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" SPRING COLLEGE ON GEOMAGNETISM AND AERONOMY "

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" Hydromagnetic Waves "

presented by :

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CHAPTER III.1.3

HYDROMAGNETIC WAVES

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Contents

1. Introduction

The Earth's magnetic field intensity is now known to vary on a variety of time scales ranging from periods of millions of years to fractions of a second as table 1 (adapted from Jacobs [41]) shows. This review is devoted to those variations known as geomagnetic pulsations: the relatively fast, low amplitude changes that typically have periods ranging from a few minutes to fractions of a second and amplitudes of a fraction of a nanoTesla (nT) to several tens of nanoTeslas (10^{-9} T $\equiv 10^{-5}$ $\Gamma = 1\gamma$). These variations, observed on the ground and on spacecraft, are now recognized as originating from a plasma phenomenon, namely hydromagnetic waves occurring in the magnetosphere. As a result the pulsations can also be thought of as the lowest frequency waves that can be sustained in the magnetospheric plasma as fig. 1 demonstrates. Schematically illustrated by the cross-hatched area is the range of power levels of geomagnetic variations typically measured on the Earth's surface in geomagnetic mid-latitudes. Substantially higher power levels (by factors of

Table 1
Periods of geomagnetic variations

Period/sec.	Origin
10^{17}	
10^{16}	
10^{15}	internal and dipolar; dipole reversals
10^{14}	
10^{13}	
10^{12}	
10^{11}	
10^{10}	internal, non-dipolar; secular variation
10^{9}	
10^{8}	
10^{7}	
10^{6}	external; magnetic storms
10^{5}	external; diurnal variations
10^{4}	external; magnetic substorms
10^{3}	
10^{2}	
10^{1}	external; magnetic pulsations
10^{0}	
10^{-1}	external; sub-acoustic

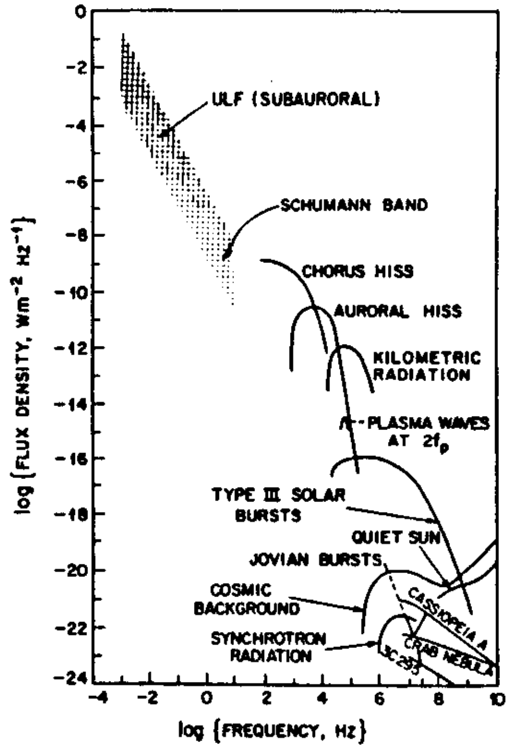

Fig. 1. Power flux levels for various frequency ranges of naturally-occurring waves in the Earth's environment and in astrophysical sources as observed at Earth.

$\sim 10^1 - 10^2$) are frequently observed in the auroral zones. The figure also contains the power levels for various other natural electromagnetic variations (waves) produced in the magnetosphere and in astrophysical sources as detected at the Earth (adapted from Helliwell [34]). The power levels over the entire frequency range vary roughly with the inverse frequency squared.

These rapid changes in the Earth's field have been measured with sensitive instruments (magnetometers) placed on the Earth's surface and, in the last two decades, on Earth-orbiting and interplanetary spacecraft. The first report of observations of few-minute time variations of the Earth's field was contained in a paper by Stewart [84], who reported on a great magnetic disturbance that was recorded at the Kew Observatory (England) in 1859. Stewart, in examining the records taken of the magnetic field measured in England, noticed that during this large magnetic storm there were very large (several hundred γ) and rapid (few minute) changes in the

Table 2
Classification of magnetospheric signals

Name	Frequency	Name	Period or rise time (secs)
SHF	3–30 GHz	Pc 1	$2\pi/\omega =$ 0.2–5
UHF	0.3–3 GHz	Pc 2	$2\pi/\omega =$ 5–10
VHF	30–300 MHz	Pc 3	$2\pi/\omega =$ 10–45
HF	3–30 MHz	Pc 4	$2\pi/\omega =$ 45–150
MF	0.3–3 MHz	Pc 5	$2\pi/\omega =$ 150–600
LF	30–300 kHz		
VLF	3–30 kHz	Pi 1	$\tau_r =$ 1–40
ELF	3–3000 Hz	Pi 2	$\tau_r =$ 40–150
ULF	$\lesssim 3$ Hz	sc, si	$\tau_r \sim$300–

field magnitude and direction. The manifestations of this large magnetic storm were observed widely in the form of aurora over Europe, North America, and Hawaii [56]. The telegraph operator in Boston, Massachusetts, Mr. George B. Prescott, reported that the variations (his actual reported description used the word "wave") of the aurora varied from fifteen seconds to half a minute [67]. He reported these "waves" in the aurora to be accompanied by similar period disturbances in the current on the telegraph lines running outward from Boston *.

Thus, the existence of few-minute variations in the Earth's field has been known for over a hundred years. Nevertheless the great impetus for the study of these "micro-pulsations" came during the International Geophysical Year (IGY) in 1957–1958. During this program, in concert with the large international search for understanding of the Earth's geophysical environment, many more magnetometer stations were established around the world in order to study the global occurrences of natural phenomena such as magnetic storms and magnetic pulsations [62]. During this time, and in the succeeding years, the first global morphology and time dependence of such magnetic disturbances became established.

These early studies ultimately led to the classification of geomagnetic pulsations into categories according to the frequency of the variations [42]. These categories, together with the designations of other magnetospheric signals, are given in table 2 [75] for purposes of reference and orientation. The differences in the physical mechanisms producing various category waves in the "Pc" and "Pi" ranges, if indeed there are any such differences, have by no means been clarified as yet. It is commonly believed that variations with periods of ~1 sec arise from processes associated with the proton gyro-frequency, and these signals in many ways form a sepa-

* As another historical note, it is interesting to point out that this magnetic storm period (August 28–September 7, 1859) was associated with a large solar disruption. This storm on the Sun (September 1, 1859) was apparently the first observation by an astronomer (Carrington) of the so-called "white light" flare.

rate class. They are for example, associated with ring current particle loss processes (see, for example, chapter III.1.4 by L.R. Lyons in this volume). The attention of this chapter is focused on frequencies <1 Hz.

2. Theoretical background

Dungey [21] was the first to suggest that hydromagnetic waves in the exosphere were a likely source of geomagnetic pulsations. Alfvén [2], some ten years earlier, had originated the basic theory of magnetohydrodynamics and magnetohydrodynamic waves. In a perfectly conducting fluid magnetic flux tubes can be thought of as "frozen into" the fluid motion. Combining this idea with the use of the Maxwell magnetic stress tensor to describe the forces on the medium due to the magnetic field B leads to descriptions by analogy of the two hydromagnetic (or magnetohydrodynamic) wave modes. One wave mode in the "cold" plasma theory (fluid pressure effects neglected) is associated with the Maxwell tension B^2/μ_0 along the magnetic field. This mode is a shear wave and only bends the field lines. It is guided along the field, B, with velocity $A = B/(\mu_0\rho)^{1/2}$ (ρ is the mass density) and the field lines thus behave like stretched strings [3]. The second hydromagnetic mode is the fast mode in which the field strength is changed by the wave and the Maxwell magnetic pressure is the important stress. The wave propagates isotropically, also with speed $B/(\mu_0\rho)^{1/2}$, and is analogous to a sound wave in a gas.

The waves described above are cold plasma waves and are only decoupled in a uniform magnetic field and plasma. The magnetosphere plasma is not uniform. Further, in the equatorial regions where the ring current is located (typically at radial distances beyond ~4–5 R_E [Earth radii]), plasma and magnetic pressures may be comparable at times; thus, the plasma is not always "cold" either. Both these facts complicate matters and lead to very interesting plasma theory in the magnetosphere.

The first complication to be examined was mode coupling due to plasma inhomogeneities. In a dipole field the hydromagnetic momentum equation governing small plasma displacements ζ_ϕ in the azimuthal direction is

$$-\mu_0\rho\omega^2\xi_\phi = -\frac{1}{r}\frac{\partial}{\partial\phi}(B\cdot b) + \frac{1}{r}B\cdot\nabla\ (b_\phi r)$$

where r is the distance from the dipole axis. The magnetic perturbation b_ϕ is related to ζ_ϕ by the "frozen in" condition

$$B = \nabla\times(\xi\times B),$$

which gives

$$b_\phi = rB\cdot\nabla\ (\xi_\phi/r).$$

Thus

$$(\mu_0\rho\omega^2 + r^{-1}B\cdot\nabla\, r^2 B\cdot\nabla\,)(\xi_\phi/r) = \frac{1}{r^3}\frac{\partial}{\partial\phi}(B\cdot b). \qquad (1)$$

Similarly, displacements in the meridian, ξ_n, satisfy

$$(rB)^{-1}(\mu_0\rho\omega^2 + rB\,B\cdot\nabla\ (rB)^{-2}B\cdot\nabla\,)(\xi_n rB) = B^2\hat{n}\cdot\nabla\ (B\cdot b)/B^2, \qquad (2)$$

where $\hat{n}$ is a unit vector along the principal normal to B. The operator on the left hand side of eq. (2) is the guided transverse wave operator; the right hand side contains the magnetic pressure terms that couple the fast mode effects. Again, from the frozen in condition

$$\frac{B\cdot b}{B^2} = -\left[\frac{1}{r}\frac{\partial\xi_\phi}{\partial\phi} + \frac{\hat{n}\cdot\nabla}{rB}\ (\xi_n rB)\right],$$

eqs. (1) and (2) only decouple in special cases (e.g. $\partial/\partial\phi = 0$). Thus, this mathematical coupling means that in general the corresponding wave modes are coupled. The coupled equations were first investigated by Dungey [21] and have stimulated a variety of studies [68–70] but have not been fully solved in a dipole background field geometry. However, much progress has been made in understanding the effects of the coupling. As shown below, the importance of the region where signals are quasi-transverse [left-hand side of eq. (2) ≈0; the field line resonance regions] has been demonstrated both by theory and experiment.

The consideration of finite plasma pressure effects first arose in the suggestion of Chamberlain [14] that some pulsations might be drift waves. Such waves can occur in an inhomogeneous plasma and at frequencies in the hydromagnetic range. Other suggestions of a drift instability as a source of pulsation signals were later proposed [31,32,48]. Drift waves when unstable draw their energy from plasma pressure gradients. Often this is accomplished through a resonant wave–particle interaction and can be regarded as inverse Landau damping (see, e.g., ref. [83]). A second effect of a plasma pressure is that the guided mode, which geometrical considerations show is important, can be strongly modified in a hot, inhomogeneous plasma [58,81,82].

Another energy source suggested early as a hydromagnetic wave source was the Kelvin–Helmholtz (wind-over-water) instability acting at the magnetopause [76,79]. This suggestion has had much success in explaining a substantial amount of observational data (see below).

A further important energy source is in processes associated with the unsteady, large-scale magnetospheric plasma convection which naturally give rise to Alfvén waves [8]. The Pi2 pulsations (see table 2) associated with magnetospheric substorms [71,73] are a prime example of such pulsations.

3. Observational background

By the 1960's some ground experiments at each end of a magnetospheric field line had established that many signals appeared to have a standing wave structure along the field [86,87]. These observations were interpreted as standing transverse Alfvén waves on flux tubes (field line resonances) as is schematically illustrated in fig. 2 for an odd mode wave. Early observations in space were reported by Patel [66] who

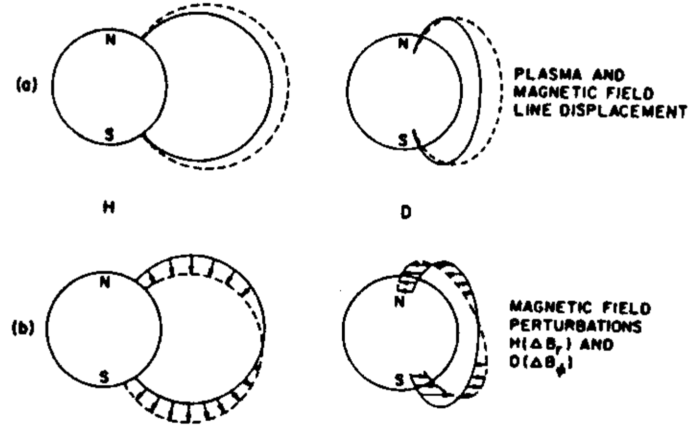

Fig. 2. (a) Plasma and magnetic field line displacements for the fundamental frequency of an odd mode standing wave. (b) Schematic illustration of the magnetic field perturbation at any point along a field line assuming excitation of the fundamental odd mode frequency.

attempted some correlations with ground signals using rather poor resolution ground magnetograms. Observations at synchronous altitude in space [19] of purely transverse sinusoidal signals confirmed the standing Alfvén wave idea and the authors calculated local eigenfrequencies using eqs. (1) and (2), ignoring the $B \cdot b$ coupling terms.

Statistical studies of ground data had demonstrated that the rotation of the pulsation horizontal polarization ellipse had a preferential sense before and after local noon at a particular station (e.g., review by Saito [72]). Most observations of long period (≳100 sec) waves showed predominant left-hand polarization (anti-clockwise

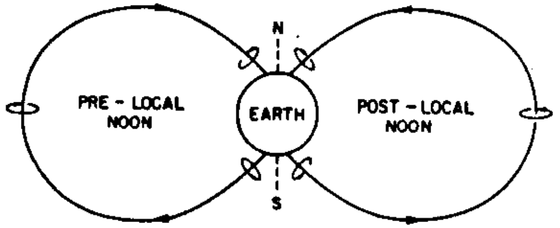

Fig. 3. Rotation of the polarization vector (seen from the Sun) of the transverse mode of hydromagnetic waves as would be expected from the Kelvin–Helmholtz excitation mechanism on the day side of the magnetosphere. Left-hand polarization (counter-clockwise rotation looking along the field line) is observed pre-noon; right-hand polarization post-noon.

looking along the field) in the local morning and the reverse in the afternoon. It was recognized that this polarization was consistent with the Kelvin–Helmholtz instability as a source of the signals as the schematic illustration in fig. 3 shows [7]. Magnetometer measurements on the spacecraft Explorer 33 showed that the polarization of turbulence near the magnetopause followed a similar pattern, directly confirming this source [23].

4. Wave localization and wave modes

Experimental results in the early 1970's from a chain of ground-based magnetometers in northern Alberta marked an important turning point in the understanding of hydromagnetic wave phenomena in the Earth's magnetosphere [74]. Systematic statistical observations were reported on the local time and latitude dependence of wave amplitudes and polarizations for hydromagnetic variations with periods ~200–600 sec. It was found that at a certain latitude, which changed systematically with local time, the wave polarizations reversed in sign (fig. 4). At low latitudes the wave polarizations tend to be left-handed (counter-clockwise rotation of transverse disturbance vector looking along field line) in the hours prior to local noon and right-handed clockwise rotation until ~2100 LT. At higher latitudes, above the "demarcation line" where the amplitudes are a maximum and the polarizations are linear the waves are oppositely polarized. The waves were also reported to be oriented approximately in the north–south direction near the demarcation line.

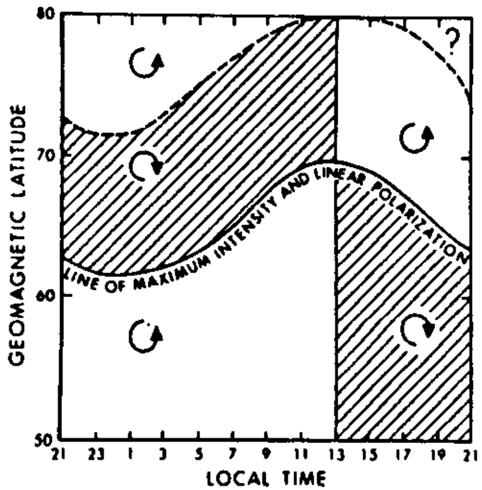

Fig. 4. The statistical diurnal variations of the polarization characteristics of quasi-monochromatic magnetic variations with frequency ~5 mHz. (Copyright by American Geophysical Union, 1971.)

These Canadian results had a strong effect on theoretical developments. Two groups independently pointed out that the observed signal structure was consistent with a theory that combined the current ideas on the Kelvin–Helmholtz instability source at the magnetopause with the notions of standing wave "field line resonances" on flux tubes mapping to lower latitudes on the Earth [16,80]. The developed theory suggested that broadband surface waves are generated at the magnetopause. At a given frequency, however, energy could "tunnel" to the magnetic shell or shells in the magnetosphere where the frequency matches the eigenfrequency of a standing transverse Alfvén wave structure along the field line. This magnetic shell corresponds to the demarcation line and, because of the standing wave resonance, the signal is largest in this region. The polarization structure is also naturally explained.

The statistical results shown in fig. 4 near 60° geomagnetic latitude often do not hold for shorter period variations. A group from Bell Laboratories, using a network of stations established around the $L = 4$ magnetic shell in North America and one station in the geomagnetically conjugate region (Siple, Antarctica) demonstrated that waves in the frequency range ~10–30 mHz are often localized within the latitude range corresponding to geomagnetic dipole L values 3.2–4.4 [26,27,49,53]. The polarizations and amplitudes behaved in the manner suggested by the Alberta results, but with the demarcation line shifted to lower latitudes and with perhaps not as large a latitude excursion with local time (although this latter point needs further study). Furthermore, the longer period waves (~100 sec) often are localized at lower latitudes than the shorter period (~30 sec) waves. A summary of these amplitude characteristics for a specific day studied is shown in fig. 5.

In addition to results for distinct wave-like events, the Bell Laboratories group also reported information on the polarization and amplitude characteristics for geo-

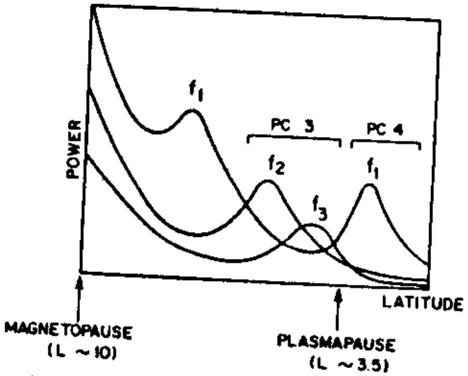

Fig. 5. Schematic profile of the excited intensities of wave variations in the Pc 3 and Pc 4 frequency range (see table 2) inferred from data measured in the interval $L = 3.2$ to $L = 4.4$. (Copyright by American Geophysical Union, 1974.)

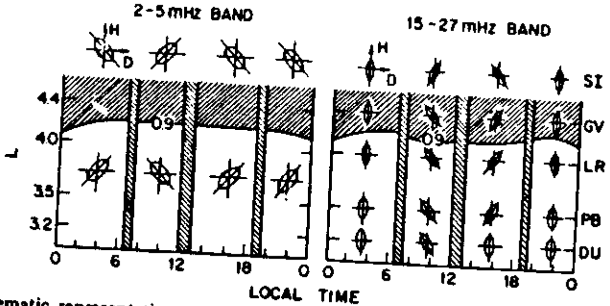

Fig. 6. Schematic representation as a function of local time of the average 0.9 relative power contour and the horizontal plane ellipticities and tilt angles for magnetic field variations in the period band (a) 2–5 mHz; (b) 15–27 mHz.

magnetic power in the frequency bands 2–5, 10–15, and 15–27 mHz using two hour power spectral and coherency analyses. Summaries of these results for the lowest and highest frequency bands are shown in fig. 6 [50]. For power in both of these bands, reversals in the sense of polarization are observed near local noon and near 1900 LT. Changes in the orientation angles of the waves "ellipses" (changes in the phase between the H-component and D-component variations) are observed near 0600 LT and local noon. Also, reversals in the polarization are observed near $L = 4$ in the local afternoon hours in the band 15–27 mHz. The results for the band 10–15 mHz varied considerably from day to day, with the regions of maximum amplitude frequently reaching $L = 3.2$ near local day [50]. The wave polarizations were reversed on opposite sides of the maximum amplitude.

Switches in the orientation angle of wave ellipses around local noon were earlier reported for distinct wave events by Van Chi et al. [89] using data from the conjugate stations Sogra/Kerguelen and by Lanzerotti et al. [54]. Both of these groups reported that the major axis of wave polarization ellipses were oriented in the northwest quadrant prior to local noon and predominantly in the northeast quadrant after local noon. The result from the Quebec/Antarctic study was reported for a continuously sunlit ionosphere over Siple Station [54] while the Sogra/Kerguelen result covered observations for an entire year [89]. No discernible seasonal effects in the ellipse orientation directions as a function of local time were reported in this last study.

Chen and Hasegawa [16] pointed out that their theory could explain such tilts in polarization ellipses. The tilt direction is decided by the gradient of the plasma density and by the azimuthal wave number. Dungey and Southwood [24] noted that the tilts indicated the direction of the energy flux in the magnetospheric signal and are independent of the precise source mechanism. An important feature of these tilts is that although the sense of wave polarization is not affected by the rotation of the signal polarization by the ionosphere (first pointed out by Dungey

[22] and Nishida [61]), the quadrant in the horizontal plane where the ellipse major axis lies clearly is (see below).

The Kelvin–Helmholtz source mechanism makes one very easily visualizable prediction: the waves it generates must move perpendicular to the Earth's magnetic field in the same sense as the wind (the solar wind) which drives them (see also fig. 3). Thus, in the morning sector, the mechanism predicts the waves should have a westward phase velocity; an eastward velocity should prevail in the afternoon. In contrast, pulsations originating as drift waves could propagate in either direction, depending upon the precise mechanism; theory shows E–W (East–West, azimuthal) wavelengths are short for such signals (e.g., refs. [31,32,83]). Signals at auroral and subauroral latitudes originating from magnetospheric convection should show a genral night to day motion, in conformity with the overall magnetospheric convection pattern. Thus, measurements of the azimuthal E–W phase of waves constitute a good test of signal origins. Studies of localized waves on the nightside have provided some evidence for night to day propagation [52,91].

Appropriate azimuthal phase gradients of pulsation signals have only recently been measured. Initial measurements were made by Herron [35] but were ambiguous, being of the total field at stations aligned geographically. Measurements in California with stations separated ~3° in longitude indicated very small phase differences between the stations [94]. A study in the British Isles reported the remarkable fact that the majority of the mid-latitude signals showed a West to East phase motion throughout the day [28]. Such a result is inconsistent with a Kelvin–Helmholtz source. The reported azimuthal wavelengths were relatively large, with most phase differences <10° per degree of longitude. Such long wavelengths preclude a drift wave source. The source of these mid-latitude pulsations remains an enigma.

Azimuthal phase gradients have now been reported from measurements made in space. Hughes et al. [39] used magnetometer data from three near-geostationary spacecraft (ATS6, SMS1 and SMS2) to obtain the measurements of the E–W angular wave numbers shown in fig. 7. The sense of propagation generally switches near midday from westward in the morning to eastward in the afternoon. This is consistent with a Kelvin–Helmholtz source mechanism. The apparent "gap" in the data in the late local afternoon is due to the fact that although at these times there is a strong wave power, the signals at the different spacecraft were not coherent. This condition precludes any estimate of the phase difference between spacecraft and suggests that the E–W wavelengths of these later afternoon signals is shorter than the spacecraft spacing (~4° longitude at a radial distance of 6.6 R_E). Such short wavelengths might be screened by the ionosphere [37] and may be a reason why an absence of waves are reported in the local afternoon from ground-based data [54] (see also below).

An analysis was made of high latitude (auroral zone) low frequency pulsation phase differences from an E–W network in Alberta [63]. These results show propagation directions consistent with a Kelvin–Helmholtz source and E–W wavelengths that are relatively large.

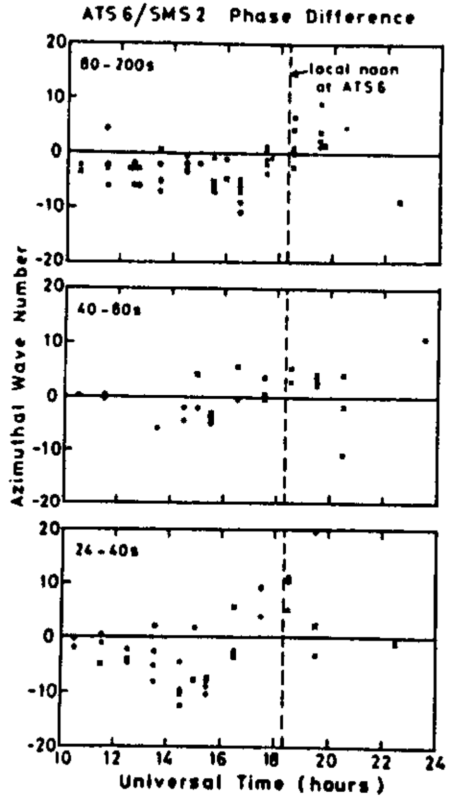

Fig. 7. Phase differences, expressed in terms of azimuthal wave number (degrees/degree longitude) measured between the pair of geosynchronous spacecraft ATS-6 and SMS-2. Results for three different period bands are shown. (Copyright by American Geophysical Union, in press.)

Two studies of mid-latitude data have shown that for ground-based stations spaced at large azimuthal distances (3 to 5 hours in magnetic local time) phase shift for individual wave events cannot be deduced [12,90]. However, simultaneous enhancements and depressions in the overall power in a given frequency band are very often seen. An example like this was first shown by Troitskaya [88] for one event observed both in the Soviet Union and at an observatory in Texas (USA). A study has shown that the enhancements and depressions in wave power over a 5 hour magnetic local time separation appeared to be controlled by the interplanetary magnetic field direction in the ecliptic plane [90]. Such results argue for an external source controlling, at times, wave amplitudes over large distances.

Another form of network study involves conjugate observations, where ground signals measured at each end of a magnetic field line on the Earth are compared. As noted above, early measurements of this nature confirmed the standing wave picture. In a review Lanzerotti and Fukunishi [47] concluded that most of the measured signals were the fundamental. The significance of this is rather subtle, for while most envisaged source mechanisms should excite the fundamental mode most readily, symmetry considerations show that even mode standing structures are most easily generated by some forms of wave–particle interactions [83].

Though the guided mode operator in (1) and (2) depends on the wave polarization, a fair guide to field line resonance eigenperiods is given by the WKB expression,

$$T_n = (2/n)\oint \mathrm{d}s/A, \qquad (3)$$

where n is the harmonic number, A is the Alfvén speed, and the integral is taken along the flux tube from ionosphere to ionosphere. More accurate calculations of eigenperiods have been done (e.g., refs. [19,60,64,65]). A direct implication of this is that localized waves can be used as a diagnostic of the magnetospheric plasma because the integral of eq. (3) is very strongly controlled by the equatorial ion mass density. A comparison has been made of this technique with the higher frequency whistler mode technique which predicts the electron density at the equator [91]. Comparable densities were deduced assuming the magnetospheric ions were protons. The use of this technique could possibly distinguish circumstances when heavier ions become dominant in parts of the magnetosphere.

5. The ionosphere and the atmosphere and boundary conditions

The ionosphere forms a thin boundary layer for many magnetospheric plasma phenomena but its relatively small volume in no way means it is unimportant. As noted above, Dungey [22] and Nishida [61] were first to examine the nature of pulsation signals in the ionosphere and atmosphere; Dungey implicitly and Nishida explicitly pointed out the rotation of the major axis of the polarization ellipse. Greifinger [30] suggested the ionosphere layers could have a dramatic influence on signal orientation on the ground and the full-wave integrations from the ground up to the base of the magnetosphere published by Inoue [40] and Hughes [36] indeed showed that the horizontal signal polarization at the ground was at right angles to the transverse magnetospheric signal. These results were initially greeted with scepticism by the experimental community.

Hughes and Southwood [37,38] developed the theory further and reached three major conclusions: the signal polarization ellipse is indeed rotated by the ionosphere; signals with horizontal wavelengths shorter than ~120 kms (the height of the conducting E region) are attenuated between the ionosphere and the ground; magnetospheric signals reflect well off a typical dayside ionosphere but absorption can be very high on a mid-latitude nightside ionosphere where conductivities are low.

The rotation of the polarization ellipse occurs because the signal above the ionosphere, being quasi-transverse, has $\nabla \cdot \boldsymbol{b} \sim 0$; near the ground however, the low conductivity of the air means $\nabla \times \boldsymbol{b}_h \sim 0$. The field transverse to $\boldsymbol{B}$ above the ionosphere, $\boldsymbol{b}_\perp$, is thus roughly at right angles to the horizontal ground signal, $\boldsymbol{b}_h$. The actual rotation of the signal ellipse is accomplished by ionosphere currents, where collisions are important and both Pedersen and Hall currents play a role. The numerical work shows that the ionosphere is thin enough that the currents can be considered sheet currents. The ionospheric Pedersen current shields the magnetospheric wave fields from the ground. The associated Hall current (at right angles to the Pedersen current) generates an unimportant localized signal above the ionosphere but this current provides the magnetic signal seen on the ground. Below the ionosphere the signal attenuates with decreasing height on a scale comparable with the scale of the horizontal variation, because the signal is essentially magnetostatic in the insulating atmosphere.

The reflection properties of the ionosphere can be understood by noting that the magnetospheric magnetic b and electric E wave fields at the top of the ionosphere are related by

$$b/E = \mu_0 \Sigma_p, \qquad (4)$$

where Σ_p is the height-integrated Pedersen conductivity. (Equation (4) has recently been used with ground magnetic and balloon electric data to deduce Σ_p for a Pc 5-type wave [57]). In a travelling Alfvén wave

$$b/E = 1/A.$$

Bad reflection occurs when impedances match and the requisite condition $A\mu_0 \sim 1/\Sigma_p$ can hold at mid-latitudes at night. Elsewhere Σ_p is large and reflection is good. Hughes and Southwood [38] suggested that this could explain the prevalence of damped pulsations observed at night and continuous pulsations observed in the day as less than perfect reflection means that field line resonance standing structures have characteristic time scales on which they damp. Day and night sources of energy do differ, however, and could be the deciding factor in determining continuous or damped wave occurrences.

The field line resonance theory also predicts that the resonance region thickness is inversely proportional to the damping time, except for waves generated at steep density gradients [17,52]. A measurement of resonance region thickness in space [39] suggests that dayside ionospheric damping is inadequate to account for that observed, and other sources of damping are important [60]. Collisionless damping processes are the alternatives.

If the rotation of a wave polarization ellipse were the only effect of the ionosphere it could easily be allowed for in the interpretation of ground data. The attenuation of signals with rapid horizontal variation is more serious and can mean some signals may only be seen in space (as mentioned above in the discussion of fig. 7). Figure 8 illustrates the manner in which a signal can be modified [38]. Solid lines indicate a model magnetospheric signal while dashed lines indicate the ground signal. A daytime sunspot minimum ionosphere model was used; the Earth was taken to be flat and to have a uniform conductivity of 10^{-2} mho/m. The azimuthal wave number is 10^{-3} rad/km, the wave frequency 10^{-1} rad/sec, and the thickness

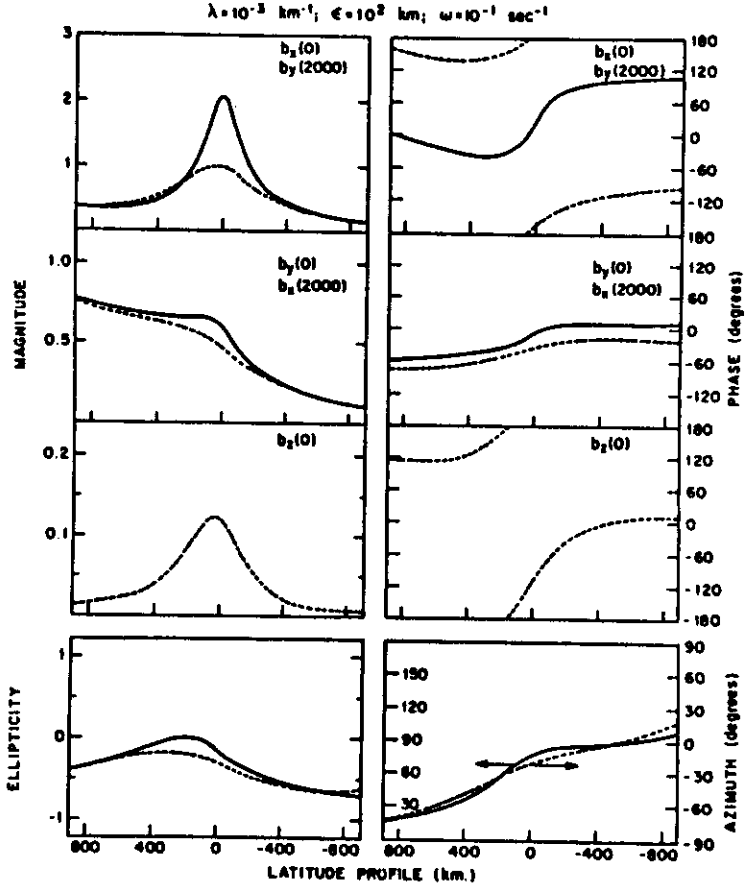

Fig. 8. Model calculations of the ionosphere/atmosphere/ground effects on hydromagnetic waves for the given set of boundary conditions shown. The solid lines correspond to the model wave parameters in the magnetosphere above the ionosphere; the dotted lines correspond to the calculated wave parameter as would be observed on the ground. (Copyright by American Geophysical Union, 1976.)

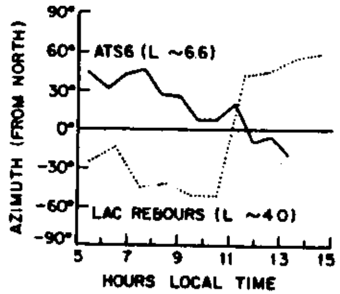

Fig. 9. Variation of the median azimuth angles of waves in the Pc 3 frequency range (see table 2) as a function of local time. Solid line corresponds to transverse waves observed on the geosynchronous satellite ATS-6; dotted line corresponds to transverse waves observed on the ground at Lac Rebours, within about an hour of the ATS-6 meridian. (Copyright by American Geophysical Union, 1977.)

of the resonance region, ϵ, is ~100 km. This model calculation predicts that the wave amplitudes at the ground are reduced near resonance and the polarization reversal on each side of the resonance in the magnetosphere does not occur on the ground. Most often, however, polarization reversals are seen on the ground even when no resonant amplitude peak is observed (see, e.g., refs. [25,52]).

A statistical study of spacecraft magnetic field data contains an analysis of waves detected on the near-equatorial (geomagnetic latitude ~10°) synchronous altitude satellite ATS-6 [6]. This result, plotted in fig. 9, shows that the major axes of the polarization ellipse of waves which are polarized in the plane perpendicular to the local satellite magnetic field (i.e., the radial–azimuthal plane) are located in the northeast quadrant during local morning and in the northwest quadrant during local afternoon. The statistical results from observations at Lac Rebours of conjugate waves (Lac Rebours/Siple) [54], show wave ellipse orientations opposite to that on the spacecraft (fig. 9). Thus, on this statistical basis the wave ellipse orientation in the magnetosphere is rotated from that observed on the ground.

Andrews [5] has discussed a set of measurements on the modulation of the Doppler shift of signals propagating in the whistler mode from the VLF station NLK in Seattle. He reports a significant number of occasions when the whistler duct is apparently acted upon by the electric field of hydromagnetic waves in the period range ~100–600 sec and concludes that the observations are consistent with the magnetospheric wave being the fundamental, odd-mode resonant field line oscillation. Andrews has inferred the wave phase in the magnetosphere and, comparing this with the ground, concludes that, within the resolution of the standard magnetograms necessarily used in his analyses, the wave perturbation vector is rotated by 90° between the space and ground.

Also in favor of the rotation effect is a general feature found in ground measurements; that is, far more latitudinal structure is observed in the north–south component of the signals on the ground while resonance theories predict such structure to occur in the azimuthal component in space. Thus, it appears that observational evidence is building in strong favor of the polarization ellipse rotation between magnetosphere and ground as predicted by theory.

6. Waves in hot plasma

The protons and electrons with energies from 1 to several tens of keV which form the ring current and plasma sheet in the outer magnetosphere can at times have a pressure comparable to the magnetic field pressure in the outer magnetosphere (that is, the plasma $\beta \sim 1$). Not only does this mean that cold plasma theory may be inadequate to explain magnetic oscillations in these regions of space but also that the plasma internal energy is a likely source of wave energy.

Observations reported near the equator at $L = 5$ during a magnetic storm were

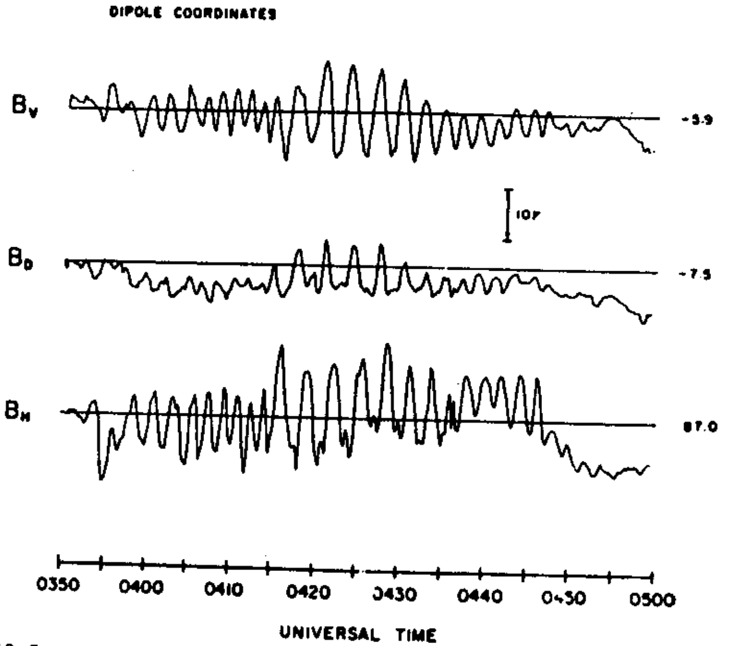

Fig. 10. Compressional wave in the Pc 5 frequency band (see table 2) measured at geosynchronous orbit by the magnetometer on the ATS-1 spacecraft. The H variation is measured along the Earth's dipole direction, D is measured in the east-west direction, and V is measured radially inward (to form a right-hand system). Local time is universal time minus approximately 10 h. The numbers on the right hand side indicate the background field magnitude (in γ).

probably the first which suggested hot plasma effects could be important at times in the magnetospehere [13,78]. Large amplitude (~20γ) magnetic oscillations which had a strong compressional magnetic component (i.e., oscillations in both field strength and direction) were observed. Such signals have since been observed at geosynchronous orbit [9–11] and further out in the magnetosphere at $L \sim 8$–9 [33]. A example from $L \sim 6.6$ is shown in fig. 10. Such events are often preceeded by depressions in the background magnetic field strength, suggesting the presence of hot plasma. The oscillations themselves also suggest this. If they were a cold plasma wave the existence of the compressional component would mean it was the fast mode. However, the signals appear to be confined principally to the late afternoon/cusk sector; fast mode signals with the observed low frequencies could not be so localized. Sonnerup et al. [78] considered several possible mechanisms to explain the $L = 5$ signals and concluded that the most likely was a "slow" mode in which particle pressure and magnetic pressure were in anti-phase. The variations of energetic protons (>98 keV) were in anti-phase with the magnetic pressure oscillations. One of the mechanisms suggested for the flux oscillations is in fact exactly that which operates in the drift-mirror instability [32,48]. This instability is a modified form of the MHD mirror instability. In an inhomogeneous plasma medium, where the proton pressure substantially exceeds the electron pressure, waves generated by the instability have a phase velocity across the magnetic field equal to the net drift of the proton plasma relative to the electron plasma – the diamagnetic drift.

Southwood [81] presented a more general treatment of instability in a non-uniform plasma with $\beta \sim 1$ and showed that the plasma would go unstable before it reached the mirror instability threshold; he suggested the waves that were observed in space were a modified form of field line resonance. The observed waves are mainly polarized in the meridian [9,33] and, in a hot inhomogeneous plasma, wave motion in the meridian generally modifies the particle pressure. Southwood [82] points out that if energy is to be trapped on a flux tube, as occurs in field line resonance, an equal and opposite magnetic pressure change must balance the particle pressure perturbation (see also refs. [18] and [58]).

A wave–particle resonance mechanism can be an important source of wave energy [8]. The relevant resonance with such low frequency, large scale signals is resonance between the particles' azimuthal motion and the field-aligned bounce motion. Resonance occurs if

$$\omega - m\tilde{\omega}_d = N\omega_b\,, \qquad (5)$$

where N is an integer, ω and m are wave frequency and azimuthal angular wave number, and $\tilde{\omega}_d$ and ω_b are the particle azimuthal and bounce frequencies. $\tilde{\omega}_d$ and ω_b are proportional to v^2 and v, respectively, so eq. (5) is a quadratic in the resonant velocity, v.

The wave standing structure along B is important. Particles can resonate with an odd mode standing structure along the field if N is even while an even mode structure requires N odd. If there is an adequate spatial gradient of resonant particles, energy is fed to the wave and instability occurs [43,46,83]. For odd mode waves to be generated, the $N = 0$ resonance is the most important and waves are only unstable if the spatial gradient of resonant particles is inwards and exceeds that generated by adiabatic particle injection [81]. As a result, waves with such symmetry (e.g., the fundamental standing wave on a field line) generally experience collisionless damping due to resonance. Even mode waves interact with particles in the $N = \pm 1$ resonances and it is hard to think of other mechanisms to generate signals with this symmetry. Early geosynchronous orbit observations were interpreted as being even mode transverse waves [19] although later work questions this conclusion [20]. As noted above, a review of evidence on the symmetry of puslations deduced from studies at magnetically conjugate sites concluded that most waves had odd mode symmetry [47]. A ground–satellite study also concluded this [53]. However, the waves generated by the $N = \pm 1$ resonance should have a short azimuthal wavelength and might be shielded from the ground by the atmosphere and ionosphere as discussed above. Short wavelength signals observed in local afternoon at synchronous orbit [39] may be generated in this way.

7. Particle flux oscillations

A way of considering resonance phenomena is to note that particles in resonance provide a current in phase (giving damping) or in anti-phase (giving growth) with the wave electric field. The current from the bulk of the plasma is in quadrature with this electric field. Thus, a particle's behavior in a low frequency wave is a strong function of its energy; as a result, a study of particle flux oscillations observed at different energies can potentially yield a variety of information about wave structure. Early measurements of flux oscillations in space were of particles in the high energy tail of the distribution [13]. Even so, the pressure of energetic protons (>98 keV) during a magnetic storm event was found to be considerable [48,78].

A study of particle and magnetic field data in the outer magnetosphere using data from the elliptical orbit OGO-5 satellite shows that waves in the Pc 5 frequency band (see table 2) are quasi-transverse [44]. 'Cold' (<600 eV) ion flux oscillations are interpreted as originating from wave-induced '$E \times B$' drift; the amplitude of the oscillation yields an estimate of the wave electric field, an otherwise difficult measurement. The electric field is in quadrature with the transverse magnetic field oscillation, a confirmation that the signals have a standing wave structure along B. The energetic electrons (>50 keV) and energetic protons (>100 keV) often showed phase shifts in the oscillations between different particle energy channels. The observation of larger proton modulations in the local morning and electron modulations in the local afternoon events could originate from drift resonance; the local time dependence of the observations is consistent with the propagation directions expected for waves generated by the Kelvin–Helmholtz mechanism.

Energy-dependent oscillations of energetic particles measured on the geosyn-

chronous satellite ATS6 have been studied [85]. In particular, distinct phase differences are observed between particle oscillations measured in detectors with 180° opening angle separations. The observations suggest that for these oscillations the wavelength across b is comparable with the Larmor radius of the detected energetic protons.

A study of low energy particle response to a low frequency wave (~55 sec period) has been made by W.J. Hughes, using data from the geosynchronous satellite ATS-6. Shown in fig. 11 are two proton and two electron energy ranges (integrated over four energy channels each) plotted against the phase of the magnetic field oscillation as measured by the on-board magnetometer. (This analysis procedure was necessary because the time for a complete scan (~24 sec) over all particle energies (0–80 keV) was comparable to the wave period.) The 0.8–1.2 keV protons which oscillate in quadrature with the magnetic field are dominated by the wave $E \times B$ drift. The 21–32 keV proton flux oscillations are interpreted as particle acceleration and deceleration in the wave field and indicate that the proton pressure oscillates in anti-phase with the magnetic field oscillations. The 34 eV electrons are much faster than the 1 keV protons and hence their $E \times B$ drift is unimportant; their response is believed due to acceleration and deceleration in the wave field. An inspection of the context of occurrence of this event suggests that it occurs close to a steep gradient in the 10.7 keV electron population. Convection of this gradient

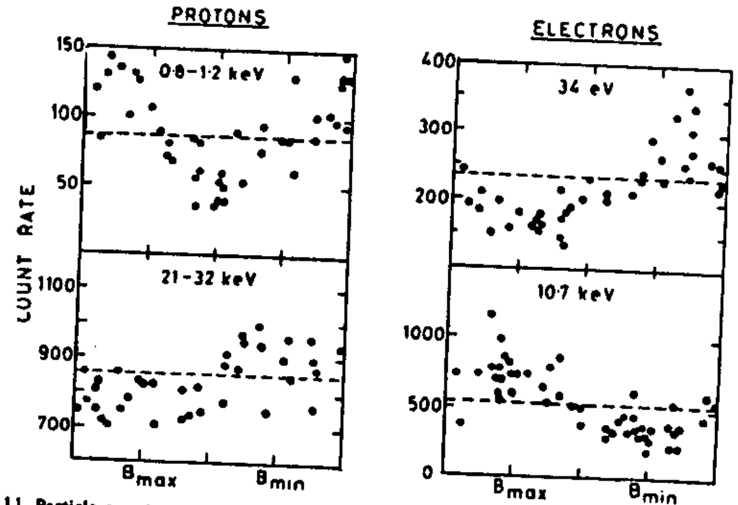

Fig. 11. Particle count rates in four energy channels from the plasma instrument (University of California, San Diego) on the ATS-6 spacecraft. Count rate is plotted as a function of the phase of the magnetic field oscillation as recorded by the on-board magnetometer (University of California, Los Angeles). Figure kindly provided by W.J. Hughes, Imperial College.

back and forth across the spacecraft is believed to be responsible for the oscillations of these electrons being in phase with the magnetic field.

Particle flux oscillations in the absence of a magnetic signal would indicate the occurrence of an electrostatic wave. Although such events appear to be uncommon, a report of particle observations made on the geosynchronous ATS-5 satellite suggested an electrostatic drift wave origin for the events [55].

8. Concluding remarks

This paper has discussed some of the areas of current research interest in the physics of low frequency waves in the earth's magnetosphere. The review is by no means exhaustive and the field is presently very active. Among current topics that we have not discussed in depth are the variety of correlations studied between interplanetary conditions and pulsation parameters in order to better understand dayside source mechanisms (e.g., recent work includes refs. [29,45,77,92,93]). The physical processes underlying these correlations are a matter of much dispute. The Kelvin–Helmholtz instability is one candidate and, as discussed above, there is much inferential data and limited direct data to suggest that this is an important dayside source mechanism. However, some reported correlations would be inconsistent with this mechanism. The existence of the correlations does, however, demonstrate the potential use of magnetic pulsations as a cheap diagnostic of solar wind parameters.

Another potentially useful role of pulsations in magnetospheric diagnostics, only briefly mentioned above, is exemplified by the nightside impulsive Pi 2 signals (see table 2) which directly correlate with changing magnetic activity on the nightside. These signals have regularly been suggested as providing a timing scheme for magnetic substorms, [71,73] and more work on their source mechanism is warranted. There is evidence that at sub-auroral latitudes these signals appear as field line resonances [25,59] and an excitation mechanism has been proposed [15].

A further major field of research ignored here is that of Earth induction, where the prime concern is to deduce the conductivity structure below ground level For this type of study to be effective, a clear delimitation of source-associated wave structure is needed. As seen above, great progress has been made in studies of source structure in the last few years. Applications to induction studies are just beginning [1,4].

To date, hydromagnetic waves have been studied in situ in the near-Earth cosmic plasmas of the terrestrial magnetosphere and interplanetary space within ~5 AU (astronomical units). In the next decade, data from spacecraft encounters with the magnetospheres of Jupiter and Saturn and with spacecraft orbiting Jupiter will provide outstanding opportunities for expanding research in hydromagnetic wave phenomena to new cosmic plasma conditions.

In summary, then, we have reviewed magnetospheric hydromagnetic waves. Many features of these waves are easy to visualize, and at times simple ideas have

been very productive in stimulating theoretical developments. A variety of experimental techniques have been used in the study of the waves. Much important work can only reasonably be done on the ground with magnetometer networks, but spacecraft alone can make measurements actually within the plasma. Some experimental techniques have yet to be fully exploited in pulsation studies. Amongst these can be included balloon-based electric field measurements, ionospheric radar systems such as STARE, EISCAT and Chatanika, and detailed studies of particle flux oscillations. As noted throughout the review, important physics questions remain to be answered by new and/or by standard techniques.

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