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THE POLAR ION FLOW: WIND OR BREEZE?

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ABSTRACT

A review of the theories of light ion flow from the polar cap in their hydrodynamic and evaporative forms is offered. Both types of theories should be able to provide correct treatments of the phenomenon. Some difficulties with the hydrodynamic theory are mainly interpretative and should disappear if the so called pressure gradient force term in the equations of motion is recognized as really inertial in nature. An important new insight has been provided recently in an evaporative theory by the realization that the electric field in the exosphere required to balance electron and ion fluxes is quite different from the electric field of gravitational separation usually used in ionospheric theory. However, an evaporative theory that is based on realistic boundary conditions as well as an acceptable electric field remains to be worked out. The actual situation in the polar ionosphere is sufficiently complex that experimental studies will undoubtedly be needed to establish the actual conditions which exist there.

INTRODUCTION

About two years ago Banks and Holzer (1968) submitted a letter entitled "The Polar Wind" to the Journal of Geophysical Research. At the same time Axford (1968) sent to the same journal a note on "The Polar Wind and the Terrestrial Helium Budget". The Banks and Holzer letter contained the outline of a hydrodynamic treatment of the outflow of plasma from the polar cap of the earth along open field lines. According to this theory the expansion velocity of helium and hydrogen ions could exceed the speed of sound at a very low altitude. Such large flow velocities, attained in regions where ion densities are large, would produce very great fluxes of H^+ and He^+ along the tubes of magnetic flux which open into the tail of the magnetosphere. As Axford pointed out in his letter such an eflux of helium ions from polar regions would result in a global loss of helium great enough to balance the radiogenic production rate and solve the ancient problem of the earth's helium budget.

Others - Nishida (1966), Bauer (1966), Dessler and Michel (1966) - had discussed the loss of ionized hydrogen on open field lines previously. But their discussion had been based on the traditional single particle collisionless orbital theory of evaporation from an exobase. The Banks, Holzer, Axford theory was hydrodynamic in nature, the flow of plasma being determined by bulk properties of the medium and supersonic flow velocities for protons were attained far below the base of the exosphere.

The eventual appearance of these two letters in the literature gave rise to a controversy - mainly between Dessler and Cloutier (1969) on the one hand and Banks and Holzer (1969) on the other. The disagreement concerns the question of whether a hydrodynamic or single particle-evaporative approach is more appropriate in treating the plasma flow. According to Dessler and

Cloutier the former treatment produces something to be called a polar wind while the second produces, by definition, a polar breeze, without regard to whether the flow velocity is supersonic or subsonic in either case. More so perhaps in this argument than in most such disagreements the discussion between the parties involved has been conducted in private rather than in the literature. The author of this review has been able to follow the development of this debate at fairly close hand. He was privileged to have several private discussions with some of the protagonists during the period between the submission of the first versions of the manuscripts of Banks and Holzer and of Axford and their eventual publication. He has also seen some of the documents and various revisions of papers which were produced during this period. It is his strong impression that positions on both sides have changed drastically since the original pre-publication confrontation and that the present official terms of reference differ in many deep and fundamental respects from those established at first. Because by now the differences appear to be mainly semantic it is difficult for the uninitiated observer to understand why the debate continues with so much vigor. The reasons are to some extent historical. The present short review is offered as a dispassionate attempt to characterize and criticise the two varieties of polar plasma flow theories as they now exist, with an occasional reference to the early and current controversies.

THE HYDRODYNAMIC THEORY

In this review the model of the polar wind which will be discussed will be that of Banks and Holzer (1969a, 1969b) in its most recent published manifestation. Unless a previous version is explicitly referred to it should be assumed that the current theory is being discussed. This, the most recent treatment by Banks and Holzer (1969a, 1969b) begins with a model atmosphere in which O^+ and He^+ ions are created by photoionization and H^+ is produced by charge transfer between O^+ and H. In the lower F_2 region ion chemistry and transport processes share in determining the ion densities. Above a certain altitude - 600 to 1000 km depending on the model - transport becomes dominant. In this region, where the principal ion is O^+, the electrons and the oxygen ions are virtually held in diffusive equilibrium with the help of the electric field set up by gravitational separation of ions and electrons. In the conventional theory of the top-side hydrostatic ionosphere this field is given by the Pannekoek (1922) - Rosseland (1924) formula

$$eE = - \frac{1}{n_e} \frac{dpe}{dz} \cong - \frac{1}{2} m(O^+) g \quad , \qquad (1)$$

This force is sufficiently large to compensate for the tendency of the electrons to distribute themselves in the gravitational field with a sacle height greater than that of oxygen by the ratio of the atomic oxygen to electron masses. But the field is much too great merely to hold the light minor ions H^+ and He^+ in diffusive equilibrium. It accelerates them upward and a mass flow results. The flow is impeded by the frictional drag which results mostly from Coulomb collisions of the light ions with oxygen ions. According to the original model of Banks and Holzer (1968) supersonic speeds (greater than $\sqrt{k\,T_i/m(H^+)}$ were attained by the H^+ fluid well below 1000 km. However, this result was obtained for a very abnormal ad hoc 0^+ distribution - one in which the 0^+ scale height was that of neutral oxygen. In their recent models Banks and Holzer predict a more gradual acceleration to flow velocities exceeding Mach 1. Nevertheless, these flows result in very large escape fluxes, of the order of 5×10^8 cm^{-2} sec^{-1} for H^+ and 2×10^6 cm^{-2} sec^{-1} for He^+.

The controversy which has followed the announcement of the original Banks and Holzer paper is reminiscent of the Parker-Chamberlain debate which pitted Parker's hydrodynamic solar wind against Chamberlain's evaporative solar breeze. (See Dessler, 1967.) Dessler and Cloutier (1969) have argued that most of the acceleration of light ions would occur in the exosphere. There, collisions would be so infrequent that the flow should be describable in terms of the standard single particle orbital theory of atmospheric escape modified by the gravitationally induced electrostatic field of Eq. (1). Dessler and Cloutier have objected particularly to a light ion pressure gradient term in the hydrodynamic equations of motion. And indeed it is difficult to understand the concept of hydrogen ions exerting a force on the hydrogen ion fluid through a gradient in the hydrogen ion pressure in a region where the H^+, H^+ mean free path is so long that these ions cannot be regarded as interacting directly with each other. This problem has caused conceptual difficulties for many who have tried to understand the hydrodynamic version of the H^+ and He^+ polar wind.

This difficulty is separate from the question of whether the hydrogen ion pressure tensor can be represented as a scalar through the traditional energy relationship

$$p = nkT \qquad (2)$$

over the altitude range in question. That is, even if it is granted that collisions between H^+ and the more abundant O^+ ions are frequent enough, as Banks and Holzer assert (without proof), to randomize the H^+ velocities, the fact remains that H^+ collisions with H^+ ions are needed if a real H^+ pressure gradient force is to exist. Midgley (1969a, 1969b) indeed has examined a simple analagous case of dilute gas flowing through a porous plug. He finds that randomizing collisions of gas molecules with a dense matrix of scattering spheres can maintain the partial pressure tensor essentially iostropic in spite of the mass flow and the low density of gas molecules. But this demonstration obviously has only a plausibility value for the question at hand. And it has not much to say to the problem of the $H^+ - H^+$ acceleration.

Resolution of the problem depends on recognizing that the pressure gradient term in the hydrodynamic fluid equation of motion represents a force per unit volume only in the sense that an inertial force is a force. It has as much reality as centrifugal or cariolis forces do. It is perfectly permissible to regard it as a force field acting on the fluid, but it is not to be expected that a physical source for such a field can be isolated. The pressure gradient "really" represents a gradient in the net particle momentum per unit area. Thus, in Newton's second law of motion, it is to be found on the inertial or right hand side of the equation, $F = dp/dt$ in an inertial coordinate system.

In fact, starting with the Boltzmann equation in an inertial system and evaluating the average time variation of the momentum per unit volume of the sth species in a many component fluid leads to the familiar equation of motion

$$n^s F_i^s - n^s m^s \left\langle u_i^s \right\rangle \nu^s = \frac{\partial}{\partial x_k} n^s m^s \left\langle u_i^s u_k^s \right\rangle + \frac{\partial}{\partial t} n^s m^s \left\langle u_i^s \right\rangle \qquad (3)$$

where F_i^s is the force acting on each particle of the species, ν^s is a somewhat symbolic "average" collision frequency and the other terms have obvious definitions (Holt and Haskell, 1965). The two terms on the left hand side of (3) can be regarded as giving the total external force acting on a unit volume of the sth species. The second of these is a frictional or drag force. The first term might, for example, be the sum of gravitational and electrostatic field forces. The right hand side of (3) is just the net rate of charge per unit volume of the momentum of the species. The two inertial terms there attest to the fact that there are two ways in which the momentum density of the sth species can change as a result of forces acting in a volume element which is fixed in the coordinate system and through which the fluid is moving. It can change explicitly with time or as a result of a spatial difference between the amount of momentum flowing into and out of the volume element. Use of the continuity (first moment) equation permits (3) to be written in the form

$$n^s F_i^s - n^s m^s \left\langle u_i^s \right\rangle \nu^s = n^s m^s \frac{\partial}{\partial t} \left\langle u_i^s \right\rangle + n^s m^s u_k^s \frac{\partial}{\partial x_k} \left\langle u_i^s \right\rangle$$

$$+ \frac{\partial}{\partial x_k} n^s m^s \left\langle (u_i^s - \left\langle u_i^s \right\rangle)(u_k^s - \left\langle u_k^s \right\rangle) \right\rangle \qquad (4)$$

where each term on the right hand side is still explicitly inertial. The first term and the second are traditionally recognized as inertial. The second accounts for momentum changes which result from spatial variations in the mean flow velocity. The third term accounts for a change of momentum because of a spatial variation in the rate at which momentum is transferred across a surface moving with the mean velocity of the species. It is this term which can be defined to be

$$\frac{\partial \Psi_{ik}}{\partial x_k} \tag{5}$$

where Ψ_{ik} is the pressure tensor. In turn (5) may sometimes reduce to

$$\frac{\partial p^s}{\partial x_k} \tag{6}$$

where the scalar pressure is given by

$$p^s = \frac{1}{3} n^s m^s \left\langle (u_k - \langle u_k \rangle)(u_k - \langle u_k \rangle) \right\rangle \tag{7}$$

In the case of quasi-equilibrium, with the help of an energy equation, the pressure may be related to the species temperature through

$$p^s = n^s k T^s \tag{8}$$

Thus, for a simple one dimentional steady state flow (4) can sometimes be written in the form

$$n^s F^s - n^s m^s \langle u^s \rangle \nu^s = \frac{dp^s}{dz} + n^s m^s \langle u^s \rangle \frac{d \langle u^s \rangle}{dz} \tag{9}$$

Special cases, such as the diffusive equilibrium of a neutral gas species in a gravitational field,

$$n^s F^s = - n^s m^s g^s = \frac{dp^s}{dz} \qquad (10)$$

can be interpreted in terms of momentum changes under the influence of a force as well as the traditional form in which the downward directed gravitational force per unit volume is balanced by the upward (inertial) force exerted by the pressure gradient. In the dynamic interpretation the gravitational force acts to extract from the gas momentum which has been imparted to it by contact with a hot surface such as the earth. Or free expansion of a gas in a force free region described by

$$0 = \frac{dp^s}{dz} + n^s m^s \langle u^s \rangle \frac{d \langle u^s \rangle}{dz} \qquad (11)$$

(with suitable boundary conditions) can be regarded as an acceleration of fluid motion produced by a pressure gradient force per unit volume and usually is. But it can also be understood as a constant momentum flow with interchange possible between two forms of momentum, one representing the momentum transfer by random motion of particles across a surface moving with the fluid and the other being the momentum of the mean fluid motion $n^s m^s \langle u^s \rangle$. It rarely makes any difference which point of view is adopted except in a case like that of the H^+ flow in the polar wind where, through the intervention of H^+, O^+ collisions there may exist a scalar partial H^+ pressure gradient even though H^+ ions do not collide with H^+ ions. Here to regard the pressure gradient as accelerating the H^+ flow, is very artificial - like transforming to a rotating coordinate system where no merry-go-round exists. But to regard the combination of electric, gravitational and frictional forces as producing a random H^+ momentum gradient as well as an organized net fluid acceleration is perfectly natural. The continuity equation will determine the apportionment between the two momentum terms.

In the ionosphere the volume force on an ionic species is taken to be

$$n^s F^s = - n^s m^s g + e E \qquad (12)$$

where

$$e E = - \frac{1}{n_e} \frac{dpe}{dz} \qquad (13)$$

care must be exercised in determining the electric field. If no more than a condition of quasi electrical neutrality

$$n_e \cong \Sigma n_j^+ \qquad (14)$$

is imposed the result is the traditional Pannekoek-Rosseland field (1). Recently, however, Lemaire and Scherer (1970) as well as Jockers (1969) (in connection with the solar wind) have emphasized that such a field will not guarantee equality of positive ion and electron fluxes. Indeed, in the presence of such a field in the exosphere electrons will escape with a flux exceeding the positive ion flux by at least the square root of the ion to electron mass ratio. Such a state of affairs is impossible, of course. In the face of this tendency for the base of the exosphere to become positively charged the electric field will increase in the exosphere. The ion flux will correspondingly increase and the electron flux will decrease until the two are equal. Thus it is to be expected that the electric fields will be larger and the ion velocities greater in the exosphere than otherwise would be calculated. In the hydrodynamic theory of Banks and Holzer it would appear that the ambipolar character of the flow is preserved through the explicit imposition of a condition that the ion and electron fluxes be equal.

AN EVAPORATIVE THEORY

Lemaire and Scherer in their calculation have considered the escape of H^+ ions into the magnetospheric tail when the electric field in the exosphere is modified to insure not only (virtual) charge neutrality but equal ion and electron fluxes as well. Theirs is an evaporative type of calculation in which the densities of O^+, H^+ and electrons are fixed at the base of the exosphere (2000 km for $T_e = T_i = 3000°K$), the ions and electrons are assumed to be in a Maxwell-Boltzmann distribution, and the escape fluxes determined by the velocity of distribution at the exobase and the field configuration above. They obtain the mass flow velocities of O^+, e and H^+ and the outward fluxes. The elastic force varies from 0.5 $m(O^+)g$ at 2000 km through about 0.4 $m(O^+)g$ at 6000 km to less than 0.1 $m(O^+)g$ above 10,000 km. In the nearest comparable model of Banks and Holzer the force is much smaller - 0.12 and 0.04 in the same units at 5000 km and 6000 km. The H^+ velocities in the high field evaporative model are correspondingly larger than in the hydrodynamic model at comparable altitudes - about 13.5 km sec^{-1} compared to 5.5 km sec^{-1} at 4000 km for example.

COMPARISONS AND CRITIQUE

Unfortunately, these comparisons lose most of their significance when it is realized that the model chosen by Lemaire and Scherer differs radically from any of those studied by Banks and Holzer. The former authors have fixed the respective number densities of H^+ and O^+ to be 10^2 cm^{-3} and 9×10^2 cm^{-3} at 2000 km. The closest approximation to this model considered by Banks and Holzer is their case for $T_e = T_i = 3000°K$ and $T_N = 1000°K$. In that case the H^+ density at 2000 km is about 4×10^2 cm^{-3} and the O^+ density 1.5×10^3 cm^{-3}. It is partly because of the reduced H^+ density that Lemaire and Scherer find a proton escape flux of only 2×10^7 cm^{-2} sec^{-1} where Banks and Holzer get 2.7×10^8 cm^{-2} sec^{-1} for their model. At high altitudes (above 5000 km) the ratio of H^+ number densities is about 10 for the two cases. The question of which model is more realistic cannot be answered by appeal to experiment in view of the recent assertion by Hoffman and his coworkers (1969) that many previous light ion density measurements may have given values much too large.

Related to the question of whether the H^+ number densities in the Banks and Holzer models are too large is the fact that these models begin with very large neutral hydrogen densities - more than twice those which Lyman α and Balmer α airglow emission rates would support. The large H^+ densities and fluxes are a consequence and so are the large vertical flows of O^+ required to supply the ions for charge exchange with hydrogen. The flow of O^+ need not continue beyond the production zone and in fact there will be a return downward flux of neutral oxygen atoms to counter it. But the flow of H^+ outward must be supplied by neutral hydrogen atoms rising through the thermosphere. It is to be emphasized also that the escape fluxes calculated by Banks and Holzer are a factor of about two larger than the rates at which friction will allow hydrogen atoms to emerge from the mesosphere. Thus if these H^+ velocities are realistic the vertical hydrogen ion flow over the polar cap will require appreciable lateral flow of hydrogen at high altitudes from lower latitudes or the hydrogen (and H^+) number densities will drop at high altitude and bring down the efflux to a level that diffusion in the lower thermosphere can support. Meier (1970) has noticed a pronounced deficiency in the Lyman α airglow below 400 km over the polar cap, indicating very great depletion of neutral hydrogen in the thermosphere there. It is possible that this observation is a manifestation of such an effect.

Banks and Holzer find that the flow of O^+ persists above the level where it is required to support the H^+ production. The calculated O^+ velocity which is of the order of 10^2 m sec^{-1} at a few thousand kilometers seems large. Lemaire and Scherer calculate an O^+ velocity less than 1 cm sec^{-1} at these altitudes even in the presence of the stronger electric field of their model.

In the Lemaire, Scherer calculation it is assumed that no important upward flow has developed below the base of the exosphere other than the diffusive flow required to supply the evaporative escape flux. If acceleration of light ions by the gravitationally induced electric field below the exobase has produced a mass flow velocity which is an appreciable fraction of escape velocity, even though H^+, O^+ collisions have maintained the H^+ ions in thermal equilibrium, the evaporative treatment would need modification before it could be compared with a hydrodynamic fluid calculation.

SUMMARY

In summary the present state of affairs appears to be as follows. In the hydrodynamic treatment a more convincing demonstration is still needed that H^+, O^+ and He^+, O^+ collisions justify regarding the light ion pressure as isotropic. Other models, involving less hydrogen should be considered and the problem of supplying neutral hydrogen and O^+ ions during the night to the charge exchange reaction zone over the polar cap must be attacked. (Dessler and Michel [1966] discuss some of these problems.) In the orbital-evaporative theory the important modification of the electric field introduced by Lemaire and Scherer and by Jockers offers the hope of reconciling the evaporative and hydrodynamic theories - not only for the polar wind/breeze but for the solar wind as well. However, in the case of the polar problem some more attention to the lower boundary conditions and the use of models comparable with those used in the hydrodynamic treatment is indicated. Both types of treatment should lead to concordant results. It is obvious that if appreciable mass flow is produced below the baropause resort must be had to a hydrodynamic type of approach in that region to fix the lower boundary conditions for a strictly orbital exospheric calculation. Some argue that the individual species coupled equations of motion solved by Banks and Holzer are not truly hydrodynamic in that the hydrodynamic approximation calls for all constituents in a continuum fluid to flow together. This is part of the semantic quarrel referred to in the introduction. Ultimately the important question is whether all of the crucial physics is contained in the equations, whether the boundary conditions are realistic and whether approximations employed are not too severe. At the present, with the important exceptions noted, there seems to be no reason to suspect failures in this regard in either the Banks-Holzer or

Lemaire-Scherer calculations. The suspicion is strong, however, that resolution of all controversy will be provided, as it was in the solar wind, by some definitive experiments of the sort already begun by Hoffman (1970).

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