PROCESSES CONTROLLING IONIZATION DISTRIBUTION IN THE F_2 REGION OF THE IONOSPHERE*

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It has been known for more than 20 years that the morphology of the principal (F_2) region of the ionosphere is complex, and inexplicable in terms only of solar ionizing radiation and recombination. The hypothesis was advanced (Martyn 1947) that movement, and especially vertical movement, of F_2 ionization was the main reason why the morphology of this region differed so profoundly from that of the lower regions E and F_1, which conform closely with Chapman's well-known theory. A principal cause of movement of F_2 ionization was held to be the drift occasioned by the electrodynamic forces and winds associated with the ionospheric electric current systems whose existence is manifested by the daily magnetic variations at the ground. There is now considerable evidence, both theoretical and observational, to show that this view may be essentially correct.

During the past few years rockets have been used, especially in the United States, in attempts to measure *in situ* the physical properties of the high atmosphere. In particular, a small number of measurements of atmospheric density has been made at heights approaching 200 km. These suggest that the density of the atmosphere in the F_2 region may be some 30 times less than had hitherto been deduced (Martyn and Pulley 1936) from radio experiments. If the air density at these levels were as low as rocket measurements suggest, it would be likely that diffusion of F_2 ionization (in electrically neutral volume) under the forces of gravity and of its own (partial) pressure gradient would notably affect the shape and height of the region. Accordingly, an investigation has been made of the possible effects of diffusion processes at such levels.

The results of this investigation, as outlined below, lead to the following conclusions.

(*a*) The rocket measurements of atmospheric densities at heights above 150 km appear to be subject to a gross systematic error, and are much lower than can be reconciled with other types of observation.

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(*b*) A Chapman (C_α) region, defined as one in which the ion pairs are produced by absorption of monochromatic radiation in an isothermal atmosphere and in which they decay by recombination, has a characteristic form given by

$$N = N_m \exp \tfrac{1}{2}\{1 - z - e^{-z}\}, \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where N is the number density of the ion pairs and z is height, measured from the level of maximum ionization, in units of H,* the "scale height" of the atmosphere. It is found that a region of any initial shape will in time assume by diffusion the form of a C_α region; the time required for this to happen at F_2 heights (*c.* 350 km) is a few hours, if the air density there is as great as was formerly believed, but only a few minutes if the rocket-measured densities are correct.

(*c*) It is found that, if the decay of electron density occurs according to the "attachment" formula

$$\partial N/\partial t = -\beta_0 e^{-z} N,$$

then in moderate to high magnetic latitudes a stable and stationary C_α region will tend to form at one particular height, which is 360 km if pre-rocket densities are accepted; this is observed to happen during the night hours in all parts of the world save the immediate vicinity of the magnetic equators.

(*d*) It is found that the formation of a C_α region by diffusion a few hours after sunset accounts for the well-known fact that at such times the under surface of the F_2 region assumes a parabolic height distribution.

(*e*) Finally, the present investigation confirms an earlier suggestion (Martyn 1954) that the well-known geomagnetic equatorial anomaly is due to the combination of large vertical electrodynamic drift velocities and inhibition of vertical diffusion by the nearly horizontal magnetic field. Thus by day the F_2 region near the magnetic equators is drawn out by upward drift until it becomes a high thick region of abnormally small peak ionization, while the shape of the under surface has no resemblance to parabolic form. During the early part of the night the peak density is sustained because the rate of disappearance of ionization is small at the great heights in question. Eventually the peak is lowered, by electrodynamic drift, to heights less than 300 km, where the relaxation time is of the order of 1 hr, and decay is rapid.

Speed of Diffusion of Ionization under Gravity and Partial Pressure Gradient

It is a safe assumption that in the ionosphere at a given point the number densities of the positive and of the negative particles N_i, N_e are almost exactly equal; even a small departure from equality would give rise to very strong electric fields which would immediately restore the balance. It is also safe to assume, for the low pressures of the F_2 region, that transport due to mechanical forces can occur only along the lines of geomagnetic force. If a particle of mass m, making an average of ν collisions per second with the surrounding gas

* In this paper g, the acceleration due to gravity, is measured in similar units.

molecules, is influenced by a force F it will drift through the gas with the mean velocity

$$v=F/m\nu. \qquad (2)$$

It is clear that the positive ions must drift with the same speed as the electrons, the more mobile particles (the electrons) being tied to the ions by powerful electrostatic fields. Thus, since $m_i\nu_i \gg m_e\nu_e$, we need only determine the speed of the ions in order to find the speed of the ionization transport.

The vertical gravity force upon an ion pair is $-(m_i+m_e)g$, or, to close approximation $-m_ig$. The vertical force upon unit volume of ionization due to its own pressure gradient is $-\partial(p_i+p_e)/\partial h$, where $p_i=p_e=NkT$, T being the mean absolute temperature of the ionization and k Boltzmann's constant. Thus this force is $-2kT\partial N/N\partial h$ per ion pair. It is clear that it will be almost wholly transferred to the less mobile particle (the ion) by electrostatic interaction. The transport speed due to gravity and pressure gradient is therefore

$$\begin{aligned} v &= -\frac{m_ig}{m_i\nu_i}-\frac{2kT}{Nm_i\nu_i}\cdot\frac{\partial N}{\partial h} \\ &= -\frac{g}{\nu_i}-\frac{2gH}{\nu_iN}\cdot\frac{\partial N}{\partial h} \\ &= -\frac{g}{\nu_i}\left(1+\frac{2}{N}\,\frac{\partial N}{\partial z}\right). \qquad (3) \end{aligned}$$

Since ionization transport can occur only along geomagnetic lines of force this equation as it stands will apply only at the magnetic poles. In regions where the magnetic inclination is ψ the effective force is $F\sin\psi$, and the *vertical* velocity is reduced by the factor $\sin^2\psi$.

The above equation has previously been derived by other workers by more complex reasoning. The above simple derivation may help to clarify the physical processes involved.

Formation of Stable C_α *Regions by Diffusion*

The continuity equation for a changing vertical distribution of ionization in the F_2 region in the absence of sunlight and decay is

$$\frac{\partial N}{\partial t}=-\text{div}\,(Nv). \qquad (4)$$

A region able to move vertically (or to remain stationary) without distortion must satisfy the condition

$$\frac{dN}{dt}=-N\frac{\partial v}{\partial z}-v\frac{\partial N}{\partial z}+v\frac{\partial N}{\partial z}=-N\frac{\partial v}{\partial z}=0$$

at all heights.

In other words v must have no height gradient. Thus, from (3), writing φ for $(1/N)\partial N/\partial z$, we must have

$$\frac{\partial\varphi}{\partial z}+\varphi=-\tfrac{1}{2}. \qquad (5)$$

The solution of (5) is equation (1) above, which is the ionization distribution of a C_α region. Also, from (3) we find

$$v = -g \sin^2 \psi / \nu_0,$$

where ν_0 is the ion collision frequency at the height $z=0$, where $N=N_m$.

Clearly, the shape of a C_α region remains unaffected by diffusion, a conclusion already reached (Martyn 1954 ; Hirono 1955) by other methods. It does not necessarily follow, however, that such a region is *stable*, or that other distributions of ionization will assume the C_α form.

The stability of a C_α region has been investigated by a perturbation method, the details of which will not be given here ; it is found that if ΔN be the perturbation, then $(1/\Delta N)\partial(\Delta N)/\partial t$ is negative in sign, thus demonstrating that the region is stable for small disturbances.

To test the second aspect a number of different initial distributions, such as $N=N_m \exp(-bz^2)$, were assumed. In all cases it was found that the ionization became redistributed in such a way as to form a C_α region. There seems little reasonable doubt that any arbitrary ionization distribution having an ionization peak will eventually, in a time of order $\nu_0/g \sin^2 \psi$ assume the form of a C_α region.

Formation of a Stable C_α *Region at a Particular Height, by Combined Action of Diffusion and Attachment Gradient*

In order to simulate actual conditions in the F_2 region at night, it is necessary to include in equation (4) a term which will take account of the decay* of ionization. Thus we write

$$\frac{\partial N}{\partial t} = -\text{div}\,(Nv) - \beta_0 e^{-z}.$$

It is important to enquire whether it is possible for a decaying C_α region to form at any particular level in the ionosphere.

The condition for this to occur would be

$$\frac{1}{N}\frac{\partial N}{\partial t} = -B,$$

where B is a constant, independent of height and time. It is readily found that a C_α region can exist in a stable, stationary (though decaying), state, with its peak at a height given by $2\beta\nu = g \sin^2 \psi$; that is to say, (taking ν as 7·6 at 300 km and H as 50 km) at a height of 359 km.

It is a well-known fact that the F_2 region rises rapidly after sunset, and settles for some hours with its peak at approximately this height, in all parts of the world save the immediate vicinity of the magnetic equator. The processes just described would be inhibited by the horizontal magnetic field near this

* Whether F_2 ionization decays according to a recombination or attachment law has been debated for many years. Ratcliffe *et al.* (1956) have produced strong evidence that an attachment law is effective, and that, between heights of 250 and 350 km, $\beta = 10^{-4} \exp-[\{h\,(\text{km})—300\}/50]$. By different methods, still unpublished, the present author has verified both these conclusions, and finds $\beta = 10^{-4} e^{-z}$.

equator. Thus it would appear that the observed behaviour of the F_2 region after sunset is consistent with the view that it is substantially controlled by the process just outlined.

Interpretation of Equatorial Anomalies, and of Parabolic Shape of F_2 *Region*

It is strikingly noticeable that the daily variation of N_m and z_m within 10–15° of the magnetic equators is very different from the corresponding variations at higher latitudes. While it is true that vertical electrodynamic drift is larger in low latitudes, it would be expected theoretically to decrease to a shallow minimum at the equator. Observations show no sign of such a minimum.

The deductions made above appear to confirm the suggestion (Martyn 1954) that *absence* of vertical diffusion at the equators is responsible for the very great height variations, and the abnormal N_m variations, there observed. The above reasoning leads to the conclusion that diffusion would prevent the F_2 region from being elevated above about 400 km in moderate to high latitudes, and even this height should seldom be attained. Moreover, the fact that diffusion leads to grouping of ionization in C_α form would tend to prevent the F_2 region from being abnormally attenuated or spread out over a large height range, with consequent reduction in N_m. No such considerations hold near the equators, where there is nothing to prevent the formation of " thick " F_2 regions of abnormally reduced N_m, and with peaks as high as 600 or more km.

Equation (**1**) may be approximated, for values of $|z|$ not much greater than unity, to

$$\begin{aligned} N &\approx N_m\{1+\tfrac{1}{2}-\tfrac{1}{2}z-\tfrac{1}{2}(1-z+\tfrac{1}{2}z^2)\} \\ &\approx N_m(1-\tfrac{1}{4}z^2). \end{aligned}$$

This is the parabolic form which the under surface of the region assumes an hour or two after sunset. It would appear that this well-known phenomenon is simply another aspect of the tendency of the region to assume C_α form when the ionizing agency is removed. This view is confirmed by the observed fact that the region does not assume this form near the magnetic equators.

The Density of the Atmosphere in the F_2 *Region*

The simple interpretation of all the above well-known F_2 phenomena assumes that the atmospheric densities derived from radio data are substantially correct, the air particle density being close to 10^{10} per c.c. at the 300 km level. On the other hand, if recent rocket-measured densities were accepted, the F_2 region would, at moderate to high latitude, move down after sunset to well below 300 km. This happens nowhere, and suggests that there must be present a systematic source of error in the devices used for density measurement by rocket at great heights.

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