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AUTUMN COURSE ON GEOMAGNETISM, THE IONOSPHERE
AND MAGNETOSPHERE

(21 September - 12 November 1982)

IONOSPHERE 3
(Lectures 1-4)

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IONOSPHERE 3 (LECTURES 1 – 4)

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The D, E, F1, F2 layers are formed within regions D (below about 90 km) E (90–150 km) and F (≳150 km) within the ionosphere:

IONOSPHERE "Ionosφ" "The part of the upper atmosphere where free electrons exist in sufficient numbers to influence the propagation of radio waves".

§1. Relation to other named regions

Most of the ionosφ lies within the thermosφ, the region of high (and variable) temperature heated by X rays and UV from the Sun — the same radiations that cause ionization and dissociation of atmospheric gases. At the top, the thermosφ merges into the exosφ: at the bottom, the thermosφ is bounded by the mesopause – the temperature minimum at 80–85 km. The lower ionosφ lies within the mesosφ (in which there is some heating due to the absorption of long UV in ozone, but that has not much to do with the ionosφ – except for tides, §6). The ionosφ also lies at the base of the magnetosφ, the region in which charged particle motions are controlled by the earth's magnetic field.

§2. Ionospheric layers and their formation

Fig. 1 Typical midlatitude $N(h)$ distributions of electron density vs height

Fig. 2 Neutral and ion species: average sunspot minimum conditions

(Note: Above 100 km each neutral gas will be distributed vertically according to its own scale height H, i.e. partial pressure $p \propto e^{-h/H}$ and $H = \frac{RT}{Mg}$ {R - gas const., M - molecular mass)

Ionization Limits (related to ioniz^{n} potential)

N_2	79.6 nm	
O	91.1	important in protonosφ
H	91.2	
O_2	102.7	important in D region
NO	134.0	
$O_2(^1\Delta)$	111.8	

(O_2 dissociated by radiation ≤ 175 nm)

compare

Some important radiations

He II	30.4 nm
He I	58.4
Ly β	102.6
Ly α	121.6

O_2 102.7 ⟷ Ly β 102.6; NO 134.0 ⟷ Ly α 121.6 (compare)

{Total ionizing radiation: few mW m^{-2}
Total solar e.m. – : ~1 kW m^{-2}
(solar constant) Ratio 1 : 10^6 !

F2 layer : same as F1, see §4.
F1 layer : 20 — 91.1 nm UV ↑ Not sharply distinguished, but merge into one another

E layer { 91.1 — 102.7 nm UV ↓
1 — 20 nm X rays — ionizes all, important at sunspot max

D layer (Fig. 3) { 0.1 — 1 nm Hard X rays {ionizes all, very variable, important if Sun disturbed
Ly α : ionizes NO only. Major source
UV (< 111.8) ionizes $O_2(^1\Delta)$ metastables

C layer Cosmic Rays — ionize all — but very small N_e

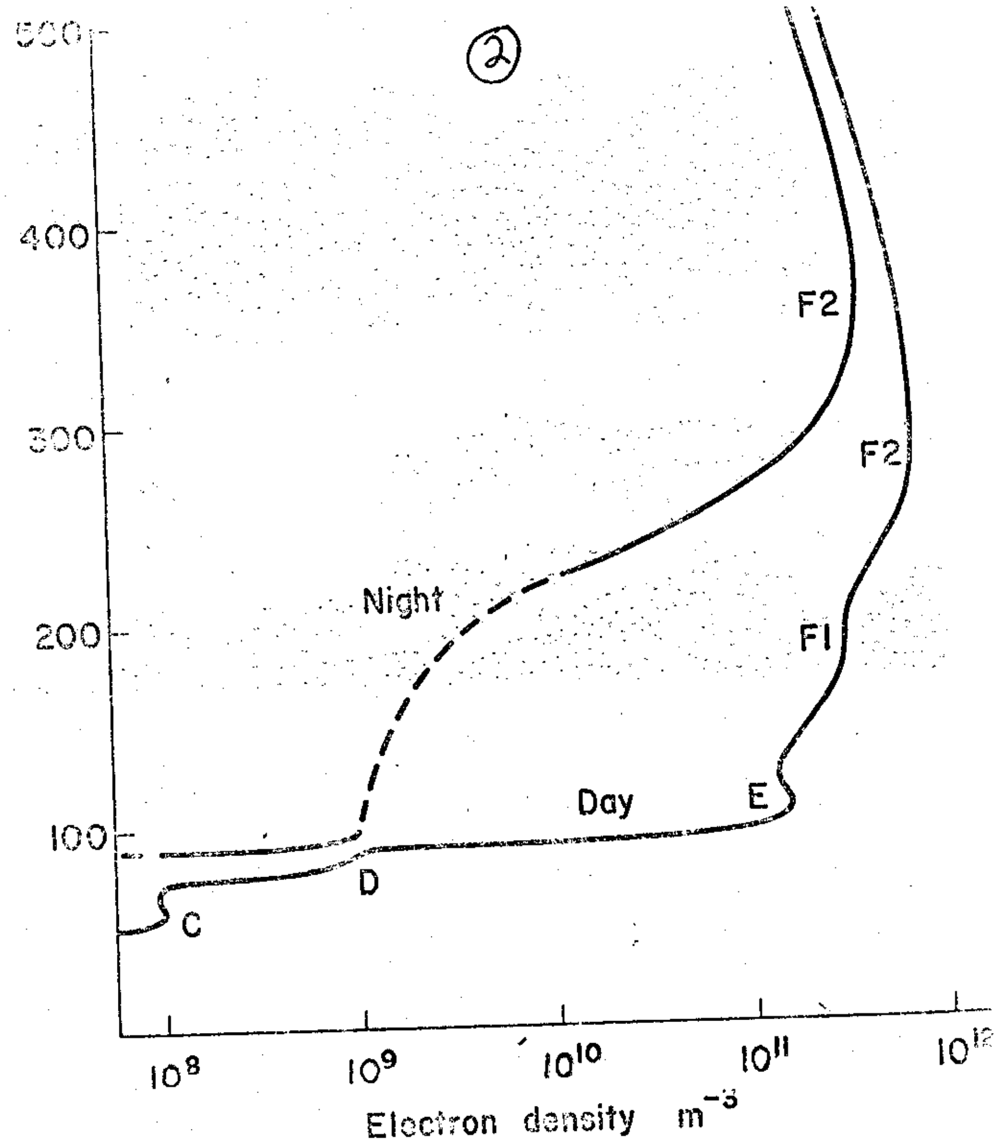

Fig. 1 Typical midlatitude electron distributions

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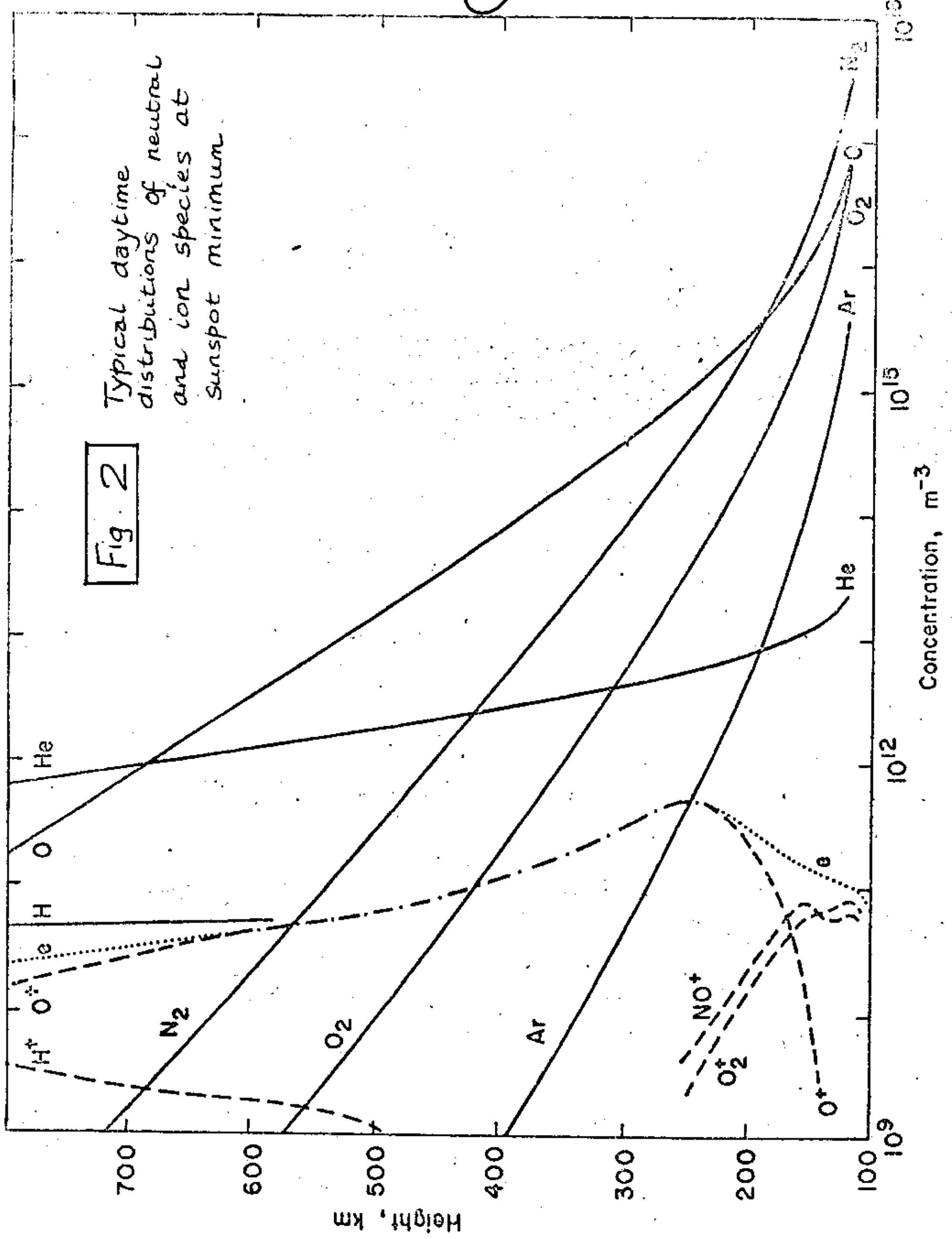

Fig. 2 Typical daytime distributions of neutral and ion species at sunspot minimum

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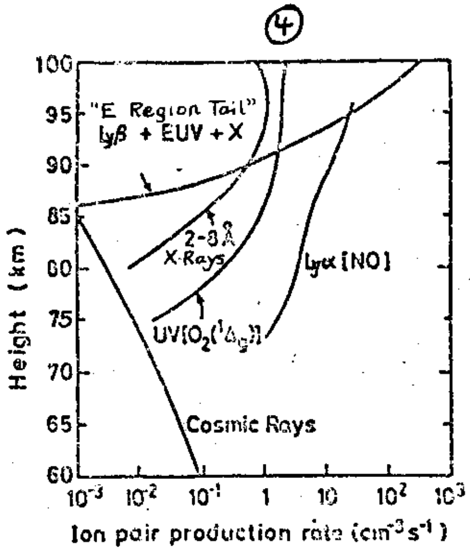


Fig. 3 Ionization rates in quiet D region, sunspot minimum (Thomas, 1974)

§3. D region chemistry

Negative ions formed by attachment of electrons to neutrals.
Needs 3-body collision (to conserve energy & momentum) so only important in D region (gas density is too low in E & F regions)

$$e + O_2 + M \rightarrow O_2^- + M$$ (any other particle)

Negative ions destroyed by
photodetachment (visible, UV): $O_2^- + h\nu \rightarrow O_2 + e$
associative detachment: e.g. $O_2^- + O \rightarrow O_3 + e$

But: many further reactions create complex ions CO_3^-, NO_2^-, NO_3^- which may become hydrated

Positive ions Ionizing processes give N_2^+ O_2^+ NO^+
gets converted to

Complex chains of reactions with H_2O give hydrated ions such as $H^+\cdot(H_2O)_n$. Ion masses ≥ 200 have been detected in rocket experiments — possibly, but not necessarily, associated with high-latitude noctilucent clouds.

Ion balance equations (simplified!)
Chemistry determines negative ion ratio $\lambda = N_-/N_e$.
Representative values:

	90 km	80 km	75 km	70 km	65 km	
$\lambda \rightarrow$	10^{-5}	10^{-3}	10^{-2}	10^{-1}	1	DAY
			~1	≫1	≫1	NIGHT

Given λ, we get the balance equation by considering +ve ions: photoionization = ion-electron recombination + ion-ion recombination

$$q = \alpha_e N_+ N_e + \alpha_i N_+ N_-$$

Note: $N_+ = N_e + N_- = (1+\lambda)N_e$

$$= \underbrace{(1+\lambda)(\alpha_e + \lambda\alpha_i)}_{\text{Effective Recombination — big in lower D region where } \lambda \text{ is big}} N_e^2$$

§4. E & F region chemistry (main reactions)

Photoionization — **Transfer reactions** — **Recombination**

$N_2 + h\nu \rightarrow e + N_2^+ \longrightarrow N_2^+ + e \rightarrow N + N$

$\quad\hookrightarrow N_2^+ + O \rightarrow N + NO^+$

$O + h\nu \rightarrow e + O^+ \quad O^+ + N_2 \rightarrow N + NO^+ \quad \Big\} \rightarrow NO^+ + e \rightarrow N + O$

$\quad\hookrightarrow O^+ + O_2 \rightarrow O + O_2^+$

$O_2 + h\nu \rightarrow e + O_2^+ \longrightarrow O_2^+ + e \rightarrow O + O$

Notes $\rightarrow$ O^+ can't recombine directly: (to conserve both momentum and energy need to emit photon (very slow) or 3-body collision (too rare in E & F regions)).

$\rightarrow$ N_2^+ is virtually absent; need reaction with O as well as recombination in order to explain

$\rightarrow$ Recombination may leave (mainly) O atoms in excited states giving airglow (which also arises from non-ionospheric reactions)

Simplified scheme, assuming steady state ($\partial/\partial t = 0$) to give essentials of loss processes:

$O + h\nu \rightarrow O^+ + e$ (rate q)

$O^+ + N_2 \rightarrow NO^+ + N$ (rate coeff. k)

$NO^+ + e \rightarrow N + O$ (rate coeff. α)

$$\frac{\partial}{\partial t}[O^+] = q - k[O^+][N_2]$$
$$\frac{\partial}{\partial t}[NO^+] = k[O^+][N_2] - \alpha[NO^+]N_e$$
$$\frac{\partial N_e}{\partial t} = q - \alpha[NO^+]N_e$$

At lower heights (E layer)

Plenty of N_2

$\therefore$ O^+ rapidly converted to NO^+

$\therefore$ Nearly all ions are NO^+

$\therefore$ $[NO^+] \doteq N_e$

Third equation gives:

$$\frac{\partial}{\partial t}N_e = 0 = q - \alpha N_e^2$$

So $N_e = \sqrt{\dfrac{q}{\alpha}}$ (Chapman Layer.)

At higher heights (F2 layer)

N_2 is scarce

$\therefore$ O^+ very slowly converted to NO^+. Once formed, the NO^+ recombines quickly

$\therefore$ Nearly all ions are O^+, $[O^+] \doteq N_e$

First equation becomes:

$$\frac{\partial}{\partial t}[O^+] = 0 = q - \beta N_e$$

where $\beta = k[N_2]$

So $N_e = \dfrac{q}{\beta} \propto \dfrac{[O]}{[N_2]}$ increases upwards. See Fig. 2

At intermediate height (F1 layer) Can show that: $\dfrac{1}{q} = \dfrac{1}{\alpha N_e^2} + \dfrac{1}{\beta N_e}$

Solution of this quadratic eqn. is

$$N_e = \tfrac{1}{2}\frac{q}{\beta}\left[1 + \sqrt{1 + 4G}\right] \quad \text{where } G = \frac{\beta^2}{\alpha q}$$

Fig. 4 shows N_e vs height for different values of G.

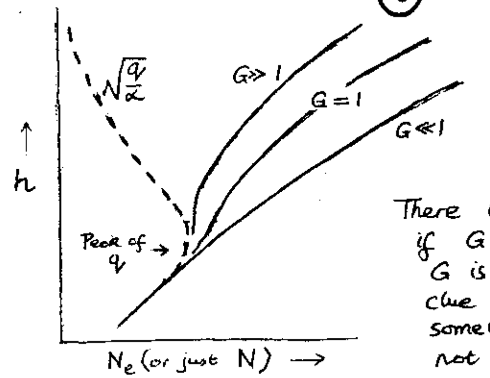


Fig. 4 Idealized F1-layer shapes, by solving the quadratic eq.

There is a marked 'F1 ledge' if G is big and none if G is small. This gives a clue as to why the F1 is sometimes seen, and sometimes not, at midlatitudes

$$G = \frac{\beta^2}{\alpha q}$$

$\beta \propto [N_2]$ so G gets bigger if there is more N_2 as happens in summer. So see F1 layer better in summer than winter

α doesn't vary much (depends slightly on temperature)

q gets bigger with increasing solar activity. So see F1 layer better at sunspot minimum. (also sometimes see F1 layer better during an eclipse when q is reduced)

F2 layer The equation $N = \dfrac{q}{\beta} \propto \dfrac{[O]}{[N_2]}$ explains why N increases upwards above the F1 layer. But it does not explain what limits N and causes the F2 peak. The answer is that the 'chemical' processes — production and loss — get weaker with increasing height. Eventually they cannot prevent the electrons and ions from taking up a gravitationally-controlled distribution, with N decreasing upwards, just as the neutral gases do (Fig. 2) (§14) 16)

§5. Ionospheric Equations

The equations we have solved are simple cases of 'conservation' equations that are very important in ionospheric theory:

Examples:	{Rate of Change of}	= {Gain}	− {Loss}	± {Transport}
Continuity eqn.	Number of particles	Production	Recombin. Attachment	Diffusion Drift
Eqn. of motion	Momentum	Driving Forces	Frictional drag	Advection Viscosity
Heat balance eqn. (energy equation)	Temperature	Heating (UV, X rays, fast particles)	Cooling (Radiation)	Conduction Convection

§6. Dynamo Theory (Fig. 5)

The atmospheric dynamo is driven by winds in the atmosphere that blow across the geomagnetic field lines, creating an induced electric field, which will drive electric current if the air is conducting. However, the conductivity is only good enough at certain heights (roughly the E layer) for significant currents to flow horizontally. Above the E layer, there is a very high conductivity along the geomagnetic field lines, which has three important consequences:

(i) Electric polarization fields generated in the E layer are transmitted to the overlying F layer (the 'motor' effect)

(ii) Electric currents can flow freely along field lines at middle and low latitudes to the opposite hemisphere

(iii) At high latitudes, electric fields generated in the magnetosp can be transmitted along field lines into the ionosp

In the E layer itself, field-aligned currents flow to prevent voltages building up.

Sources of the atmospheric dynamo

(a) Solar heating (much more important for atmosphere than for ocean tides, because the atmosphere can be heated more quickly)

UV, X rays heat the thermosp
Long UV heats the ozone layer in the mesosphere
Infra Red heats the lower atmosphere and ground (probably of minor importance for tides)

} { Basic diurnal (24 hour) period, with harmonics 12, 8, ... hours.

(b) Gravitational Force Mainly lunar. Produces weaker 12.4 hour tide

These forces excite various 24, 12, 8, 12.4 (etc) hour oscillations with different vertical wavelengths and different latitudinal structures. The atmosphere responds to these selectively. In addition there are long-period variations (planetary waves, etc, – up to 26 months period).

The major tidal modes are designated (n, m) — n: cycles per day 1 = diurnal, etc; m: latitude structure; can be –ve
Each has its own horizontal & vertical structure.

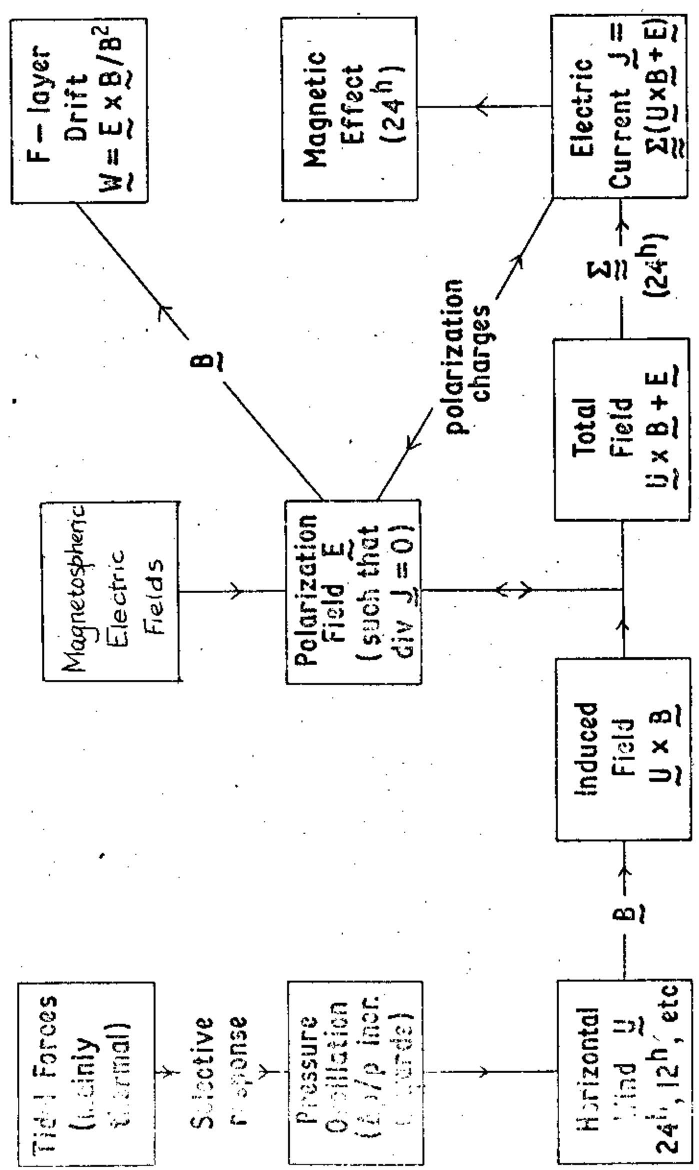
(c) Variation of amplitude with height The amplitude $\Delta p/p$ (i.e. the relative pressure perturbation) increases upwards as ρ (air density) decreases, and so does the amplitude $|U|$ of the associated tidal wind, such that the kinetic energy density $\frac{1}{2}\rho|U|^2$ remains constant:

Ground level : $(\Delta p/p) \sim 10^{-3}$, $|U| \sim 5\ \mathrm{cm\,s^{-1}}$
100 km : $(\Delta p/p) \sim 0.1 - 1$, $|U|$ $50\ \mathrm{m\,s^{-1}}$
$\Big\}\ \frac{\rho(0)}{\rho(100)} \sim 10^6$

The upward increase of amplitude may be interrupted by:

(i) reflection or trapping at certain levels – depends on temperature structure
(ii) non-linear 'breaking' of waves into smaller-scale motions when $\Delta p/p \to 1$
(iii) viscous and electrical dissipation in the ionosp

Fig. 5 Dynamo Theory



§7 Electrodynamics

General points about charged particle motion.

We use simple 'kinetic theory' approach. Motions due to electric fields and winds (say tens of $m\,s^{-1}$) can be superimposed on much larger random thermal motions ($1\ km\ s^{-1}$ for ions, $200\ km\ s^{-1}$ for electrons).

Ionosph almost exactly neutral, probably to within 1 part in 10^{10}

Thus $N_e = N_i$ (electrons, positive ions). More precisely $N_e = N_+ + 2N_{++} - N_-$ (Can ignore these at dynamo layer heights for practical purposes.)

Generally write $N_e = N_i = N$, drift velocity $\underset{\sim}{V}_i$, $\underset{\sim}{V}_e$

For neutral particles concentration n, wind velocity $\underset{\sim}{U}$
If need to identify what species, use [ ].

Current equation $\underset{\sim}{j} = Ne(\underset{\sim}{V}_i - \underset{\sim}{V}_e)$

Must have $\text{div}\,\underset{\sim}{j} = 0$. If not true, immediately polarization charges build up (to the extent that $|N_i - N_e| \lesssim 10^{-10} N_e$) and the resulting polarization field modifies the V_i & V_e such that $\text{div}\,\underset{\sim}{j}$ becomes zero.

So have induced field $\underset{\sim}{U} \times \underset{\sim}{B}$ and polarization field $-\nabla\Phi$ {electric potential}

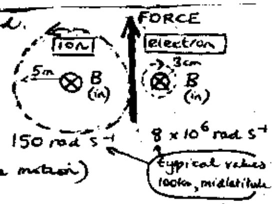
Thus $\underset{\sim}{E}_{total} = \underset{\sim}{E}_{induced} + \underset{\sim}{E}_{polariz^n} = \underset{\sim}{U} \times \underset{\sim}{B} - \nabla\Phi$

The current is given by the conductivity $\underset{\approx}{\sigma}$ (tensor) $\qquad \underset{\sim}{j} = \underset{\approx}{\sigma} \cdot \underset{\sim}{E}_{total}$

(Later we find that $\underset{\sim}{E}$ is constant with height (almost)
(We can then use height-integrated (layer) current & conductivity $\rightarrow \quad \underset{\sim}{J} = \underset{\approx}{\Sigma} \cdot \underset{\sim}{E}_{total}$

To compute the current we must see how {ions / electrons} respond to {electric field / wind}

Consider motion of particle in magnetic field.



Microscopic picture

Gyration about magnetic field is interrupted by collisions. If many collisions per gyration, particle moves in direction of applied force.
If no collisions, particle moves sideways (cycloidal type motion) gaining & losing energy on each gyration.

Macroscopic picture : we want relation between velocity and force

Particle has mass m, charge $\pm e$ ($= +e$ for ion, $-e$ for electron)
Collision frequency ν with neutral particles. Gyrofrequency $\omega = Be/m$
Electric field imposes force $\pm e\underset{\sim}{E}$ (upper sign ion, lower sign electron)
Neutral-air wind imposes force $m\nu\underset{\sim}{U}$ (with appropriate definition of ν).
So force is $\underset{\sim}{F} = \pm e\underset{\sim}{E} + m\nu\underset{\sim}{U}$

On average $m\,d\underset{\sim}{V}/dt = 0 = \underset{\sim}{F} - m\nu\underset{\sim}{V} \pm e\underset{\sim}{V} \times \underset{\sim}{B}$
{Steady drift} {Driving force} {drag} {Lorentz force}

Take z-axis parallel to B.:

Resolve:
$$0 = F_x - m\nu V_x \pm eV_y B$$
$$0 = F_y - m\nu V_y \mp eV_x B$$
$$0 = F_z - m\nu V_z$$

Solution is : $\underset{\sim}{V} = \underset{\approx}{k} \cdot \underset{\sim}{F}$ where $\underset{\approx}{k} = \begin{pmatrix} k_1 & \pm k_2 & 0 \\ \mp k_2 & k_1 & 0 \\ 0 & 0 & k_0 \end{pmatrix}$ (Upper sign) ions (Lower sign) electrons

Tensor

§8. Components of Mobility

Longitudinal / Direct } component $\parallel \underset{\sim}{F}$ and $\parallel \underset{\sim}{B}$ $\quad k_0 = \dfrac{1}{m\nu} = \dfrac{1}{Be}\dfrac{\omega}{\nu}$

Transverse / Pedersen } component $\parallel \underset{\sim}{F}$ but $\perp \underset{\sim}{B}$ $\quad k_1 = \dfrac{1}{m\nu}\dfrac{\nu^2}{\nu^2+\omega^2} = \dfrac{1}{Be}\dfrac{\nu\omega}{\nu^2+\omega^2}$

Hall component $\perp \underset{\sim}{F}$ and $\perp \underset{\sim}{B}$ $\quad k_2 = \dfrac{1}{m\nu}\dfrac{\omega\nu}{\nu^2+\omega^2} = \dfrac{1}{Be}\dfrac{\omega^2}{\nu^2+\omega^2}$

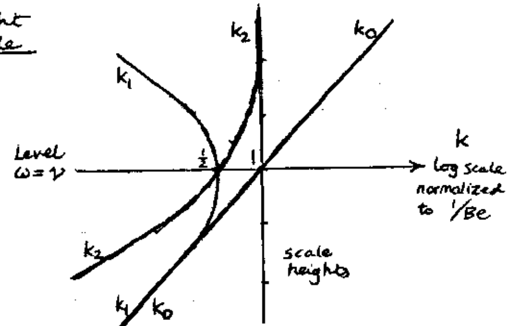
Note that $\nu \propto n$ so decreases exponentially with height
Whereas $\omega = \dfrac{Be}{m}$ varies slowly with height (but B differs by 2:1 between pole & equator)
So these forms can be useful.

Fig 6 Mobility versus height for one kind of particle

k_0 increases upwards exponentially

k_1 has peak value $\frac{1}{2Be}$ at level $\omega = \nu$

k_2 is also $\frac{1}{2Be}$ at level $\omega = \nu$, increasing upward to limiting value $\frac{1}{Be}$



Now use these equations to see how ions & electrons move, if $\underset{\sim}{F}$ is due to a field $\underset{\sim}{E}$ or wind $\underset{\sim}{U}$, directed either parallel to B (z) or perp to $\underset{\sim}{B}$ (say, x)
(Upper sign ions, lower sign electrons):

	ELECTRIC FIELD Fig. 7	WIND Fig. 8
Force in z-direction ($\parallel \underset{\sim}{B}$)	$V_z = \binom{+}{-}\dfrac{eE_z}{m\nu}$	$V_z = \binom{+}{+}U_z$ (move with wind)
Force in x-direction ($\perp \underset{\sim}{B}$)	$V_x = \binom{+}{-}\dfrac{E_x}{B}\dfrac{\nu\omega}{\nu^2+\omega^2}$	$V_x = \binom{+}{+}U_x\dfrac{\nu^2}{\nu^2+\omega^2}$
	$V_y = \binom{-}{-}\dfrac{E_x}{B}\dfrac{\omega^2}{\nu^2+\omega^2}$	$V_y = \binom{-}{+}U_x\dfrac{\nu\omega}{\nu^2+\omega^2}$

Note: $V_x/V_y = \dfrac{\nu}{\omega}$ so motion is inclined at angle θ to force, where $\tan\theta = \dfrac{k_2}{k_1} = \dfrac{\omega}{\nu}$

SUMMARY OF HOW IONS & ELECTRONS MOVE

Driven by:	$\parallel \underset{\sim}{B}$ (any height)	$\perp \underset{\sim}{B}$ LOW DOWN $\nu \gg \omega$	$\perp \underset{\sim}{B}$ $\nu \simeq \omega$	$\perp \underset{\sim}{B}$ HIGH UP $\nu \ll \omega$
Field $\underset{\sim}{E}$	σ_0 applies. Current flows freely at any height > 70 km	σ_0 applies. Move parallel to $\pm\underset{\sim}{E}$	Motion inclined to force at angle θ. Current flows because ions & electrons move differently	Both move with velocity $\underset{\sim}{E}\times\underset{\sim}{B}/B^2$ NO CURRENT
Wind $\underset{\sim}{U}$	Move with component of $\underset{\sim}{U} \parallel \underset{\sim}{B}$	Move with wind		Don't move (to first order)

Note carefully that level $\omega = \nu$ is different for electrons and ions } { 125 – 140 km for ions / 70 – 80 km for electrons (Highest at equator)

(11)

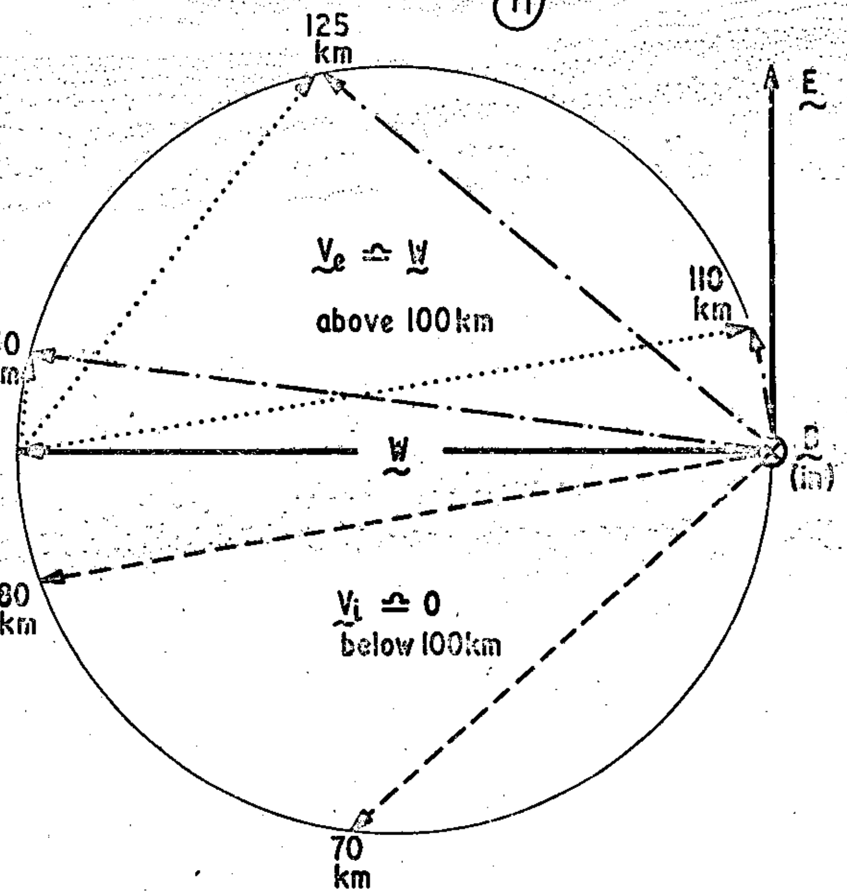


Fig. 7 **Drifts Due to Electric Field**

$$W = \frac{E \times B}{B^2}$$

Electric Current ·······►

Ions —·—·—► Electrons – – –►

(12)

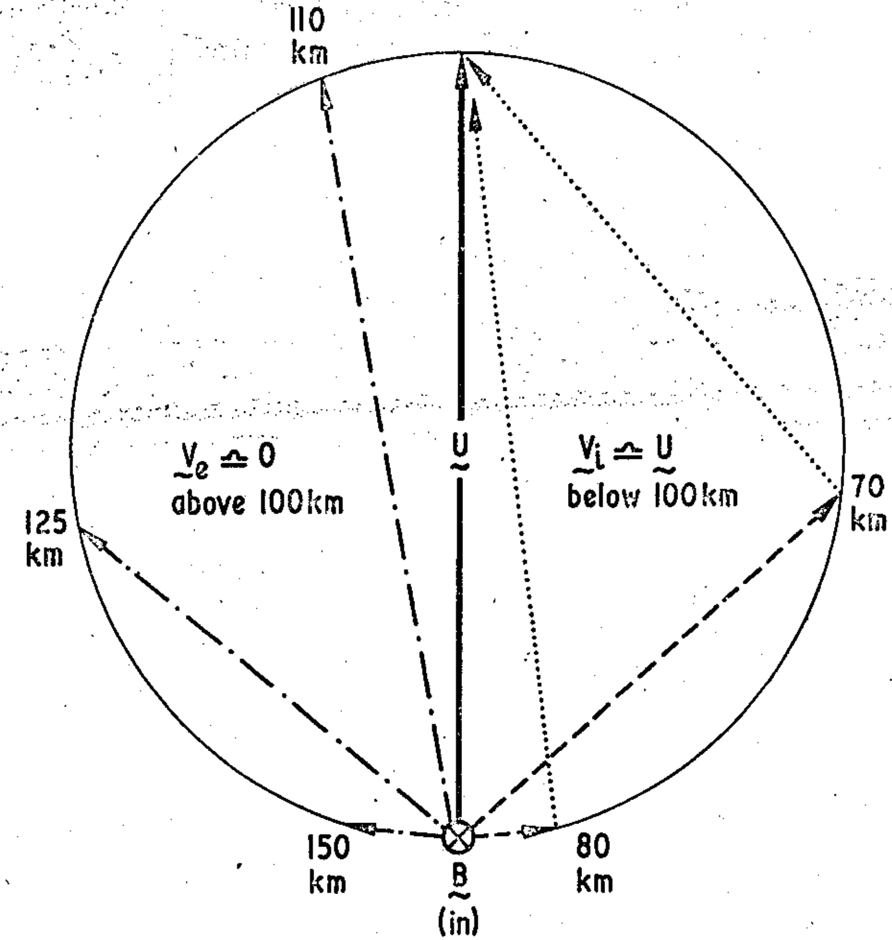


Fig. 8 **Drifts Due to Wind**

Electric Current ·······►

Ions —·—·—► Electrons – – –►

§9. Conductivity

"Ohm's Law" for ionosϕ: $\underset{\sim}{j} = \underset{\approx}{\sigma} \cdot \underset{\sim}{E}$ (total $\underset{\sim}{E}$)

We also have $\underset{\sim}{j} = Ne(\underset{\sim}{V_i} - \underset{\sim}{V_e})$ and $\begin{cases} \underset{\sim}{V_i} = \underset{\approx}{k_i} \cdot e\underset{\sim}{E} \\ \underset{\sim}{V_e} = -\underset{\approx}{k_e} \cdot e\underset{\sim}{E} \end{cases}$

(using mobility equation with just $\underset{\sim}{F} = \pm e\underset{\sim}{E}$)

Putting these together, we find

$$\underset{\approx}{\sigma} = Ne^2(\underset{\approx}{k_e} + \underset{\approx}{k_i})$$

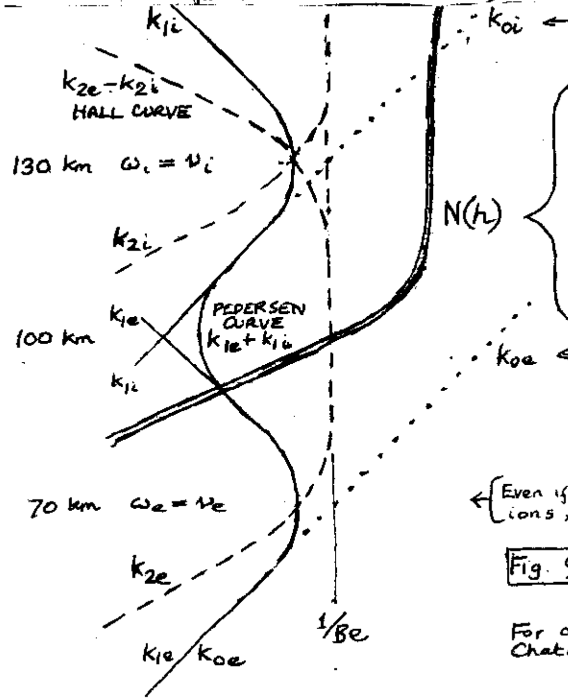
The components are:

$$\sigma_0 = Ne^2(k_{0e} + k_{0i})$$
$$\sigma_1 = Ne^2(k_{1e} + k_{1i})$$
$$\sigma_2 = Ne^2(k_{2e} - k_{2i})$$

and

$$\underset{\approx}{\sigma} = \begin{pmatrix} \sigma_1 & -\sigma_2 & 0 \\ \sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix}$$

To see how these vary with height, we have to add two diagrams like Fig. 6 (one for electrons at about 70 km, one for ions at about 130 km)



k_{0i} ← unimportant compared to k_{0e}

To get conductivity components, the mobility components have to be multiplied by the thick curve which represents the ion & electron N(h) distribution. The multiplication by N(h) suppresses the lower (electron) Pedersen peak and cuts off the Hall conductivity, too, below about 100 km

k_{0e} ← very large above about 80 km, which means that there is a very high conductivity along magnetic field lines, due to the high mobility of electrons

← Even if we took the trouble to include negative ions, they wouldn't contribute much

Fig. 9 Electron & ion mobility and conductivity vs height

For actual examples, measured at Chatanika (Alaska) see Fig. 10

Note on Collision Frequency

(Somewhat different definitions may be found in the literature)

We have used a definition of ν such that the 'Force per unit volume' between any two kinds of particle (call them a & b) is

See §13 $\underset{\sim}{F}_{ab} = N_a m_a \nu_{ab}(\underset{\sim}{V_b} - \underset{\sim}{V_a})$ and $\underset{\sim}{F}_{ba} = N_b m_b \nu_{ba}(\underset{\sim}{V_b} - \underset{\sim}{V_a})$

Since $\underset{\sim}{F}_{ab} = -\underset{\sim}{F}_{ba}$, in general we have $\nu_{ab} \neq \nu_{ba}$

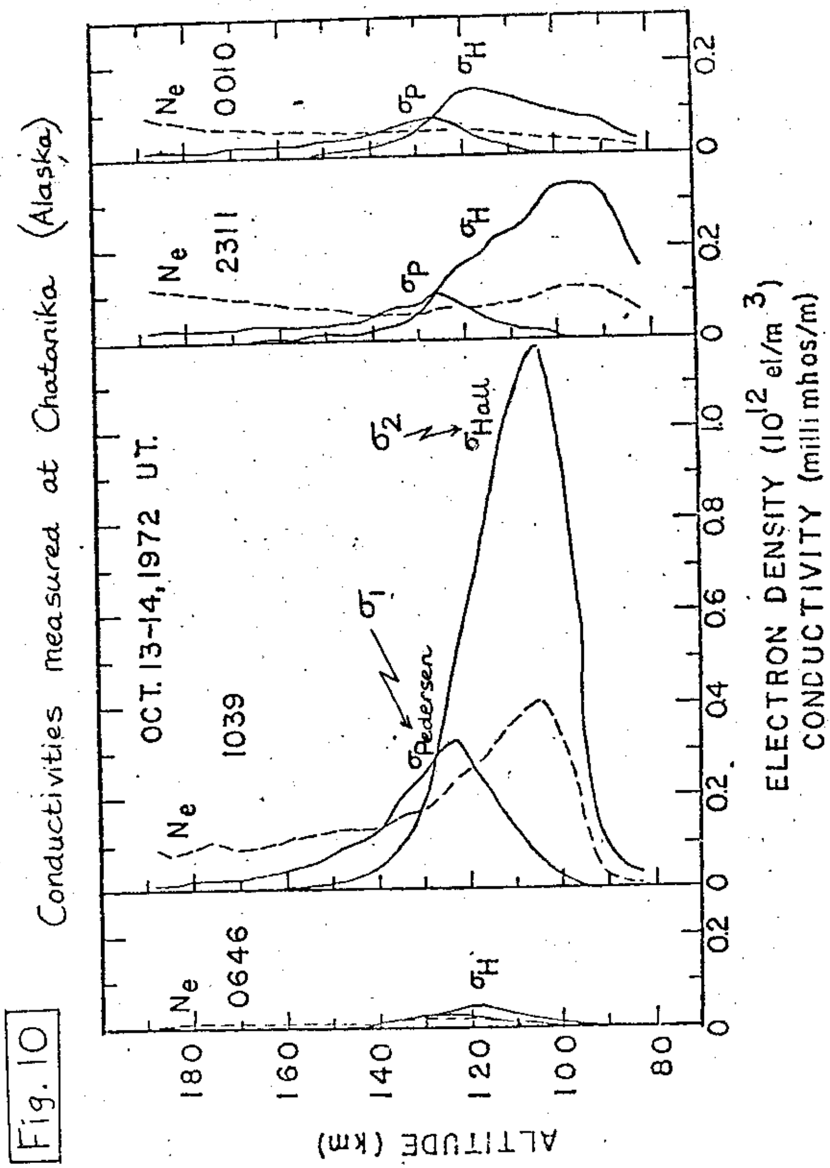


Fig. 10

§10. Current Systems in Dynamo Layer

The quiet day Sq current system flowing in the ionosphere (almost all in the E layer) has a great day-to-night variation imposed by the variation of conductivity — the E layer electron density is normally about 50 times greater by day than by night. Fig. 11 shows the pattern of the Sq current. The conducting field lines at midlatitudes link opposite hemispheres and carry quite high electric currents with very little voltage drop, because of the high σ_0. Furthermore, they transmit the E layer polarization field to the F2 layer. At night the F2 layer may actually carry more current than the E layer (despite its low Pedersen conductivity). This is because the relatively high F2 layer electron density, combined with the strong winds (§ 13) may make the night F2 layer a better dynamo than the night E layer.

Since $\underset{\sim}{E}$ is height-independent it is often useful to define a height-integrated layer current and layer conductivity components:

$$\underset{\sim}{J} = \int \underset{\sim}{j}\, dh \qquad \Sigma_1 = \int \sigma_1\, dh \qquad \Sigma_2 = \int \sigma_2\, dh$$

The other big contribution to ionosphere electric field comes from magnetospheric potentials injected at high latitudes. For effects of polarization fields see Fig. 12

§11. A Simple Summary of Dynamo Theory (usual notation)

a. Tidal winds are produced by heating at different levels. The atmosphere responds in various modes (24, 12, 8, .. 12·4 hrs. etc)

b. Wind $\underset{\sim}{U}(t)$ produces an induced field $\underset{\sim}{E}_{ind} = \underset{\sim}{U} \times \underset{\sim}{B}$; current flows.

c. Ionosphere is bounded, so current is restricted, resulting in polarization field $\underset{\sim}{E}_{polz}$ which so adjusts itself that the resulting current flow $\underset{\sim}{j} = \underset{\approx}{\sigma} \cdot (\underset{\sim}{E}_{ind} + \underset{\sim}{E}_{polz})$ satisfies $\operatorname{div} \underset{\sim}{j} = 0$.

d. To compute conductivity $\underset{\approx}{\sigma}$, have to consider ion & electron motions separately, since current $\underset{\sim}{j} = Ne(\underset{\sim}{V}_i - \underset{\sim}{V}_e)$

e. Therefore solve equation of motion (assuming steady drift $\underset{\sim}{V}$)
$d\underset{\sim}{V}/dt = 0 = \underset{\sim}{F} - m\nu \underset{\sim}{V} \pm e \underset{\sim}{V} \times \underset{\sim}{B}$

f. Force is produced by field and/or wind. $\underset{\sim}{F} = \pm e \underset{\sim}{E} + m\nu \underset{\sim}{U}$

g. Solution is $\underset{\sim}{V} = \underset{\approx}{k} \cdot \underset{\sim}{F}$ where mobility $\underset{\approx}{k} = \begin{pmatrix} k_1 & \pm k_2 & 0 \\ \mp k_2 & k_1 & 0 \\ 0 & 0 & k_0 \end{pmatrix}$

Depends on $\begin{cases} \text{collision frequency } \nu \text{ (decreases upwards)} \\ \text{gyrofrequency } Be/m = \omega \end{cases}$

Level $\nu = \omega$ is 70 – 80 km for electrons, 125 – 140 km for ions

h. Put ions & electrons together to get current. Find $\underset{\approx}{\sigma} = Ne^2(\underset{\approx}{k}_i + \underset{\approx}{k}_e)$
Not enough N below 100 km to give much σ, so current nearly all at 100 – 150 km

i. Current systems have great day-to-night variation. Usually possible to use 'layer current' and 'layer conductivity'.

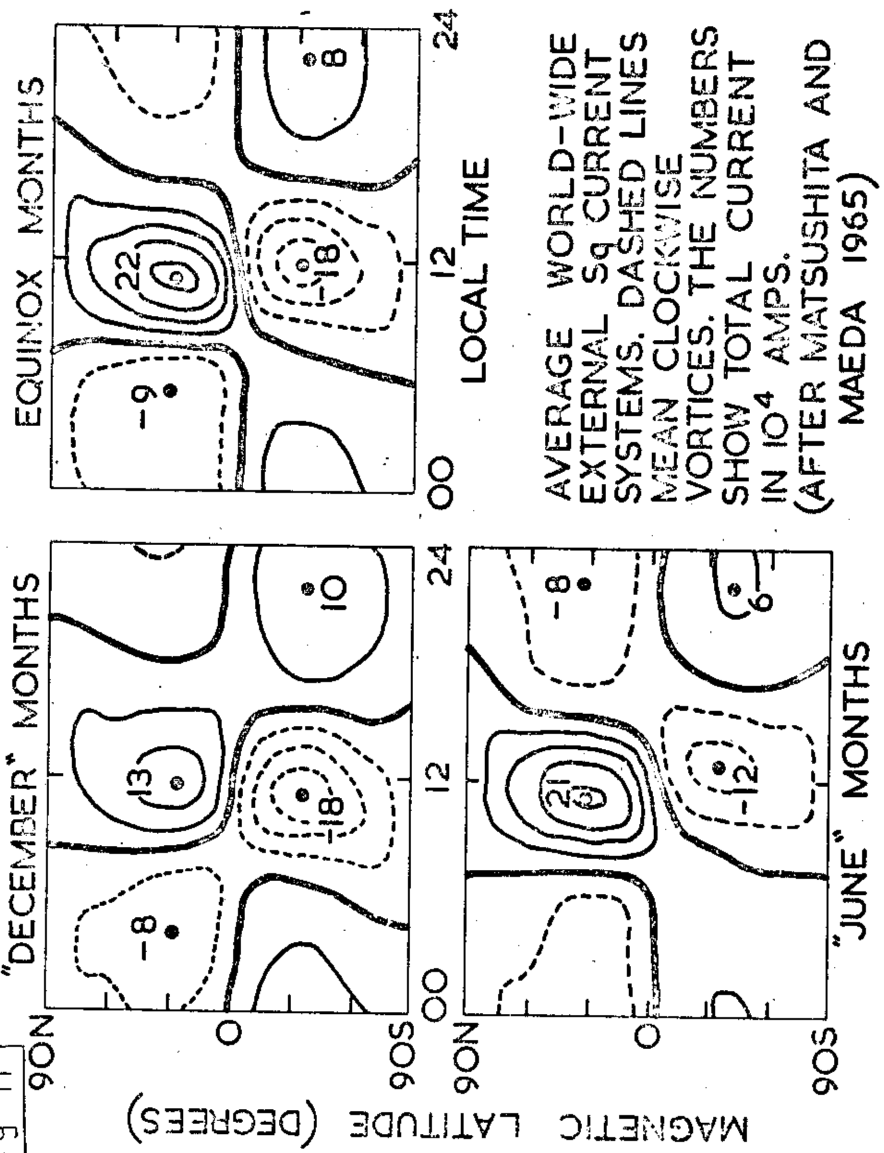
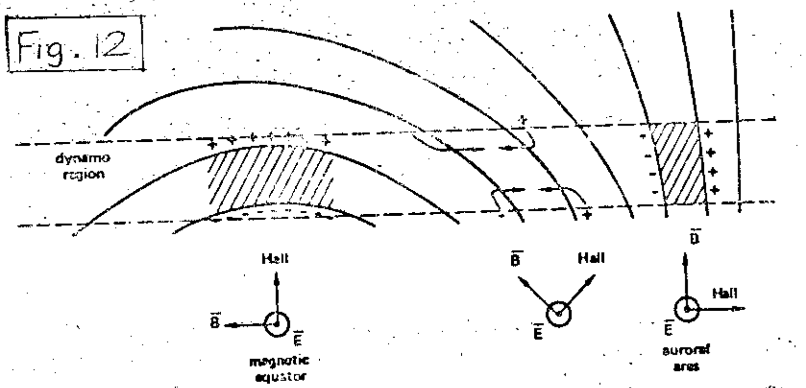


Fig 11

AVERAGE WORLD-WIDE EXTERNAL Sq CURRENT SYSTEMS. DASHED LINES MEAN CLOCKWISE VORTICES. THE NUMBERS SHOW TOTAL CURRENT IN 10^4 AMPS. (AFTER MATSUSHITA AND MAEDA 1965)

Fig. 12



When Hall currents due to an applied $\vec{E}$ field (out of the plane of the figure) cannot flow because a conductive region is bounded in the $\vec{E} \times \vec{B}$ direction by strong negative conductivity gradients, polarization charges appear, and their Hall effect raises the effective Pedersen current (parallel to the applied field). This happens permanently at the magnetic equator because of the field geometry, and sporadically in auroral arcs because of a local increase in conductivity by precipitations, explaining the existence of the equatorial and auroral 'electrojets'. (Giraud & Petit, 1978)

[The result of the polarization field is to raise the east-west conductivity to the Cowling value, $\sigma_3 = \frac{\sigma_1^2 + \sigma_2^2}{\sigma_1}$, which can be almost as large as the 'no field' value, σ_0.]

§12. Thermospheric Temperature & Pressure Variations

The large input of solar radiation by day causes heating and thermal expansion, with cooling and contraction at nights. These are really large tidal oscillations, primarily diurnal (modes with $n=1$) but with harmonics.

A common way to display the models is by maps of isotherms of exospheric temperature T_∞ (essentially the temperature above 400km or so). The temperature is defined in such a way as to represent the density and pressure variations deduced from satellite drag or other techniques. Use of such data to compute winds is risky, but is nevertheless often done.

The simple Jacchia model represents the daytime maximum (14 LT) and minimum (04 LT) centred in low latitudes. Other models try to represent the enhanced auroral-zone temperatures due to auroral particle and joule heat input. Experimental models (OGO-6, MSIS) show more detail, usually with a summer-to-winter decrease of temperature, and thus contain more harmonics. $\boxed{\text{See Fig. 13, 14}}$

More recent models are purely computational, based on 3-D solutions to the continuity, momentum and energy equations for the air. (e.g. UCL, NCAR), and these also give the winds.

§13. Thermospheric Winds

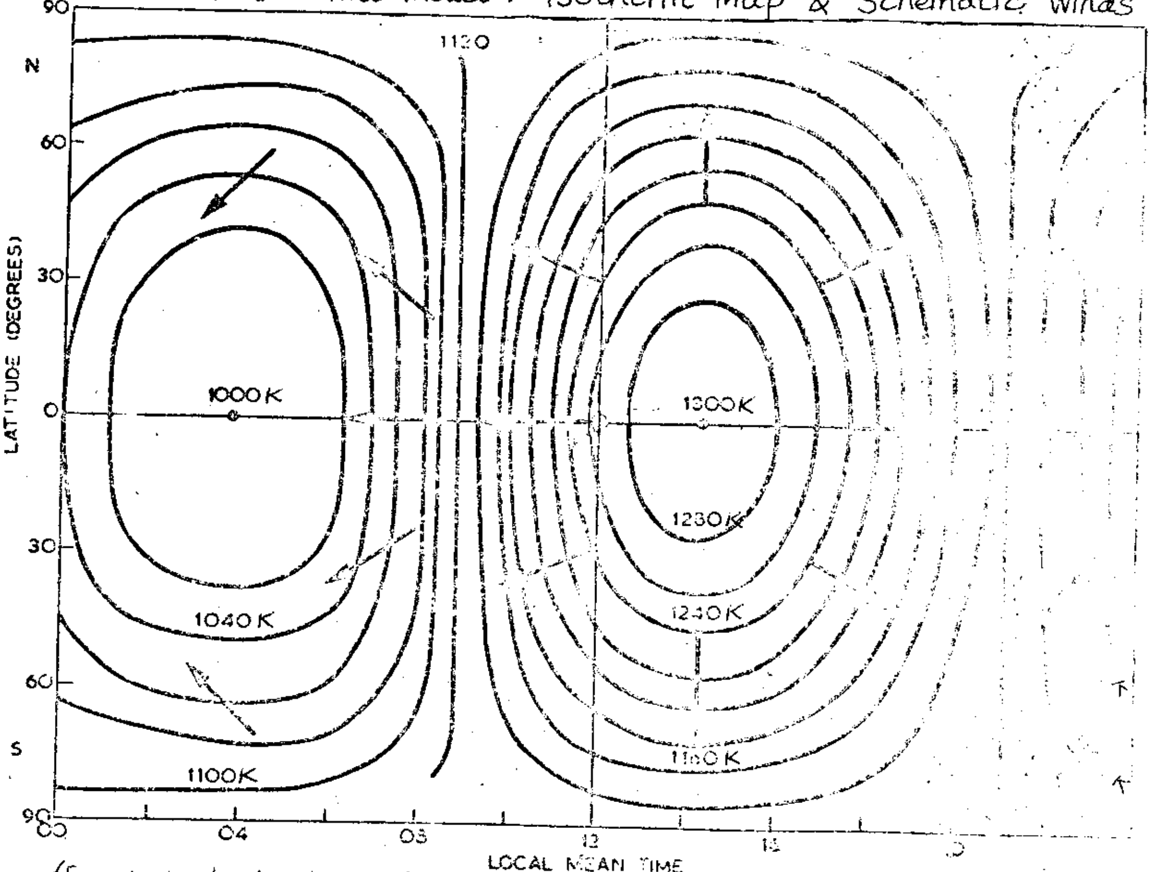
{Note! In the ionosphere a wind blowing from South to north is called a northward wind!

Computational models of winds are based on models of the pressure distribution (even though these may be unreliable!). The equation of motion of the air is: (simplified)!

$$\underbrace{\partial \underset{\sim}{U}/\partial t}_{\text{Acceleration}} + \underbrace{(\underset{\sim}{U}\cdot\underset{\sim}{\nabla})\underset{\sim}{U}}_{\text{Advection}} + \underbrace{2\underset{\sim}{\Omega}\times\underset{\sim}{U}}_{\text{Coriolis force}} = \underbrace{\underset{\sim}{g}}_{\text{Gravity}} \underbrace{- \frac{1}{\rho}\underset{\sim}{\nabla} p}_{\text{Pressure-gradient force}} + \underbrace{\nu_{ni}(\underset{\sim}{V} - \underset{\sim}{U})}_{\text{Ion Drag}} + \underbrace{\frac{\mu}{\rho}\nabla^2 \underset{\sim}{U}}_{\text{Molecular Viscosity}}$$

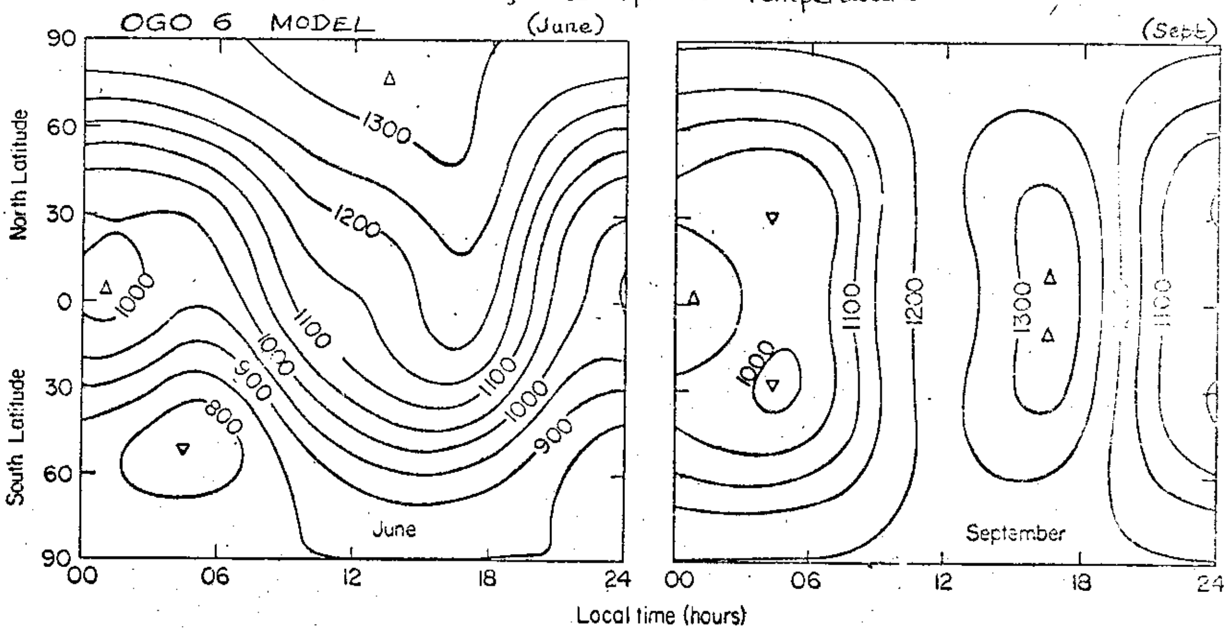
By far the largest terms are gravity and the vertical pressure gradient force. They are of order 10 m s^{-2}, whereas other terms are at most $\sim 5 \text{ cm s}^{-2}$. We can remove these terms because they merely give the hydrostatic eqn $g = \frac{1}{\rho}\frac{dp}{dh}$, which completely dominates the vertical distribution of the air (any other vertical acceleration $(\partial U_z/\partial t)$ is of order 10^{-4}m s^{-2}). Furthermore, the 'nonlinear advection term' $(\underset{\sim}{U}.\underset{\sim}{\nabla})\underset{\sim}{U}$ is only noticeable under certain circumstances. The viscosity term has an important vertical component $\frac{\mu}{\rho}\frac{\partial^2 U}{\partial h^2}$. It is significant because (μ/ρ) becomes large at great heights; but the effect is merely to smooth out vertical variations of U, such that the horiz. winds are almost height independent

Fig. 13 Jacchia Model : Isotherm Map & Schematic Winds



(Exospheric temperatures for average solar activity. Winds as at about 300 km)

Fig. 14 Isotherms of Exospheric Temperature



above 200 km or so. Given this, we are only left with the following approximate equation of motion for the horizontal components of U:

$$\frac{\partial \underset{\sim}{U}}{\partial t} + 2\underset{\sim}{\Omega} \times \underset{\sim}{U} = \underset{\sim}{\mathcal{F}} + \nu_{ni}(\underset{\sim}{V} - \underset{\sim}{U})$$

where the pressure gradient force $\underset{\sim}{\mathcal{F}} = -\frac{1}{\rho}\nabla_{horiz} P$

and ν_{ni} is related to the ion-neutral collision frequency ν (more properly, ν_{in}) used in dynamo theory (§8) by $N_i m_i \nu_{in} = n m_n \nu_{ni}$

See §9 Since $N_i/n \simeq \frac{1}{1000}$ in the F region (and $m_i \doteq m_n$) we have $\nu_{in} \simeq 1000\,\nu_{ni}$

Typical values at 300 km: $\nu_{in} \simeq 0.5\ s^{-1}$

NIGHT/DAY: $\nu_{ni} \simeq (1-5)10^{-4} s^{-1} \simeq (0.3 - 1.5)\ hour^{-1}$

In contrast, Coriolis term contains $2\Omega = 4\pi/24\ hrs \simeq 1.4 \times 10^{-4} s^{-1} \simeq 0.5\ hour^{-1}$

Ω is earth's angular velocity : note that $2\underset{\sim}{\Omega} \times \underset{\sim}{U}$ contains a factor $\sin\lambda$ (latitude).

Hence the ion drag is generally more important than the Coriolis force, especially at low latitudes, unless the ion density is very low. As a result, the winds tend to blow down the pressure gradient ("across the isobars") instead of normal to the pressure gradient ("along the isobars") as meteorological winds do.

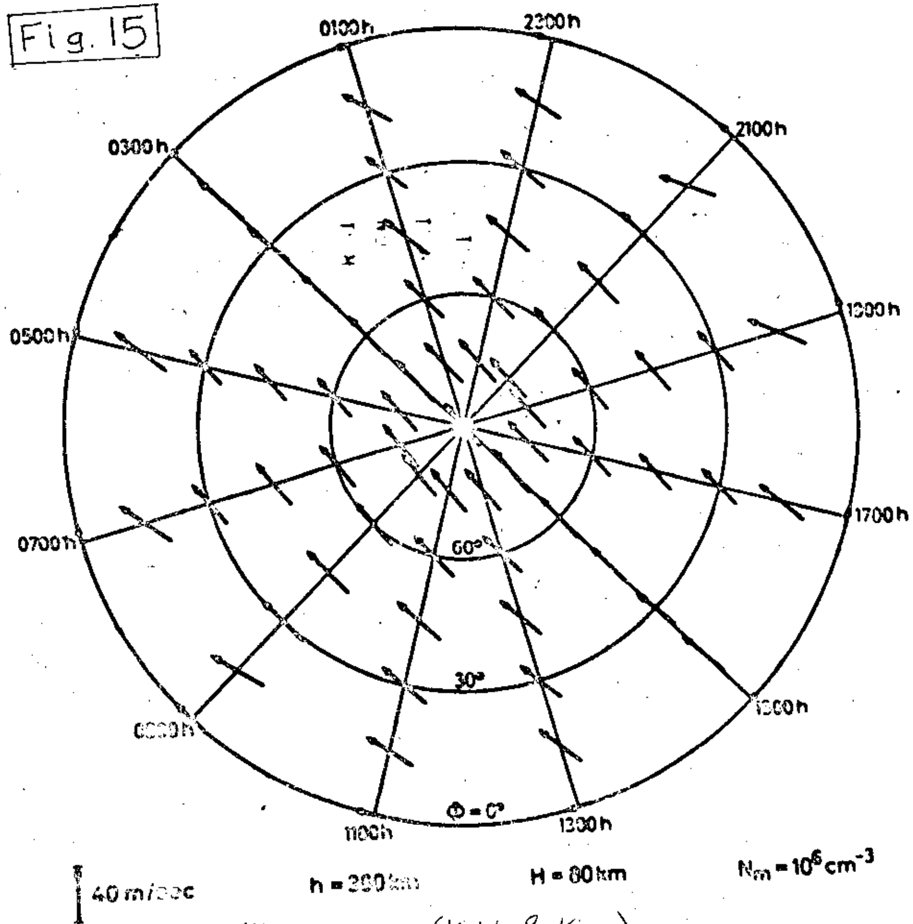
So	Ion drag $\gg$ Coriolis force	:	Wind $\parallel$ Pressure gradient
	" " $\ll$ " "	:	" $\perp$ " "
	" " $\simeq$ " "	:	" inclined to " "

{ There is an interesting analogy to the motion of a particle, §8. We had motion inclined at angle $\theta = (\arctan \frac{\omega}{\nu})$ to the force $\underline{F}$. In the wind case, we can show that in a 'steady state' ($\partial \underset{\sim}{U}/\partial t \simeq 0$) in wind direction is inclined at an angle $(\arctan \frac{2\Omega \sin\lambda}{\nu_{ni}})$ to the force $\underset{\sim}{\mathcal{F}}$ }

Fig. 15 shows a computed wind pattern, viewed from above the north pole, blowing from the afternoon sector to the early morning sector. This however neglects auroral zone heating and possible magnetospheric-related contributions to the wind system.

Fig. 16 shows a computed wind pattern at about 51° lat, equinox, with relative magnitudes and directions of $\underset{\sim}{U}$ at 200 km and 400 km, compared to the direction of the driving force $\mathcal{F}$. Notice that by day (12-18 LT) all are nearly in the same direction (strong ion-drag) but at night the wind vectors lead $\mathcal{F}$ in direction (coriolis effect), especially at 200 km where N becomes very small at night so ion-drag is weak.

Fig. 15



Wind pattern (Kohl & King)

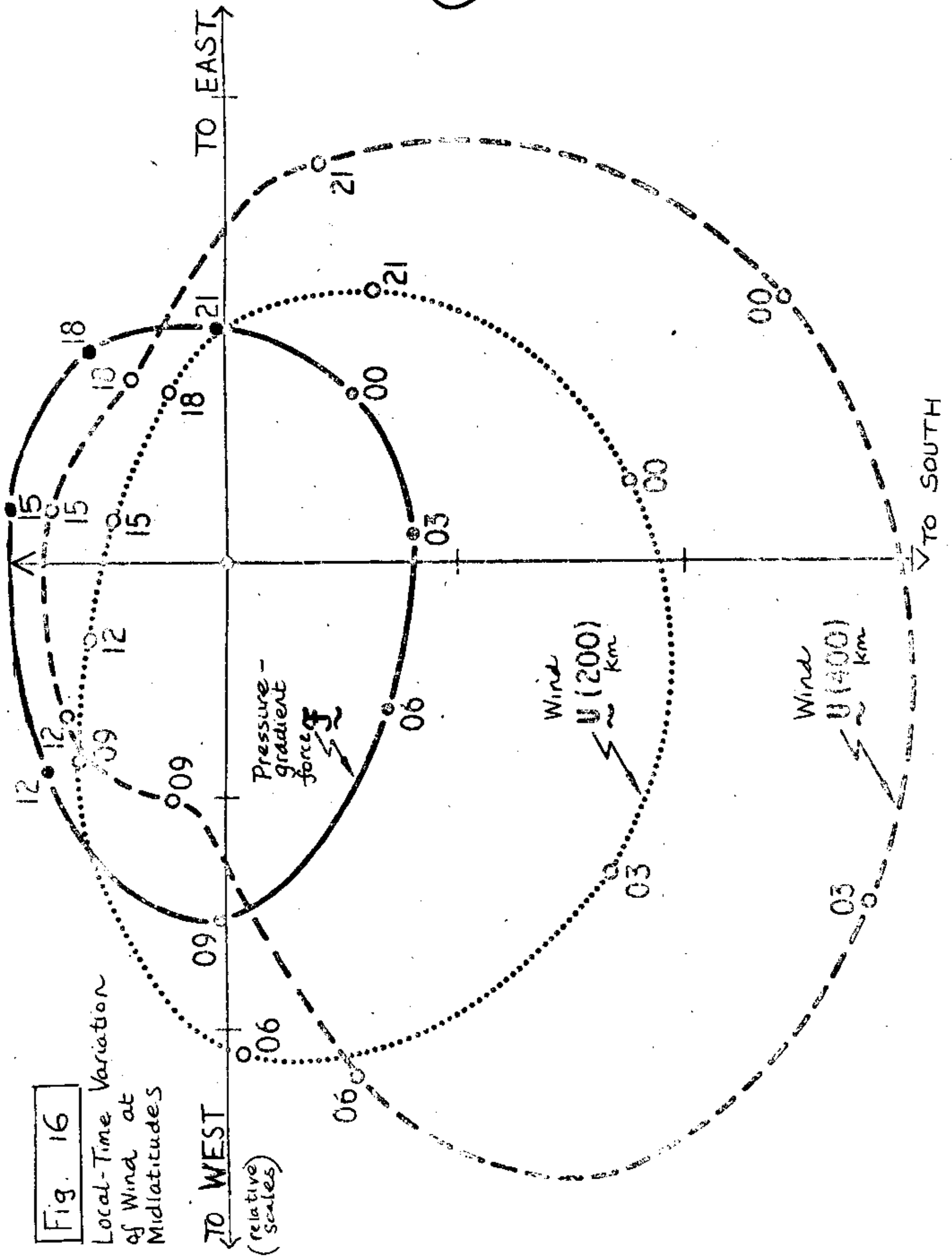


Fig. 16
Local-Time Variation of Wind at Midlatitudes

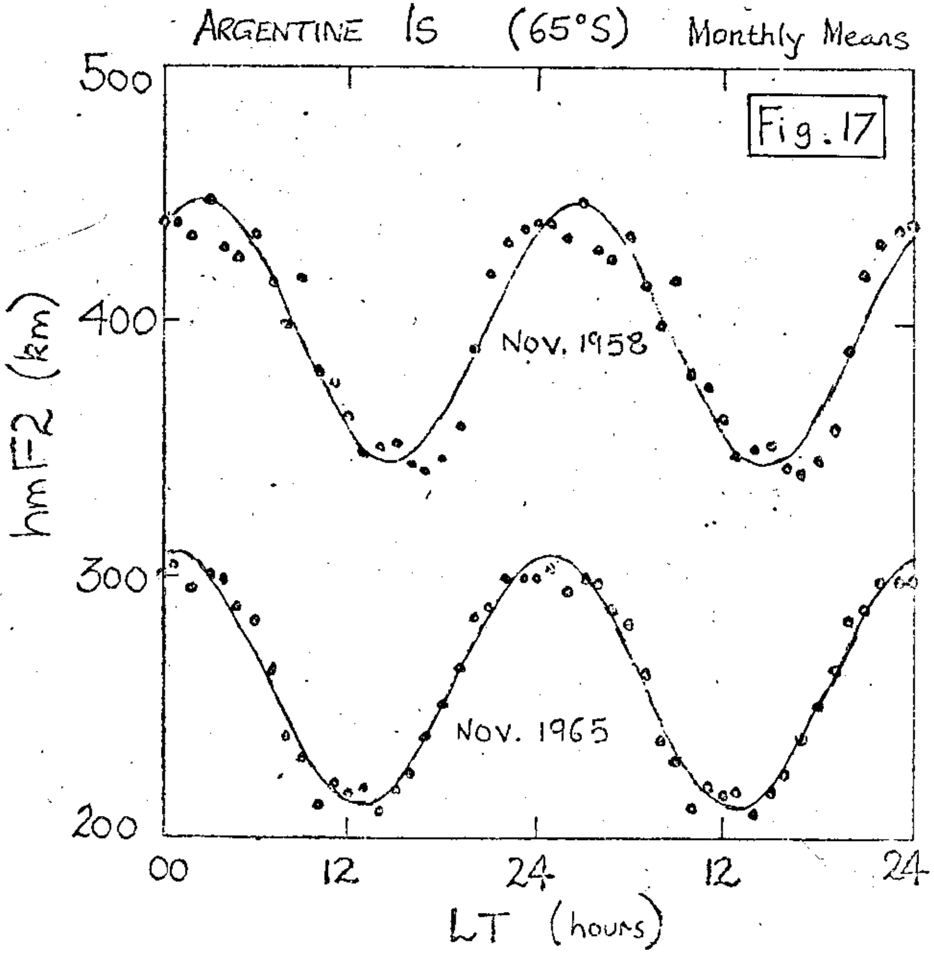


Fig. 17

$\boxed{\text{Fig. 17}}$ Shows how the peak of the F2 layer responds to the wind system — the height hmF2 is observed to be raised when the wind blows towards the equator at night, lowered when it blows towards the equator by day (See §14)

§14. Formation of the F2 peak

§4 explained that, above the F1 layer, N increases upwards because q/β increases. We now consider what limits this increase. Diffusion of the ions and electrons through the neutral gas becomes rapid at great heights because the diffusion coefficient $D \propto \frac{2kT}{m\nu_{in}}$ (from kinetic theory) ν_{in} is proportional to neutral gas concentration n.

Theory shows that the peak is formed at around the level where

$$\frac{D}{H^2} = \beta$$

(Recall that the loss coeff. $\beta \propto [N_2]$ decreases rapidly upwards)

Furthermore, if there is a vertical drift W of ions and electrons, (due either to a wind $\underline{U}$, or electric polarization field $\underset{\sim}{E}$ transmitted from the dynamo layer (§10)), the peak will be lifted or lowered by a distance of order

$$\Delta h_m = W/\beta$$

The equation of diffusion for the ions & electrons (the 'plasma' diffusion equation) resembles the ordinary diffusion equation for a minor constituent of the atmosphere, which is

$$\frac{\partial N}{\partial t} = D\,\nabla^2 N$$

Simplify:

(a) Vertical gradients (scale size ~50 km) are much greater than horizontal (scale ~ 1000 km) under normal conditions. So can replace ∇ by just d/dh

Add

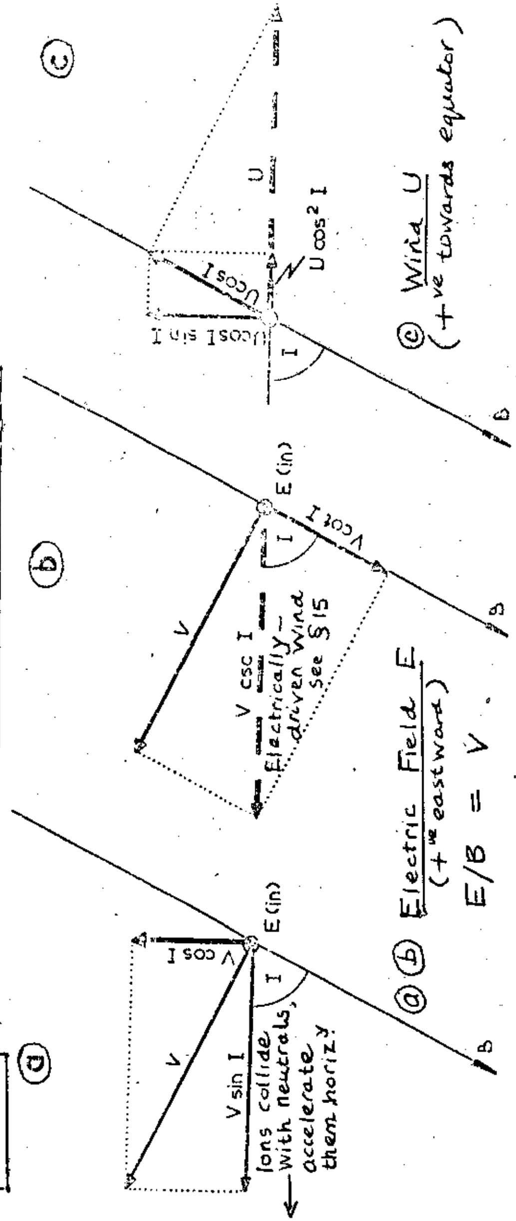
(b) Production term q, loss term $-\beta N$

(c) Drift term $-\nabla(N\underline{V})$, which reduces to $-\frac{d}{dh}(NW)$, due to ion drift $\underline{V}$ — essentially the vertical component W.

From §8 find: Wind $\pm$U blowing towards equator gives drift ($\pm U\cos I$) along field lines; vertical component is $\pm U\cos I\sin I$.

Electric Field $\underset{\sim}{E}$ (eastward) produces vertical drift $(E/B)\cos I$.

See $\boxed{\text{Fig. 18}}$ sketch (a) field, sketch (c) wind.



$\boxed{\text{Fig. 18}}$ Effect of Electric Field and Wind in F2 layer

Take account of :

(d) Height variation of $D \propto e^{h/H}$ (i.e. D increases exponentially).
Can show that this necessitates replacing one factor $\frac{d}{dh}$ by $\left(\frac{d}{dh} + \frac{1}{H}\right)$

(e) Gravitation, which tries to impose on N an exponential distrib^n $\propto e^{-h/2H}$ (see §16). Can show that this causes the other factor $\frac{d}{dh}$ to be replaced by $\left(\frac{d}{dh} + \frac{1}{2H}\right)$

(f) Electrostatic attraction between ions and electrons. Contributes to (e) and also results in (approx) doubling of D.
Kinetic theory then gives $D \simeq \frac{2kT}{m_i \nu_{in}}$

(g) Ions & electrons can diffuse only along geomagnetic field lines. Multiply D by $\sin^2 I$. Complicated geometry near equator.

DIFFUSION EQUATION with (a) - (f) becomes

$$\frac{\partial N}{\partial t} = D\left(\frac{d}{dh} + \frac{1}{H}\right)\left(\frac{d}{dh} + \frac{1}{2H}\right)N - \frac{d}{dh}(NW) + q - \beta N$$

Features of solution: ('m' denotes value at peak)

(i) Peak is near level where $\frac{D_m}{H^2} \simeq \beta_m$
(ii) Displaced by vertical drift, $\Delta h_m \sim W/\beta_m$
(iii) Well below peak, $N \sim q/\beta$ (chemical distribution)
(iiii) Well above peak, diffusive distribution $N \propto e^{-h/2H}$
(v) Peak electron density $N_m \sim q_m/\beta_m$ by day.
(vi) At night, decays with coefficient β_m, i.e. like $e^{-\beta_m t}$

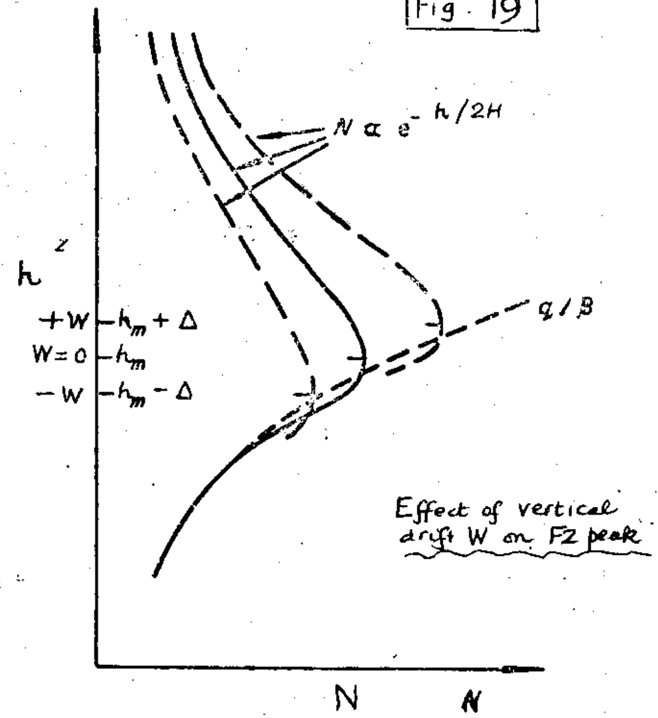
Fig. 19 illustrates (ii, iii, iiii) and shows how :
$\frac{\text{Upward}}{\text{Downward}}$ drift $\frac{\text{raises}}{\text{lowers}}$ h_m, $\frac{\text{increases}}{\text{decreases}}$ N_m

Similarly at night, $\frac{\text{upward}}{\text{downward}}$ drift $\frac{\text{raises}}{\text{lowers}}$ h_m, gives $\frac{\text{slower}}{\text{faster}}$ decay

§15. Electrically - Driven Wind

§13 gave the equation of motion of the neutral air in the thermosphere, with the ion-drag term $\nu_{ni}(\underset{\sim}{V} - \underset{\sim}{U})$ acting as a frictional or drag term. But, if the ions & electrons are drifting in an electric polarization field $\underset{\sim}{E}$ (transmitted from the dynamo layer, §10) then the term $\nu_{ni}(\underset{\sim}{V} - \underset{\sim}{U})$ provides a driving force. The drifting ions accelerate the air

Fig. 19



Effect of vertical drift W on F2 peak

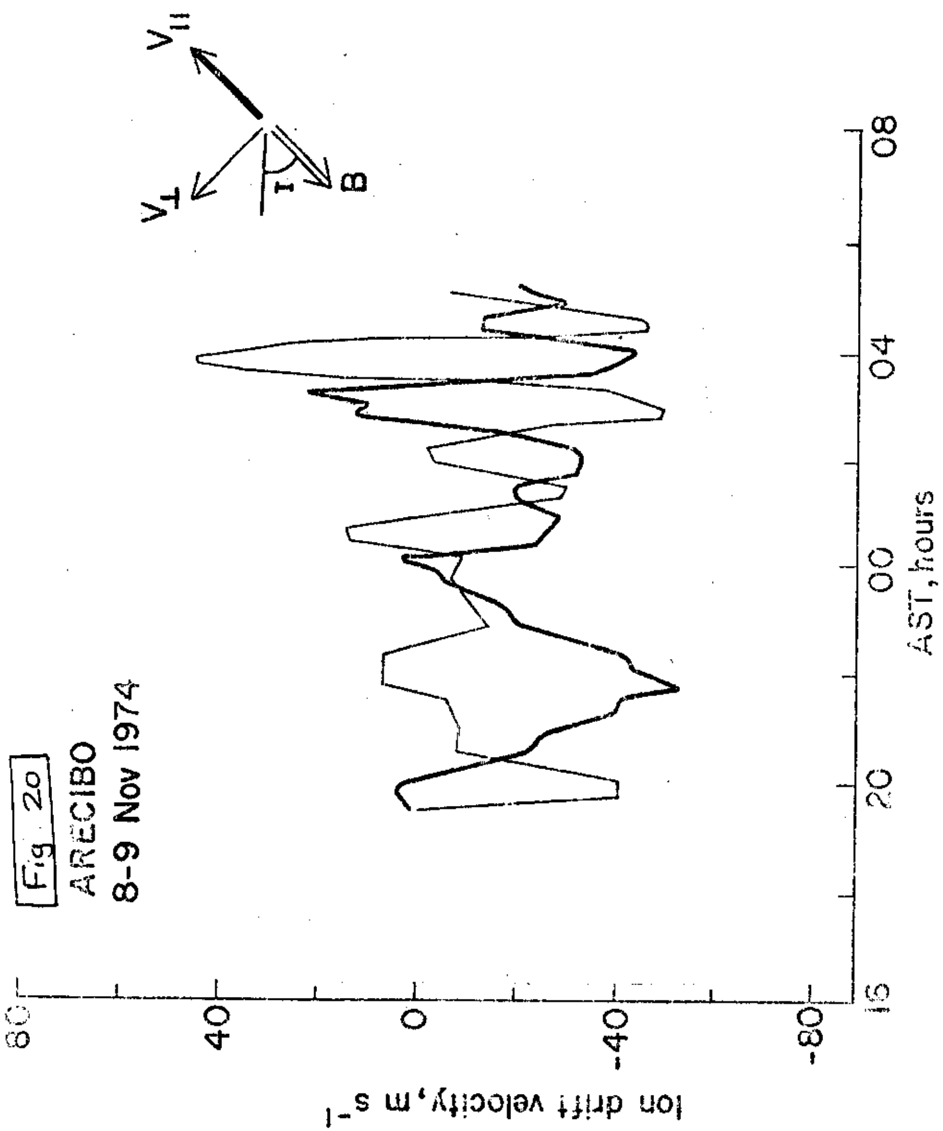


Fig. 20
ARECIBO
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with time constant $(\nu_{ni})^{-1}$, typically (0·3 – 1·5) hour^{-1} (§13). This is shown by sketch (a) of Fig. 18. Sketch (b) shows that the resulting wind imposes an ion drift $V \cot I$ along field lines.* Its vertical component just cancels the vertical component of the electric field drift ($V \cos I$). The net result is that both ions and neutrals (also electrons) drift horizontally at speed $V \csc I$.

So electric fields can drive winds. This is particularly important at high latitudes where there are strong electric fields, both in the auroral zone and in the polar cap.

* Fig. 20 shows an interesting example of drift $V_{\parallel}$ (along $\underline{B}$) attributed to ion-drag resulting from electric-field drift $V_{\perp}$.

§16. Diffusion in Topside of F2 layer

At great heights, with no collisions and no significant production & loss, ions and electrons try to take up hydrostatic distributions. Without electric charges, these would be $N_i \propto \exp\left(-\frac{m_i g h}{kT}\right)$, $N_e \propto \exp\left(-\frac{m_e g h}{kT}\right)$

Because $m_i \gg m_e$ these distributions would be very different. However, electrons and ions cannot separate because of their strong electrostatic attraction. Instead they take up a distribution, in which the ions and electrons are separated, on average, by a minute distance which gives rise to a vertical polarization field* but in which $N_e = N_i = N$ (almost exactly). Ions & electrons are then approximately in equilibrium under this polarization field; gravity; and their partial pressure gradient force, $\frac{1}{N}\frac{dp_i}{dh}$ per particle (where $p_{i,e} = NkT_{i,e}$)

Ion equilibrium (+ve upwards) : $0 = eE - \frac{kT_i}{N}\frac{dN}{dh} - m_i g$.

Electron equilibrium : $0 = -eE - \frac{kT_e}{N}\frac{dN}{dh} - m_e g$

FORCES ACTING ON IONS ELECTRONS
$m_i g$
$\frac{kT}{N}\frac{dN}{dh}$
eE

Assume $T = T_i = T_e$ (not essential, but simplifies). Neglect m_e.
Add equations to get $\quad 0 = -\frac{2kT}{N}\frac{dN}{dh} - m_i g$

Solution is $N \propto \exp\left(-\frac{m_i g h}{2kT}\right)$, or $N \propto \exp\left(-\frac{h}{2H}\right)$

where H is the scale-height $kT/m_i g$ for a neutral gas of molecular mass m_i. This accounts for the distribution shown in Fig. 19; see (iiii) in §14.

*[This small electric field, equal to $\frac{m_i g}{2e}$, is an essential part of the equilibrium of the plasma. Even though it has a component parallel to $\underline{B}$ (except at the equator) it can be maintained permanently.]

<u>Flow to protonosphere</u>. We note that the diffusion equation is 2^{nd} order and has two independent solutions, the diffusive equilibrium solution just derived: $N \propto \exp\left(-\frac{h}{2H}\right)$

and a 'flux' solution: $N \propto \exp\left(-\frac{h}{H}\right)$.

The latter corresponds to a flux of ions and electrons to or from "infinity". Actually, a small part of the distribution is of this type. This "protonosphere flux" is important because it enables the ionosphere to exchange with the protonosphere. This involves exchange of charge between ionospheric O^+ ions and protonospheric H^+ ions:

$$O^+ + H \rightleftharpoons O + H^+$$

This reaction can go freely either way, because O and H have almost exactly the same ionization potential (see table in §2). This flow and exchange has some importance, in that it fills the protonosphere by day, and allows the protonosphere to feed back ionization into the ionosphere at night.