intersect over a magnetometer located on Macquarie Island allowed them to directly measure the polarization of a Pi2 pulsation simultaneously in the ionosphere and on the ground, confirming the rotation.

7.3 Probing the Magnetosphere with Field Line Resonances

By the 1980s digital spectral data analysis and computer displays had advanced to the point, and spacecraft magnetometer data was clean enough, that Dungey's field line resonances could be dramatically and beautifully confirmed directly using spacecraft data. When the dayside magnetosphere is quiet enough that the signal is not hidden by larger disturbances, each geomagnetic field line can be seen to be ringing with multiple resonant harmonics. Figure 7.4, taken from Takahashi et al. (1984), shows dynamic spectra of the magnetic field observed by three spacecraft in geosynchronous orbit over a 24 h period (one orbit). Multiple harmonics equally spaced in frequency, in one case going up to the sixth harmonic, are clearly visible on the 10–100 mHz range, i.e., with periods between 10 and 100 s. corresponding to the Pc3 geomagnetic pulsations. The frequencies of the harmonics are set by the length of the field line and the variation of the Alfvén velocity along it. The frequencies slowly vary throughout the day as the spacecraft move onto field lines of different lengths and plasma densities. If the length and shape of the field line are known (or can be estimated using a geomagnetic model) the plasma mass density on that field line can be determined. As spacecraft instrumentation has improved, so has our ability to observe these almost omnipresent small amplitude harmonics. Magnetometer data from the recently launched Van Allan Probes have detected resonances up to the 11th harmonic (Craig Kletzing, GEM Workshop tutorial lecture, June 2013).

Using the frequencies of geomagnetic field line resonances, observed either from the ground or from space, to deduce magnetospheric plasma densities is now a standard practice. Figure 7.5 shows an example where this technique, sometimes referred to as magnetoseismology, is used. By combining the plasma mass density estimates with measurements of the electron number density, the mean ion mass is obtained providing clues to the ionic composition of the magnetospheric plasma. The data on the right are taken during the outbound and inbound legs of the orbit of the CRRES spacecraft that is illustrated on the left of the figure. The top panels show the frequency of the fundamental harmonic of the field line as a function of the spacecraft's L shell (a parameter that labels the geomagnetic field line on which the spacecraft is located using the distance from the center of the earth to the point on that field line furthest from the Earth). During both outbound and inbound legs the frequencies drop from about 6 to 2 mHz as the spacecraft moves onto longer field lines, going from $L \approx 4$ to $L \approx 6.5$. The center panels show the plasma mass densities (black dots) derived from these frequencies as well as the electron number

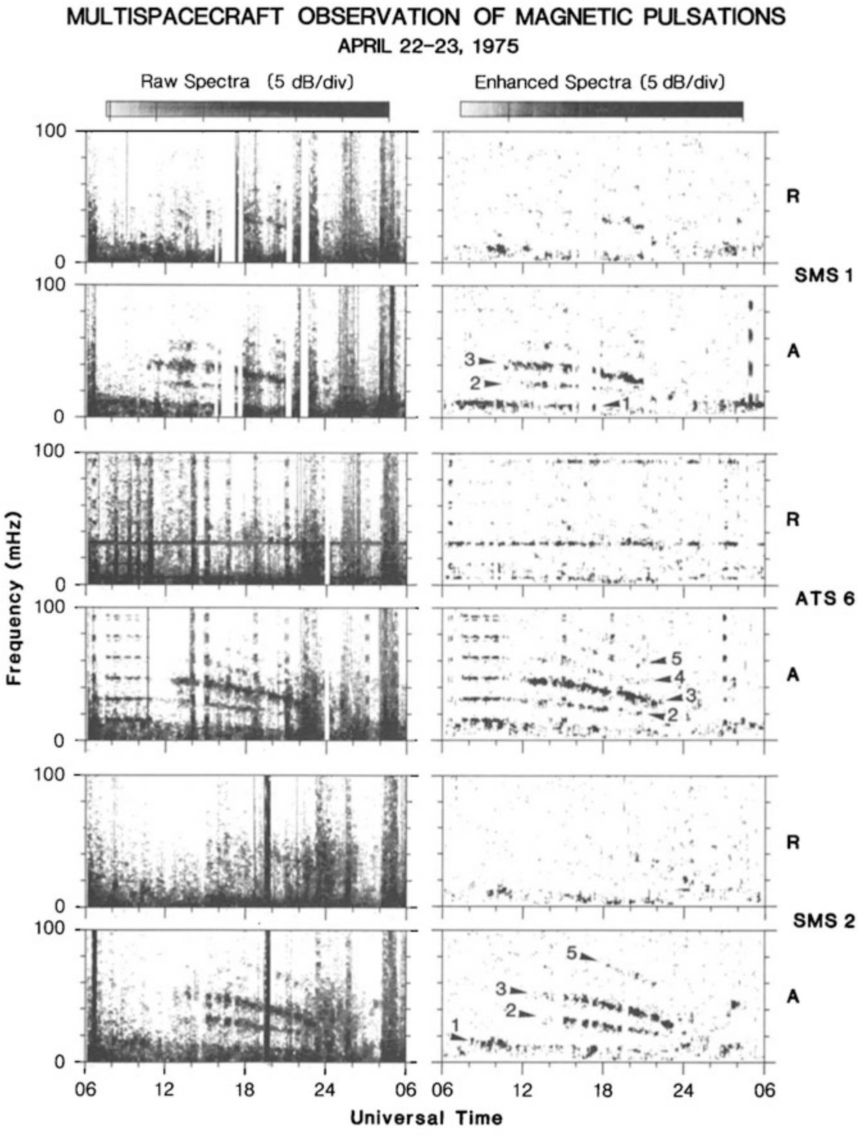

Fig. 7.4 Dynamic spectra of the variations observed in the radial (R) and azimuthal (A) components of the magnetic field by three geosynchronous spacecraft over a 24 h period. Local noon is near the center of the spectra. Multiple harmonics approximately equally spaced in frequency are evident especially in the azimuthal components. These are the signatures of field line resonant harmonic oscillations (after Takahashi et al. 1984)

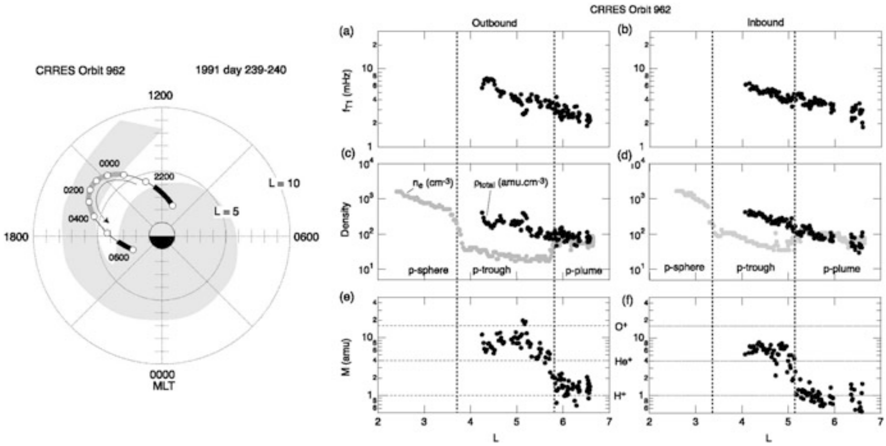

Fig. 7.5 *Left*: Orbit 962 of the CRRES spacecraft with apogee in the late afternoon. CRRES passed out of the plasmasphere (*shaded*) into the plasma trough (*not shaded*) then into a plasma plume shown attached to the plasmasphere (*shaded*) on its outbound leg, and back through these regions on the inbound leg. *Right*: Observations made during the outbound (*right*) and inbound (*left*) legs of orbit 962 of the frequency of the fundamental field line resonance (*top panels*) of the electron number density (*grey*) and ion mass density (*black*) deduced from the frequencies in the *top panel* (*middle panels*) and of mean ion mass obtained by dividing the ion mass density by the electron number density (*bottom panels*) (after Takahashi et al. 2008)

densities (grey dots) derived from the upper hybrid frequency measured using the CRRES wave instrument. The electron number density at low L valves is high as the spacecraft is in the plasmasphere, it drops to a lower value as the spacecraft enters the plasma trough and then increases again as the spacecraft enters a higher density plasmaspheric plume near the orbit's apogee, as illustrated by the shading in the orbit plot. Since the electron number density must equal the ion number density (assuming the ions are all signally ionized), the ratio of these two densities provides an estimate of the mean ion mass which is shown in the bottom panels. These values can be compared to the horizontal dashed lines showing the mass of a hydrogen, helium and oxygen ion. The estimates of the mean ion mass in the plasmasphere and plasmaspheric plume are around 1 amu or not much larger, indicating that the ions are predominantly protons, but in the plasma trough, which contains plasma that has convected from the geomagnetic tail, the mean ion mass approaches 10 amu, indicating a large fraction of oxygen ions. Thus Dungey's field line resonances can be used to show that the composition of these two plasma populations are quite different, indicating their different origins in spite of their proximity.

7.4 ULF Wave-Particle Resonances

Another important aspect of Dungey's work on ULF waves is his work on ULF resonant wave-particle interactions (Dungey 1963a, 1964; Southwood et al. 1969; Dungey and Southwood 1970). Jim recognized early that energetic particles trapped in the radiation belts could resonantly interact with ULF waves standing on a field line through the particles' bounce and drift motions (Dungey 1964), somewhat analogous to wave-particle gyroresonance. If the ULF wave variation in time and azimuth are represented as exp $i\,(\omega t - m\phi)$ then the important parameters are the ULF wave frequency, ω, and azimuthal wave number, m, and the particle's bounce and drift frequencies, ω_b and ω_d. Resonance occurs when $\omega - m\omega_\mathrm{b} = N\omega_\mathrm{d}$ where N is an integer (Dungey 1964). Jim recognized immediately that the symmetry of the wave mode was important. Resonance only occurs for N an odd integer if the wave electric field is antisymmetric about the equator, as in a second harmonic oscillation (see Fig. 7.1) and for N even if the wave is symmetric. Somewhat later Southwood and Kivelson (1982) graphically illustrated this using the diagram reproduced in Fig. 7.6 which illustrates the drift of bouncing ions through an antisymmetric wave. In this example resonance only occurs on the left where the ions drift one azimuthal wave length during each bounce, or $N = 1$, and not on the right where $N = 2$. Using a similar figure it is easy to show that symmetric modes

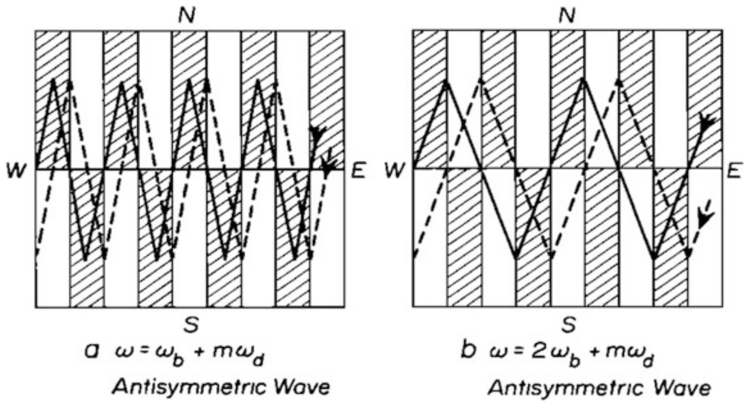

Fig. 7.6 Sketches showing the paths of trapped energetic ions that are both bouncing back and forth along field lines and drifting westward through a standing ULF wave. The *plane* depicts the drift or *L* shell. Field lines are *vertical straight lines* and the *horizontal line* is the equator. The ULF wave is a second harmonic (see Fig. 7.1) for which the direction of the azimuthal electric field (*shading*) is antisymmetric about the equator. On the *left* particles drift westward one azimuthal wavelength per bounce period, while on the *right* they drift two wavelengths per bounce. The particle on the *left* moving along the *solid line* remains in *shaded areas* so experiences only one direction of electric field hence is either continually accelerated or decelerated by the wave depending on the direction of the field. All other particles pass through equal amounts of *shaded* and *unshaded region* over the course of each bounce so receive no net acceleration (after Southwood and Kivelson 1982)

only resonate when N is even. Again, Dungey's initial insight was not appreciated by others until much later.

After ULF waves were first observed at geosynchronous orbit (Cummings et al. 1969) Jim thought that such sinusoidal waves could only be generated by a wave-particle mechanism and not by a hydromagnetic instability such as the Kelvin-Helmholtz instability (Dungey and Southwood 1970). Pursuing this track, Jim pushed to get good observational estimates of the value of the azimuthal wave number m. The first measurements of m made on the ground (Green 1976) and in space (Hughes et al. 1978) were both the result of his efforts.

Dungey's early work on ULF wave-particle resonance, which was largely ignored at the time, laid the foundation for much subsequent work, which continues today as we try to understand the connection between enhanced ULF wave activity and the enhancements observed in radiation belt particle fluxes during the passage of high speed solar wind streams.

7.5 Conclusion

Jim Dungey's insightful recognition in 1954 of the existence of an Outer Atmospheric Cavity filled with a cold plasma whose dynamics can be described using hydromagnetics was an idea way ahead if its time. At the time hydromagnetics was a new idea that few people had taken the time to understand, in sharp contrast to today when magnetohydrodynamics (MHD) is widely accepted as the best description of the large scale dynamics of the magnetosphere and its interaction with the interplanetary medium. Today several global MHD computational models compete to provide the "best" description of magnetospheric dynamics and similar codes are used to explore the dynamics of the solar corona, solar wind structures, and the interaction between the heliosphere and the local interstellar medium, as well as similar astrophysical applications. Jim's pioneering work on field line resonances began to be appreciated a decade later during the 1960s and came fully to the fore two decades later as our observational abilities caught up with Jim's foresight.

As with the initial idea of field line resonances, the importance of Dungey's early work on the effect of the ionosphere on ULF waves and on ULF wave particle resonances were both largely initially unappreciated. Only later did the importance of these ideas become apparent. As often happened with Dungey's ideas, the work continued to be developed at his urging by his students and others, usually without explicit acknowledgement of Dungey's contribution, so that by the time the importance of the idea became generally apparent, Dungey's leading role in its development was far from clear.

Although Dungey is best known for his work on magnetic reconnection and its control of magnetospheric dynamics (Dungey 1961), his earlier work on field line resonances provided the foundation for an entirely different field of magnetospheric physics, the study of the ULF waves that are ubiquitous. This is but another example of how Jim Dungey's pioneering work had a profound influence on almost all subsequent research in magnetospheric physics.

Acknowledgements I thank David Southwood and others for organizing the symposium to celebrate Jim Dungey's 90th birthday, and for inviting me to participate and to write this paper, and the Royal Astronomical Society for hosting the event. But most of all I thank Jim for the stimulation, help, example, and encouragement he gave me first as his graduate student and then throughout my career. He made it all possible.

References

Chapman, S., Ferraro, V.C.A.: A new theory of magnetic storms. Terr. Magn. Atmos. Electr. **36**, 77–97 (1931a)

Chapman, S., Ferraro, V.C.A.: A new theory of magnetic storms. Terr. Magn. Atmos. Electr. **36**, 171–186 (1931b)

Chapman, S., Ferraro, V.C.A.: A new theory of magnetic storms. Terr. Magn. Atmos. Electr. **37**, 147–156 (1932)

Chapman, S., Ferraro, V.C.A.: A new theory of magnetic storms. Part II. The main phase. Terr. Magn. Atmos. Electr. **38**, 79 (1933)

Chen, L., Hasagawa, A.: A theory of long period magnetic pulsations: 1. Steady state excitation of field line resonance. J. Geophys. Res. **79**, 1024–1032 (1974)

Cummings, W.D., O'Sullivan, R.J., Coleman Jr., P.J.: Standing Alfvén waves in the magnetosphere. J. Geophys. Res. **74**, 778–793 (1969)

Dungey, J.W.: Electrodynamics of the outer atmosphere. Scientific Report 69, Ionosphere Research Laboratory, Pennsylvania State University, University Park, PA (1954)

Dungey, J.W.: Electrodynamics of the outer atmosphere. In: Proceedings of the Ionosphere Conference, p. 255. The Physical Society, London (1955)

Dungey, J.W.: Interplanetary magnetic field and the auroral zones. Phys. Rev. Lett. **6**, 47–49 (1961)

Dungey, J.W.: The structure of the exosphere or adventures in velocity space. In: Dewitt, C., Hieblot, J., Lebeau, A. (eds.) Geophysics: The Earth's Environment, pp. 503–550. Gordon and Breach, New York (1963)

Dungey, J.W.: Hydromagnetic waves and the ionosphere. In: Proceedings of the International Conference on the Ionosphere, pp. 230–232. Institute of Physics, London (1963b)

Dungey, J.W.: Effects of electromagnetic perturbations on particles trapped in the radiation Belts. Space Sci. Rev. **4**, 199–222 (1964)

Dungey, J.W.: Hydromagnetic waves. In: Matsushita, S., Campbell, W.H. (eds.) Physics of Geomagnetic Phenomena, p. 913. Academic Press, New York (1968)

Dungey, J.W., Southwood, D.J.: Ultra low frequency waves in the magnetosphere. Space Sci. Rev. **10**, 672–688 (1970)

Green, C.A.: The longitudinal phase variation of mid-latitude Pc 3-4 micropulsations. Planet. Space Sci. **24**, 79–85 (1976)

Hughes, W.J.: The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations. Planet. Space Sci. **22**, 1157–1172 (1974)

Hughes, W.J.: Magnetospheric ULF waves: a tutorial with a historical perspective. In: Engebretson, M.J., Takahashi, K., Scholer, M. (eds.) Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves. American Geophysical Union Geophysical Monograph Series, vol. 81, pp. 1–11. American Geophysical Union, Washington, DC (1994)

Hughes, W.J., Southwood, D.J.: Effect of atmosphere and ionosphere on magnetospheric micropulsation signals. Nature **248**, 493–495 (1974)

Hughes, W.J., Southwood, D.J.: The screening of micropulsation signals by the atmosphere and ionosphere. J. Geophys. Res. **81**, 3234–3240 (1976)

Hughes, W.J., McPherron, R.L., Barfield, J.N.: Geomagnetic pulsations observed simultaneously on three geostationary satellites. J. Geophys. Res. **83**, 1109–1116 (1978)

Ponomarenko, P.V., Waters, C.L.: Transition of Pi2 ULF wave polarization structure from the ionosphere to the ground. Geophys. Res. Lett. **40**, 1474–1478 (2013). doi:10.1002/grl.50271

Southwood, D.J.: Some features of field line resonances in the magnetosphere. Planet. Space Sci. **22**, 483–491 (1974)

Southwood, D.J., Dungey, J.W., Etherington, R.J.: Bounce resonant interaction between pulsations and trapped particles. Planet. Space Sci. **17**, 349–361 (1969)

Southwood, D.J., Hughes, W.J.: Theory of hydromagnetic waves in the magnetosphere. Space Sci. Rev. **35**, 301–366 (1983)

Southwood, D.J., Kivelson, M.K.: Charged particle behavior in low-frequency geomagnetic pulsations 2. Graphical approach. J. Geophys. Res. **87**, 1707–1710 (1982)

Storey, L.R.O.: An investigation of whistling atmospherics. Philos. Trans. R. Soc. Lond. **246**, 113–141 (1953)

Takahashi, K., McPherron, R.L., Hughes, W.J.: Multispacecraft observations of the harmonic structure of Pc3-4 magnetic pulsations. J. Geophys. Res. **89**, 6758–6774 (1984)

Takahashi, K., Ohtani, S.-I., Denton, R.E., Hughes, W.J., Anderson, R.R.: Ion composition in the plasma trough and plasma plume derived from a combined release and radiation effects satellite magnetoseismic study. J. Geophys. Res. **113**, A12203 (2008). doi:10.1029/2008JA013248

Walker, A.D.M., Greenwald, R.A., Stuart, W.F., Green, C.A.: STARE auroral radar observations of Pc 5 geomagnetic pulsations. J. Geophys. Res. **84**, 3373–3388 (1979)