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## THE MAGNETOSPHERE AND ITS TAIL

Since the last report was written (in the spring of 1966), there has been a remarkable advance in our knowledge and understanding of the structure and behavior of the magnetosphere, especially with regard to the fundamental problems of the aurora and geomagnetic storms.

The average structure of the quiet magnetosphere has been studied in considerable detail [*Ness et al.*, 1966; *Spieser and Ness*, 1967; *Behannon*, 1968; *Fairfield*, 1968; *Mihalov et al.*, 1968], and it has been shown that the tail and 'neutral' sheet extend well past the moon, and possibly to much greater distances [*Ness et al.*, 1967]. The nature of the changes that occur in the geomagnetic field during disturbed periods has been observed, especially by magnetometers on the geostationary satellite ATS 1 [*Brown et al.*, 1968; *Cummings et al.*, 1968; *Cummings and Coleman*, 1968]. It has been found that the ring current, which is usually situated between 3 and about 10 $R_E$ depending on the degree of geomagnetic activity, commonly has a pronounced asymmetric component, with the maximum inflation of the geomagnetic field occurring in the evening sector.

The magnetospheric substorm has been investigated from many points of view [*Akasofu*, 1968]. It now seems clear that this is probably the most important feature of geomagnetic storm phenomena; in particular, it strongly influences the acceleration and injection of particles into the magnetosphere to form the ring current and radiation belts [*Davis and Parthasarathy*, 1967].

A most important development has been the successful detection of low-energy (~10 kev) particles that carry most of the trapped energy in the magnetosphere during storms and that also contribute the auroral primaries. A region of low-energy (~1 kev) plasma has been found to be associated with the tail of the magnetosphere [*Bame et al.*, 1967], and the inner parts are found to connect to the auroral zones [*Vasyliunas*, 1968*a, b*]. The inward motion of the plasma sheet during magnetospheric substorms is consistent with the suggestion that the auroral and ring current particles originate in the tail of the magnetosphere. The motion appears to stop at the plasmapause, judging from the behavior of the ring current protons observed by *Frank* [1967], and in agreement with the general features of the convection theory of magnetic storms.

The large-scale magnetospheric electric fields that are associated with convection have been detected by a variety of techniques, notably the barium ion cloud method developed originally by the Munich group [*Westcott et al.*, 1968], by direct probe measurements in the ionosphere [*Mozer and Bruston*, 1967; *Kelley et al.*, 1968] and in more distant regions of the magnetosphere [*Aggson*, 1968], and from balloons [*Mozer and Serlin*, 1968]. Direct observations of the convection itself have been made by low-energy particle detectors on ATS 1 [*Freeman and Maguire*, 1967; *Freeman*, 1968]. On the whole, the results of these experiments and others appear to be consistent with the convection theory in its simplest form (for reviews see *Axford* [1969]; *Kennel*, [1969].

## THE PLASMAPAUSE

Satellite studies have verified and extended our knowledge of the plasmapause by confirming its persistence, its essentially worldwide nature, its reduction in radius during increases in magnetic disturbances, and also details such as the diurnal increase in plasmapause radius in the dusk sector [*Binsack*, 1967; *Brinton et al.*, 1968; *Vasyliunas*, 1968*a*; *Taylor et al.*, 1968; *Carpenter et al.*, 1969]. Correlation studies have shown close agreement between plasmapause position as determined from a mass spectrometer and from a VLF receiver on the same EOGO satellite [*Carpenter et al.*, 1969]. Comparison of satellite ion data on plasmapause crossings with ground whistler data on plasmapause radius showed good agreement for a wide variety of longitudinal separations between experiments, thus confirming earlier findings on the shape of the plasmasphere [*Carpenter et al.*, 1969].

Pronounced changes in whistler and VLF noise activity at the plasmapause were identified both in polar orbit near 1000 km and at high altitudes near the equator [*Carpenter et al.*, 1968*a, b;* 1969]. The observed sharp decrease with increasing $L$ in the rate of propagation of whistlers to the conjugate hemisphere may, in part, be an ionospheric effect, since abrupt latitudinal cutoffs of upgoing fixed-frequency VLF waves have been observed near $\Lambda = 60°$ [*Heyborne et al.*, 1969].

During the main phase of the magnetic storm of July 9, 1966, the position of the plasmapause was identified by Taylor's ion mass spectrometer on OGO 3 as near, or just inside, the region of nightside ring-current activity identified by Frank from the same satellite [*Taylor et al.*, 1968; *Frank*, 1967].

There is little published information on the fine structure and dynamics of the plasmapause, although it is evident that the boundary may sometimes be very thin (<10 km at 1000-km altitude) [*Carpenter et al.*, 1968*b*], and that it has special properties as a waveguide at VLF [*Carpenter*, 1968*a*].

Cross-$L$ drifts of tubes of ionization within the plasmasphere during magnetospheric substorms were found to correlate well with displacements of the plasmapause. During an intense relatively isolated substorm, rapid cross-$L$ drifts of whistler ducts to lower $L$ values were observed near midnight. The drifts were accompanied by a corresponding inward shift of the plasmapause near the longitudes of observation [*Carpenter and Stone*, 1967]. In another case, an apparent dayside longitudinal variation in plasmapause radius of the order of 0.5–1 $R_E$ was interpreted in terms of the difference in substorm activity experienced by separate longitudinal sectors of the plasmasphere during the preceding local night [*Carpenter et al.*, 1969].

Interpretive work on the plasmapause phenomenon has attempted to explain the low plasma densities in the region exterior to the plasmapause in terms of processes that couple a significant part of the outer region of closed field lines to the distant tail and/or solar wind. In Brice's 1967 study (which draws upon earlier work by *Axford and Hines* [1961], *Dungey* [1961], and *Nishida* [1966], the coupling is accomplished by magnetospheric convection in the outer magnetosphere, with emphasis on a sunward flow from the magnetotail. A similar mechanism, based on calculation of individual particle trajectories, was discussed by *Kavanaugh et al.*, [1968]. In a study by *Mayr* [1968], the coupling is accomplished by turbulent diffusion across field lines in the outer magnetosphere.

## WHISTLERS AND ION EFFECTS

Observations of whistlers at high altitudes in the magnetosphere with the OGO 1 satellite have led to the discovery of a new class of whistlers called magnetospherically reflected (MR) whistlers [*Smith and Angerami*, 1968]. The MR whistler confirms earlier ray tracing calculations by *Kimura* [1966], which demonstrated that unducted whistler-mode waves can reflect within the magnetosphere by propagating transverse to the geomagnetic field at frequencies below the lower hybrid resonance frequency. *Carpenter* [1968*a*] has extensively studied the upper cutoff frequency of ducted nose whistlers and has concluded that the cutoff is controlled by propagation effects [*Smith*, 1961] and not by cyclotron damping [*Scarf*, 1962].

Several new ion effects on magnetospheric radio waves have been found with satellite and rocket-borne ELF-VLF receivers. The sharp low frequency cutoff of magnetospheric ELF emissions observed by low altitude satellites [*Smith et al.*, 1969; *Guthart et al.*, 1968] has been explained as a reflection point for downward propagating ELF whistler-mode waves [*Gurnett and Burns*, 1968]. This reflection is due to a cutoff for the extraordinary mode at the two-ion cutoff frequency between the proton and helium (or oxygen) gyrofrequencies. This same reflection has also been observed to occur for downward propagating whistlers [*Muzzio*, 1968]. Lower hybrid resonance (LHR) noise and related phenomena have been studied extensively with satellite-borne electric antennas [*Carpenter et al.*, 1968*a*; *Laaspere et al.*, 1969]. Recent rocket [*Gurnett*, 1968] and satellite [*Anderson and Gurnett*, 1968] data showing pronounced spin modulation of LHR noise suggest that at least some of the observed LHR noise may be caused by the spacecraft moving through the ionosphere. Noise bands associated with harmonics of the proton gyrofrequency have been identified from recent rocket and satellite data [*Mosier and Gurnett*, 1969].

## WAVE-PARTICLE INTERACTIONS, VLF EMISSIONS, AND ELECTROSTATIC WAVES

### *Wave-particle interactions*

*Solar wind, bow shock, and magnetosheath.* The discovery of proton thermal anisotropies in the solar wind [*Wolfe et al.*, 1966; *Hundhausen et al.*, 1966] has led to the prediction that ion cyclotron whistlers [*Scarf*, 1966; *Scarf et al.*, 1967; *Scarf and Fredricks*, 1968; *Kennel et al.*, 1968] and firehose [*Kennel and Scarf*, 1968] turbulence might prevent thermal anisotropies from growing too large. Electromagnetic whistler modes [*Holzer et al.*, 1966; *Heppner et al.*, 1967] and electrostatic ion acoustic [*Fredricks et al.*, 1968; *Fredricks and Coleman*, 1969] mode turbulence has been observed in the earth's bow shock. Large amplitude low frequency waves, which have been observed upstream from the shock [*Fairfield*, 1968; *Greenstadt et al.*, 1968], might be associated with upstream energetic electrons [*Anderson*, 1961] and protons [*Asbridge et al.*, 1968; *Frank*, 1968]. *Tidman* [1967*a*, *b*] has discussed the theory of ion acoustic turbulence in shocks; *Kennel and Sagdeev* [1967] have proposed generation of Alfvén wave turbulence, criticized by *Abraham-Shrauner* [1968]. *Siscoe et al.* [1967] have discussed measurements of intense hydromagnetic turbulence in the magnetosheath.

*Van Allen belts.* The proposal of *Kennel and Petschek* [1966] that whistler mode instabilities might limit the fluxes of 40 kev electrons has stimulated many experimental investigations. *Liemohn* [1967] has performed extensive calculations of whistler amplification, and *Roberts* [1969] has summarized evidence that >200-kev electron fluxes do diffuse in pitch angle. He has also proposed that bounce resonance interactions with whistlers are important. *McDiarmid et al.*, [1968] have found that >40-kev electrons return to the stably trapped limit after substorm acceleration. ELF whistler hiss of the appropriate frequency to resonate with Van Allen electrons is commonly detected at high latitudes [*Taylor and Gurnett*, 1968] and at low latitudes within the plasmapause [*Helliwell*, 1969; *Russell et al.*, 1969]. Beyond the plasmapause the noise in the same frequency band has 'chorus' structure [*Burtis and Helliwell*, 1969; *Russell et al.*, 1969]. Chorus and precipitation microbursts are apparently related [*Roberts*, 1969]. The amplitudes, averaged over space, are in agreement with the Kennel and Petschek theory [*Helliwell*, 1969]. A major question is why the observed wave spectrum is so structured. *Helliwell* [1967] has a promising theory for both chorus and triggered emissions, involving a nonlinear wave-particle interaction in an inhomogeneous magnetic field.

Other wave-particle interactions proposed include Landau amplification of oblique whistlers when the electron energy distribution has a secondary peak [*Thorne*, 1968] and scattering from enhanced ion acoustic fluctuations [*Eviatar*, 1966]. It is likely that fluxes of >100-kev protons are limited by ion cyclotron instability [*Cornwall*, 1966; *Kennel and Petschek*, 1966].

A major unknown is how electrons and protons are accelerated to high energies. Van Allen electrons are apparently locally accelerated at disturbed times near the plasmapause [*Williams et al.*, 1968]. *Kennel* [1969] has proposed that, in the strong pitch angle diffusion limit, electrons will be accelerated to high energies. Protons apparently radially diffuse across lines of force conserving their first adiabatic invariant [*Krimigis and Armstrong*, 1966]. *Cornwall* [1968] has proposed that this is Bohm diffusion due to drift instabilities.

*Auroral zone and tail.* There has been a great improvement in our experimental understanding of auroral zone phenomena. We now have some understanding of particle distributions in the tail [*Bame et al.*, 1967]. A striking discovery is the sharp inner boundary of the auroral electron distribution [*Vasyliunas*, 1968*a*, *b*], its association with the outer boundary of the Van Allen belts [*Frank*, 1967*a*], and the spatial separation of ring current protons from auroral electrons [*Frank*, 1967*b*]. Extremely strong pitch angle diffusion, resulting in intense auroral precipitation, may account for this morphology [*Petschek and Kennel*, 1966; *Kennel*, 1969; *Vasyliunas*, 1969]. Preliminary evidence indicates that the night side equatorial plane has intense chorus emissions [*Brody et al.*, 1969] and high frequency electrostatic noise [*Kennel et al.*, 1969]. No such intense turbulence at proton frequencies has yet been reported.

*McPherron et al.* [1968] have studied intense micropulsation activity in association with auroral substorms. Ten-second modulations of electron precipitation are associated with micropulsations of the same period. *Vasyliunas's* [1968*a*, *b*] electron boundary may be unstable to low frequency drift oscillations [*Coroniti and Kennel,* 1969]. *Liu* [1969] has discussed low frequency interchange and drift instabilities of the ring current belt. The parallel electric field arising from these instabilities rapidly relieves the particle pressure in space.

Auroral hiss ≈10 kHz is observed at low altitudes associated with auroral electron precipitation [*Gurnett,* 1966]. *Jorgenson* [1968] has conjectured that auroral hiss is due to Cherenkov radiation from precipitating electrons, and *Perkins* [1967] has proposed that the monoenergetic electron fluxes observed in the auroral zone ionosphere may be unstable to electrostatic upper hybrid resonance emissions. Little information exists on noise in the tail. This presents a significant gap in our knowledge.

*Electrostatic waves*

The growing awareness of the importance of electrostatic waves in space plasmas has led to a greatly increased use of electric field antennas on U. S. spacecraft. The various approaches for VLF and ELF electric field measurements within a plasma were evaluated in several recent reports [*Scarf,* 1968; *Scarf et al.,* 1968; *Shawhan and Gurnett,* 1968]. It appears that very different techniques are appropriate for high and low density plasmas. The transition region depends on the wave frequency being examined and on the plasma parameters. Successful VLF electric field experiments were conducted on many recent rocket flights; on OV3-3, OGO 4, Injun 5, and other polar-orbiting spacecraft, on OV2-5 (synchronous), on OGO 3 and 5 (elliptical, with apogee near 24 $R_E$), and on the deep space probes Pioneer 8 and 9.

At low altitudes, new information on ion Bernstein modes (ion gyrofrequency harmonics, ion hybrid resonances) is being accumulated [*Anderson and Gurnett,* 1968; *Guthart et al.,* 1968; *Scarf et al.,* 1969], and the simultaneous measurement of $E$ and $B$ components helps to distinguish between true electrostatic noise signals (polar or auroral lower hybrid noises) [*Anderson and Gurnett,* 1968] and quasi-electrostatic hiss bands (typified by some midlatitude LHR observations) [*Shawhan and Gurnett,* 1968]. These measurements have stimulated extensive reanalysis of the warm plasma dispersion relations, and it is now clear that the conventional classification into electromagnetic and electrostatic waves is not always a very useful one [*Fredricks,* 1968*a*, *b*; *Fredricks and Scarf,* 1969].

Large amplitude low frequency electrostatic noise bursts are observed in the bow shock region, and it appears that these waves play an important role in providing a dissipation mechanism for the collisionless shock [*Fredricks et al.,* 1968; *Fredricks and Coleman,* 1969; *Crook et al.,* 1969]. Similar large noise enhancements are detected in the solar wind when interplanetary shocks or other disturbances are encountered [*Scarf et al.,* 1968]. More moderate low frequency noise levels are found in the solar wind and magnetosheath during quiet times, but these levels are still generally higher than the background levels measured in the magnetosphere [*Crook et al.,* 1969; *Wolfe et al.,* 1968]. The relationship of increased noise levels with onset of plasma streaming suggests that Doppler shifts are important in the wind. High frequency electric emissions [*Brody et al.,* 1969; *Kennel et al.,* 1969] and noise bursts are also detected in the outer magnetosphere and at the magnetopause [*Fredricks et al.,* 1968].

## HYDROMAGNETIC DISTURBANCES

New satellite observations, systematic analyses of ground observations, and new theoretical developments have improved our understanding of hydromagnetic disturbances in the magnetosphere.

The concept of a magnetospheric substorm has emerged to describe those physical processes that simultaneously produce major geomagnetic activity, enhanced particle precipitation, and disturbed auroral forms. Mainfield variations during a substorm are attributed [*Akasofu and Meng,* 1969] to ionospheric Cowling and Hall current loops that close in the magnetosphere. A close connection between micropulsation noise and modulated electron precipitation is suggested [*McPherron et al.,* 1968] by their simultaneous occurrence and similar periodicities. Geostationary satellite observations [*Cummings et al.,* 1968] have revealed that substorm field variations are localized in the dusk to midnight sector, and partial ring currents are proposed as the explanation. Knowledge of the morphology of major geomagnetic storms has also improved through satellite observations that show that the bow compression wave propagates through the magnetosphere and out of its tail during the sudden commencement [*Sugiura et al.,* 1968], and the tail field remains enhanced during the main phase as well [*Behannon and Ness*, 1966].

Micropulsation oscillations in the frequency band from 0.001 to 5 Hz have been detected in the vicinity of the magnetosheath by several satellite magnetometers [*Holzer et al.*, 1966; *Heppner et al.*, 1967; *Greenstadt et al.*, 1967; *Siscoe et al.*, 1967]. The magnitude and shape of the power spectrum is similar to that measured by ground stations. Theoretical studies of propagation properties have provided more realistic estimates of the poloidal and toroidal mode periods [*Carovillano and Radoski*, 1967], better justification for field-line guidance of Alfvén waves in the magnetosphere [*Fejer and Lee*, 1967], and a comprehensive treatment of transmission, mode coupling, and guidance in the ionosphere [*Greifinger and Greifinger*, 1968]. Continuous sinusoidal oscillations with periods of 50–300 sec, which are routinely observed at geostationary altitudes, have been interpreted [*Cummings et al.*, 1969] as the second harmonic of a magnetohydrodynamic standing-wave resonance. The physics of one class of Pc 1 signals (called ULF whistlers), which propagate back and forth along field-line paths, is sufficiently documented to permit its use as a magnetospheric probe. Statistical analysis of data from conjugate ground stations [*Campbell*, 1967] has shown that Pc 1 signals do not heat the ionosphere significantly and that their latitude dependence follows the auroral oval. Dispersion measurements of a large collection of Pc 1 data have been analyzed [*Kenney et al.*, 1968] to obtain plasma density distributions, which agree substantially with other estimates.

## INCOHERENT BACKSCATTER

The presunrise heating of the $F$ region by photoelectrons from the conjugate hemisphere [*Carlson*, 1966] and its relation to enhancements of the plasma line and airglow emissions have been further examined by several groups [*Carlson*, 1968; *Yngvesson and Perkins*, 1968; *Kwei and Nisbet*, 1968; *Carlson and Weill*, 1967; *Evans*, 1967*a*, 1968; *Fontheim et al.*, 1968]. The temperature effect is less pronounced at Millstone than at the lower latitude of Arecibo.

Studies of the heat budget in the ionosphere made possible by simultaneous determinations of $T_e$, $T_i$, and $N_e$ from the scattered signal have revealed the importance of heat conduction within the ionosphere, thermal coupling with the protonosphere, and nonlocal heating by the photoelectrons [*Nisbet*, 1967, 1968; *Evans and Mantas*, 1968; *Nagy et al.*, 1968; *Moorcroft*, 1969]. *Hanson and Cohen* [1968] found the energy delivered to the thermal electrons by each photoelectron to be 10–20 ev above 300 km at the magnetic equator, but below 240 km the values obtained were unexpectedly small. The discrepancy apparently results from the neglect of the recently pointed out [*Dalgarno and Degges*, 1968; *Dalgarno et al.*, 1968] loss mechanism involving the fine structure of the ground state of atomic oxygen. This loss process probably also accounts for the fact that the daytime peak in $T_e$ at the equator is typically at 230–250 km [*Farley*, 1966*a*; *Farley et al.*, 1967] rather than near 200 km, as predicted previously.

Measurements of the variation of the neutral gas temperature in the exosphere from data taken at several observatories [*Nisbet*, 1967; *Evans*, 1967*b*; *McClure*, 1969] are in general agreement and show a diurnal maximum at 16–17h, rather than the value of about 14h indicated by satellite drag observations [*Jacchia*, 1966].

Sporadic-$E$ layers have been studied by *LaLonde* [1966]. Spectral measurements in the normal $E$ region indicate that $T_e/T_i \approx 1$ [*Wand and Perkins*, 1968], whereas some rocket measurements have yielded substantially higher ratios [*Spencer et al.*, 1965]. A few recently reported satellite measurements of $T_e$ in the equatorial $F$ region were about 70% higher than those obtained simultaneously from scatter observations [*Hanson et al.*, 1969], a discrepancy much larger than the estimated experimental errors. On the other hand, *Sagalyn et al.* [1968] find satisfactory agreement between rocket and scatter results at Arecibo. The $E$-region scatter measurements in Puerto Rico have revealed wavelike perturbations that are probably associated with some form of gravity wave, as are almost certainly the $F$-region disturbances at Arecibo studied by *Thome* [1968].

High altitude scatter observations of electron density at Jicamarca in 1965 gave values of the order of $6\text{–}7 \times 10^3$ at 4000 km, with diurnal variations of about $\pm 30\%$ about the mean [*Farley*, 1966*b*].

Temperature and composition measurements in the $O^+-H^+$ transition region at Arecibo [*Carlson and Gordon*, 1966; *Prasad*, 1968; *Moorcroft*, 1969] and Jicamarca [*Farley et al.*, 1967] do not reveal any region in which the concentration of $He^+$ is more than 10–20%.

Plasma drift velocities have been measured directly with the remarkable accuracy of about 1 m/sec at Jicamarca [*Woodman and Hagfors*, 1969]. A related measurement permits determination of the direction of $B$ to within about 1 minute of arc [*Woodman,* 1968].

The predicted effects of the magnetic field on the scattered power, the plasma line, and the general shape of the ionic component of the spectrum, have been verified at Stanford [*Baron and Petriceks,* 1967; *Fremouw and Petriceks,* 1968]. Detailed agreement with theory for the ion gyroresonance for protons was obtained at Jicamarca [*Farley,* 1967]. The enhanced resonance at the lower hybrid frequency predicted by *Perkins* [1967] has not yet been seen. *Banks* [1968] has recently found theoretically that, under certain conditions, $H^+$ ions in $O^+-H^+$ mixtures may be 10–20% hotter than the $O^+$, an effect which has so far been neglected in the scatter theory and data analysis.

Much of the above has been treated more fully in a recent review by *Evans* [1969].

## TOPSIDE RESONANCES

The resonances observed by topside sounders (see review by *Calvert and McAfee* [1969]) are persistent oscillations excited by the pulsed transmitter at the local plasma, electron-cyclotron, and upper hybrid frequencies, plus some harmonics. They are attributed to slow, short-wavelength, electrostatic waves. It was felt that such waves, traveling with the spacecraft, could produce the resonance signals.

In a new explanation of the plasma resonance, *McAfee* [1968, 1969] contends that the received signals are, instead, echoes caused by the vertical electron-density gradient. As weak as it is, the gradient is sufficient to produce echoes because the dispersion is so sensitively dependent on electron density. The frequencies near the plasma frequency and within the pulse bandwidth can produce the whole range of delays observed. Two echoes, each at slightly different frequencies, are predicted for each delay. Beating between them accounts for some of the observed fringe patterns [*Calvert and VanZandt,* 1966]. An alternative explanation of these beats in terms of antenna resonances was tentatively suggested by *Fejer and Schiff* [1969].

The waves responsible for the upper hybrid and cyclotron-harmonic resonances have been studied in a laboratory plasma [*Crawford et al.,* 1967]. Group delays of pulses propagating across a magnetic field were found consistent with cyclotron wave dispersion. Conspicuous ringing, strikingly like that observed in space, occurred at the expected frequencies.

Frequency shifts ($<1\%$) from exact harmonics are reported for the cyclotron harmonic resonances [*Benson,* 1967]. Such shifts are consistent with a current explanation [*Shkarofsky,* 1968].

The Alouette 2 satellite has revealed more resonances at lower frequencies. *Barry et al.* [1967] noted that some occurred at simple fractions (1/2, 3/5, etc.) of the cyclotron frequency and proposed that they were spin-reversal transitions of the free-radical ionospheric constituents. *Barrington and Hartz* [1968] noted that others occurred at fractions of the plasma frequency or upper hybrid frequency and proposed that they were, instead, images of the usual resonances, harmonically excited. A nonlinear theory of such subharmonic resonances was proposed by *Lewak* [1968].

## DIRECT OBSERVATIONS OF PLASMA COMPOSITION AND TEMPERATURE ABOVE THE $F_2$-LAYER PEAK

In recent years, in situ measurements of ion composition and electron temperature have made important contributions toward establishing the structure and behavior of the upper ionosphere and its interactions with the magnetosphere.

The global distribution of ions in the upper $F$ region and lower protonosphere has been measured on OGO 2 by *Taylor et al.* [1968*a*], who find a high degree of solar and geomagnetic control. The heavier ions $O^+$ and $N^+$ are more abundant at high latitudes, whereas the lighter ions are more abundant near the equator.

At solar minimum, the dayside altitude of the $O^+ - H^+$ transition level (the lower boundary of the protonosphere) varied from about 700 km at the equator to over 1000 km at 60° latitude [*Mayr et al.,* 1967]. Explorer 32 measurements at higher levels of solar activity show that, by 1966, the daytime transition level had increased to 1000 km at the equator and to over 2000 km at 60° latitude [*Brinton et al.,* 1968].

Observations of electron temperature $T_e$ from probes on Explorer 22, have shown that the global distribution of $T_e$ in the lower protonosphere also exhibits a high degree of geomagnetic control [*Brace et al.,* 1967]. The nightside $T_e$ approaches the neutral gas temperature $T_n$ at low latitudes, rises to a maximum ($T_e \approx 3T_g$) at 60° latitude, and then decreases over the poles. On the dayside of the earth, $T_e$ exceeds $T_n$ slightly at low latitudes and increases to very high values at middle latitudes ($T_e \approx$ 3–4 $T_g$).

These high temperatures at middle and high latitudes are probably caused by downward conduction of heat from the relatively hot protonosphere.

*Mayr et al.* [1967] have shown that this global temperature distribution is theoretically consistent with the global ion composition structure, except at high latitudes (>55°). Apparently the energy and particle balance of the polar ionosphere is still poorly understood.

*Taylor et al.* [1968*a*] and *Hoffman* [1968] also report a high latitude trough in the light ions $H^+$ and $He^+$. The location of the trough correlates well with that of the plasmapause as observed on the OGO 3 satellite by ion spectrometers [*Taylor et al.*, 1968*b*] and by whistler observations [*Carpenter et al.*, 1968*b*]. The trough, like the plasmapause, moves to lower magnetic coordinates during magnetically disturbed periods. Troughs and peaks are also observed in the heavier ions $O^+$ and $N^+$, but their locations do not correlate with the plasmapause. Instead, the heavy ion features appear to be associated with particle precipitation and other phenomena occurring within the polar cap [*Nishida,* 1967; *Taylor et al.*, 1968*b*].

## THEORIES OF ION COMPOSITION AND DIFFUSION ABOVE THE $F_2$-LAYER PEAK

The increasing weight of experimental evidence indicates that the geomagnetic field exerts a strong influence upon the spatial distributions of thermal ions [*Brinton et al.*, 1968; *Taylor et al.*, 1968*a, b*; *Donley,* 1967]. The geomagnetic low- and mid-latitude regions lying within the magnetic shells $L \leq 5$ (called the plasmasphere) are characterized by reasonable densities of $He^+$ and $H^+$ arranged roughly in the model of diffusive equilibrium discussed by *Angerami and Thomas* [1964]. Above $L \sim 5$, it is found that a sudden decrease which has been related to the open topology of the high-latitude magnetic field lines occurs in the plasma density [*Dessler and Michael,* 1966; *Nishida,* 1966; *Axford,* 1968; *Banks and Holzer,* 1968].

Within the plasmasphere, theories describing the motion of plasma along a given field tube have been developed to explain latitudinal changes in ion composition, and electron and ion temperature [*Mayr et al.*, 1967], as well as nighttime changes associated with protonospheric cooling [*Nagy et al.*, 1968]. The problem of $He^+$ and $H^+$ in the topside ionosphere has received special attention with regard to the specific ion composition [*Rush and Venkateswaran,* 1965; *Moorcroft,* 1969; *Prasad,* 1968; *Carlson and Gordon,* 1966; *Hoffman,* 1967*a*; *Colin and Dufour,* 1968]. In particular, diffusive equilibrium for $He^+$ and $H^+$ does not seem to always be a valid assumption, and the possibility of ion transport has been studied [*Geisler,* 1967; *Maier,* 1968; *Maier,* 1969] in its effect upon the minor ion densities. *Walker* [1967] pointed out that thermal diffusion could explain some anomalous features of the $H^+$ and $He^+$ density distributions. *Nakada and Singer* [1968] used thermal diffusion in new magnetospheric models for $O^{++}$. The discrepancy between laboratory and ionospheric measurements for $He^+$ has not been resolved [*Bauer,* 1966; *Maier,* 1968]. The possible presence of $He_2^+$ was introduced [*Hoffman,* 1967*b*; *Banks and McGowan,* 1968] but then discounted [*Ferguson and Fehsenfeld,* 1969; *Banks and McGowan,* 1969].

The problem of thermal plasma in polar regions was discussed by *Nishida* [1966], *Brice* [1967], and *Dessler and Michel* [1966] in terms of constant flow into the tail of the magnetosphere. It was later pointed out [*Axford,* 1968; *Banks and Holzer,* 1968] that a supersonic expansion process was involved, and the name 'polar wind' was coined. Because of the escape flow, $H^+$ and $He^+$ densities are greatly reduced along open field lines, and the $O^+$ to $H^+$ transition occurs at altitudes of 2000–4000 km. *Mayr* [1968], adopting the presence of an outward flow, argued for transfield line plasma turbulent diffusion as an explanation for the plasmapause density structure. Magnetic field convection, on the other hand, can be thought of as sweeping the almost empty polar region field tubes to relatively low magnetic latitudes ($L \simeq 5$), thereby creating the observed sharp plasmapause boundary [*Nishida,* 1966].

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