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Morphological Studies of Rising Equatorial Spread F Bubbles

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Analytical electrodynamic morphological studies of rising equatorial Spread F bubbles, within the context of the collisional Rayleigh-Taylor regime, are presented. The analogy between bubbles (plasma density depletions) and barium clouds (plasma density enhancements) is noted. Bubbles tend to steepen on their top and elongate in the vertical direction and they narrow horizontally as they rise through the equatorial F region ionosphere. Linear and nonlinear models of constant shape bubbles are presented. It is shown, for these models that the vertical bubble rise velocity, $V_B = (g/v_{in})f(\delta n/n_o)$, where v_{in} is the ion-neutral collision frequency and f is an increasing (Continues)		

20. Abstract (Continued)

function of $\delta n/n_0$ (fractional density depletion), depending on the shape of the bubble. Consequently, high altitudes and/or large percentage plasma depletions yield large vertical bubble rise velocities. The models are extended to include arbitrary electric fields in addition to the gravitational force.

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MORPHOLOGICAL STUDIES OF RISING EQUATORIAL SPREAD F BUBBLES

I. INTRODUCTION

Recently, experimental (Kelley et al., 1976; Woodman and La Hoz, 1976; and McClure et al., 1977) and numerical simulation studies (Scannapieco and Ossakow, 1976) of the nighttime equatorial F region have given evidence for rising bubbles (plasma density depletions). The vertical speed of these bubbles has been observed (McClure et al., 1977) to range from very low (several meters/sec and even zero) to very high (~ 100 m/sec or more) velocities. Hudson [1977] has attempted to describe these rising bubbles within the context of the collisionless Rayleigh-Taylor mechanism using techniques in two dimensions that Chaturvedi and Kaw (1975 a,b) used in one dimension. Ott [1977] has described the rise of equatorial Spread F bubbles, in both the collisional and collisionless Rayleigh-Taylor regimes, by noting the analogy with bubbles in fluids. Szuszczewicz [1977] has discussed the chemistry and transport of equatorial Spread F ionospheric holes.

It has been pointed out (Scannapieco and Ossakow, 1976; and Scannapieco et al., 1976) that there is a considerable analogy between equatorial Spread F (in the collision-dominated regime) and barium cloud studies. Indeed barium clouds can be viewed as Pedersen conductivity or plasma density enhancements while natural equatorial Spread F bubbles (or artificially created ionospheric holes, e.g., see Mendillo et al.,

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1975; and Bernhardt and da Rosa, 1977) can be viewed as Pedersen conductivity or plasma density depletions. In the present paper, we wish to discuss equatorial Spread F bubble shapes and vertical rise rates within the context of the collisional Rayleigh-Taylor regime (as invoked by Scannapieco and Ossakow, 1976), making use of the electrodynamic analogy (i.e., the electrical properties of the bubbles) with barium clouds. In section II we present the general theory, with subsections dwelling on linear and nonlinear bubble rise velocity models. Section III deals with the discussion and summary.

II. THEORY

The equations governing equatorial Spread F (within the context of the collisional Rayleigh-Taylor instability) are (see Scannapieco and Ossakow, 1976)

$$\frac{\partial n}{\partial t} + \nabla_{\perp} \cdot \left[\frac{nc}{B} \left(\frac{M}{e} \underline{g} \times \hat{b} - \nabla_{\perp} \psi \times \hat{b} \right) \right] = -v_R(n - n_0) \quad (1)$$

$$\nabla_{\perp} (v_{in} n \nabla_{\perp} \psi) = \frac{M}{e} \underline{g} \cdot \nabla_{\perp} (v_{in} n) + \frac{B}{c} (\underline{g} \times \hat{b}) \cdot \nabla_{\perp} n \quad (2)$$

where c is the speed of light, B the magnetic field (taken to be constant), e the electronic charge, M the mass of the ions, $\underline{g}$ acceleration of gravity, $\hat{b} = \underline{B}/|B|$ (pointing North), the subscript $\perp$ means perpendicular to $\hat{b}$ (Note: the geometry we will be employing for equatorial Spread F is such that x is upward, y is horizontal and eastward and z is northward and along the earth's magnetic field), v_R is the recombination rate, n the ion number density (or equivalently a field line integrated number density in a slab geometry), $E = -\nabla\psi$, where ψ is the electrostatic potential (in this model there is no ambient, i.e., zero order, horizontal electric field), v_{in} the ion-neutral collision

frequency (a function of altitude) and n_0 the equilibrium ionospheric electron (ion) number density.

If we neglect recombination effects, neglect the variation of v_{in} with altitude, and set $\psi = \phi_0 + \phi$ (where from (1) and (2) $\nabla \phi_0 = \frac{Mg}{e}$), then we have

$$\frac{\partial n}{\partial t} - \frac{c}{B} (\nabla_1 \phi \times \hat{b}) \cdot \nabla_1 n = 0 \quad (3)$$

$$\nabla_1 \cdot (n \nabla_1 \phi) = \frac{\Omega}{v_{in}} \frac{M}{e} \underline{g} \times \hat{b} \cdot \nabla_1 n \quad (4)$$

(Note: The same potential equation (4) can be obtained by keeping terms of $O(1)$ compared with v_{in}/Ω , where $\Omega = eB/Mc$, in eq. (2)). The simplest set of equations describing F region barium cloud morphology and striations (for a one level model and in the $\underline{E}_0 \times \underline{B}$ drift frame) is (see Perkins et al., 1973 and Zabusky et al., 1973)

$$\frac{\partial N}{\partial t} - \frac{c}{B} (\nabla_1 \phi \times \hat{b}) \cdot \nabla_1 N = 0 \quad (5)$$

$$\nabla_1 \cdot (N \nabla_1 \phi) = \underline{E}_0 \cdot \nabla_1 N \quad (6)$$

where $\underline{E}_0$ is taken to be the ambient electric field perpendicular to $\underline{B}$ ($\underline{E} \equiv \underline{E}_0 - \nabla_1 \phi$) and N is the magnetic field line integrated Pedersen

conductivity or equivalently the magnetic field line integrated plasma density. (Note: In these equations v_{in} is taken to be a constant and so represents a rotated geometry, i.e., the barium cloud equations are more applicable to high latitudes where $\underline{B}$ is vertical, ∇N and $\underline{E}_0$ are horizontal.) If gravitational effects were also included in (6) then $\underline{E}^* \equiv \underline{E}_0 + (\Omega/v_{in})(M/e) \underline{g} \times \hat{b}$ would replace $\underline{E}_0$ on the right hand side of (6) (see Perkins et al., 1973). The two sets of equations (3) and (4), and (5) and (6) are essentially the same with $(\Omega/v_{in})(M/e) \underline{g} \times \hat{b}$ playing the role of an electric field in the potential eg. (4) (recall also the definition of $\underline{E}^*$).

Let us now discuss some depletion and enhancement cloud morphology. The separate coupled sets of equations (3) and (4) and (5) and (6) have no steady state solutions if the cloud, as described by n or N , has a finite size (with the gradient of n or N finite) in two dimensions perpendicular (x,y) to the magnetic field (see Perkins et al., 1973 and Dungey, 1958). Another result concerns the initial deformation of a cylindrical plasma density or Pedersen conductivity enhancement (barium cloud) and a cylindrical plasma density or Pedersen conductivity depletion (equatorial Spread F bubbles or artificially created ionospheric holes). The situation is illustrated in Figure 1. Here in this context eq. (4) or (6) is simply the problem of cylindrical dielectric immersed in a uniform electric field (where in the equatorial Spread F situation $(\Omega/v_{in})(M/e) \underline{g} \times \hat{b}$ plays the role of an equivalent electric field). In the case (A) of the density enhancement (e.g., barium cloud) the induced

electric field is opposed to the uniform electric field, $\underline{E}_0$, so that $\underline{E}'$, the total electric field inside the enhancement is less than $\underline{E}_0$. In the case (B) of the density depletion (e.g., equatorial Spread F bubble or artificially created "hole") the induced electric field is in the direction of the uniform electric field, $\underline{E}_0$, so that $\underline{E}'$, the total electric field inside the depletion is greater than $\underline{E}_0$. (Note: the formulas for $\underline{E}'$ are approximate and specific models will be discussed later on in the text.) It should be pointed out that in Fig. 1a the circles representing the isodensity contours are such that the enhancement and depletion are maximum in the center and fall off as one moves away from the center. In this way the induced electric field goes to zero outside of the enhancement or depletion (Note: for the enhancement the induced electric field is $-\delta N \underline{E}_0 / (N_0 + \delta N)$, where N_0 is the ambient ionospheric density and δN is the enhanced density, while for the depletion the induced electric field is $\delta n \underline{E}_0 / (n_0 - \delta n)$ where δn is the magnitude of the depletion and n_0 is the ambient density). In case (A) the $\underline{E}' \times \underline{B}$ drift of the center of the enhancement counteracts the general $\underline{E}' \times \underline{B}$ drift and the center of the enhancement (cloud) has the slowest drift. The backside (side opposite to $\underline{E}_0 \times \underline{B}$ motion) of the enhancement catches up with the center and a steep density gradient forms there (depicted in Fig. 1b). Similarly, the frontside elongates. The area enclosed by any isodensity contour remains constant during the motion and the maximum value of $|N|$ is a constant of the motion (incompressibility).

In case (B), the $\underline{E}' \times \underline{B}$ drift of the center of the depletion (bubble) acts in concert with the general $\underline{E}' \times \underline{B}$ drift and the center of the

depletion has the fastest drift. The center now catches up to the front-side and a steep density gradient forms there (depicted in Fig. 1b). In this case the so-called backside (using barium cloud terminology) elongates. In the context of eq. (3) and (4) in Fig. 1, the area enclosed by any isodensity contour remains constant during the motion and the maximum value of $|n|$ is a constant (incompressibility). In both the enhancement and depletion cases the density piles up in the direction formed by the induced electric field crossed with the magnetic field. In both cases where these steep gradients form instabilities should be generated. In some sense the density depletion can be likened to an "antibarium cloud." Within the context of Fig. 1 we have spoken about depletions in general and the general results apply to natural Spread F bubbles or artificially created ionospheric holes (using H_2O , H_2 , or high explosives). Let us now specialize these results to equatorial Spread F bubbles. In this case, neglecting for the moment any horizontal ambient electric field, $\underline{E}_0$ in Fig. 1 is really $(\Omega M / ev_{in}) \underline{g} \times \hat{b}$ and it is the polarization (induced) electric field (in the direction of $\underline{E}'$ and equal to $(\Omega M / ev_{in}) (\delta n / (n_0 - \delta n)) \underline{g} \times \hat{b}$ which causes the bubble to rise with respect to the ionosphere via the local $\underline{E} \times \underline{B}$ convective drift motion. The picture exhibited in Fig. 1 for Spread F bubbles (using essentially eq. (4) which contains collisional Rayleigh-Taylor effects) shows that the bubbles spread more vertically than horizontally. This agrees with the radar observations [Woodman and La Hoz, 1976] and of course the numerical simulations [Scannapieco and Ossakow, 1976] which utilized eq. (1) and (2).

Linear Spread F Bubble Rise Velocity Model

Let us now look at Spread F bubble rise velocities for various bubble models. We will utilize eq. (4) and in our first case let us include a horizontal ambient electric field, $\underline{E}_0$, to show its effects. Then the equation becomes

$$\nabla_1 (n \nabla_1 \phi) = \underline{E}^* \cdot \nabla_1 n \quad (7)$$

$$\underline{E}^* \equiv \underline{E}_0 + \frac{\Omega}{v_{in}} \frac{M}{e} \underline{g} \times \hat{b}$$

Our first model will be a linearized model such that

$$n = n_0(x) + n_1 e^{i(ky - \omega t)} \quad (8)$$

$$\phi = \phi_1 e^{i(ky - \omega t)}$$

where $n_0(x)$ is the equilibrium altitude dependent density profile and subscript one refers to perturbed quantities. Substituting (8) into (7) and taking $\underline{E}_0$ to be in the y direction yields for the polarization potential

$$\phi_1 = -i \left(\frac{\Omega}{v_{in}} \frac{M}{e} \underline{g} + \underline{E}_0 \right) \frac{1}{k} \frac{n_1}{n_0} \quad (9)$$

The bubble velocity is

$$\underline{v}_B = \frac{c}{B} \underline{E} \times \hat{b} \quad (10)$$

In eq. (10) we use $\underline{E} = -\nabla\phi_1 = -ik\phi_1$ so that for the linear case $|v_B| = |cE/B| = |ck\phi_1/B|$ and we have for the vertical velocity ($\delta n \equiv n_1$)

$$v_B = \frac{\delta n}{n_0} \left(\frac{g}{v_{in}} + \frac{cE_0}{B} \right) \quad (11)$$

(Note: Here δn is positive and taken to mean the magnitude of the depletion.) It is interesting to note that adding $\underline{E}_0$ in the direction parallel (antiparallel) to $\underline{g} \times \hat{b}$ increases (decreases) the polarization field (as given by $-\nabla\phi_1$) and makes the bubbles rise faster (slower). The numerical simulations of Scannapieco and Ossakow [1976] did not have a horizontal electric field and adding one in the proper direction would make the bubble rise faster. However let us look at the effect of E_0 . We wish to compare the two terms inside the parenthesis of eq. (11). If we assume $E_0 \sim 1\text{mV/m}$, $B = 0.3$ gauss then $cE_0/B \sim 33$ m/sec. At 350 km altitude $g/v_{in} \sim 40$ m/sec, whereas at 450 km $g/v_{in} \sim 220$ m/sec. Thus we see that as one goes to higher altitudes E_0 makes a more negligible contribution to the bubble rise velocity. Indeed, even if the electric field reverses, once the bubble gets to higher altitudes (decreasing v_{in}) the bubble would keep rising. This bubble rising even after the electric field reverses has been seen experimentally [Kelley, private communication, 1976].

Neglecting E_0 in eq. (11) we have

$$V_B = \frac{g}{v_{in}} \frac{\delta n}{n_0} \quad (12)$$

Using Fig. 2 for v_{in} as a function of altitude, Fig. 3 depicts V_B as a function of altitude for various values of percentage depletions, $\delta n/n_0$ (large $\delta n/n_0$ represents usage of eq. (12) beyond the range of validity and perhaps represents a lower bound). Immediately it can be seen from this figure that large bubble velocities (~ 100 m/sec) requires large depletions and/or high altitudes.

Nonlinear Spread F Bubble Rise Velocity Model

In the case of a so-called sheet geometry in which we allow n and ϕ to be functions of y only, eq. (4) can be integrated once to yield

$$\frac{\partial \phi}{\partial y} = \left[1 - \frac{n_0}{n} \right] \frac{\Omega}{v_{in}} \frac{M}{e} g \quad (13)$$

where n_0 is the ambient density outside the bubble. For this case the dimension of the bubble in the vertical direction is extremely long compared with its horizontal dimension. Using eq. (13), the vertical bubble rise velocity now becomes

$$V_B = \frac{\frac{\delta n}{n_0}}{1 - \frac{\delta n}{n_0}} \frac{g}{v_{in}} \quad (14)$$

where we have used $\underline{V}_B = -\frac{c}{B} \frac{\partial \phi}{\partial y} \hat{y} \times \hat{b}$ and $n = n_0 - \delta n$ for a depletion. A peculiarity of this model is that $V_B \rightarrow \infty$ as $\delta n/n_0 \rightarrow 1$, i.e.; for a 100% depletion. Fig. 4 shows the bubble rise velocity as a function of altitude for various values of $\delta n/n_0$, using eq. (14) and values of v_{in} depicted in Fig. 2. Here, as in Fig. 3, high altitudes and/or large depletions yield high vertical bubble velocities.

As we have stated previously, eq. (3) and (4) in general do not admit of a two dimensional ($\perp \underline{B}$) solution. However, there is a pathological case where one can obtain exact solutions and we will discuss this now. We write for the density

$$n(x,y) = n_0 - n_D(x,y) \equiv n_0 \left[1 - \frac{\delta n}{n_0} F(x,y) \right] \quad (15)$$

where n_0 is the ambient ionospheric density, n_D represents the depletion or bubble ($\delta n/n_0$ is the magnitude of the ratio of maximum depleted density to ambient density), and F describes the shape of depletion. If $n_D(x,y) \rightarrow 0$ as $x,y \rightarrow \infty$ and $\nabla_{\perp} n$ is finite then there is no equilibrium solution to eq. (3) and (4). However, if the depletion density is a constant and the shape of the density depletion contour is an ellipse described by

$$n_D = \delta n H \left[1 - \left(\frac{x}{a} \right)^2 - \left(\frac{y}{b} \right)^2 \right]$$

[where $H(x)$ is the Heaviside step function and a and b represent the vertical dimension (axis of the ellipse) and horizontal (east-west)

dimension respectively], then the electric field inside the depletion is a constant and the depletion (bubble) moves with constant velocity without changing its shape. This method was first employed by Linson [1972] for barium clouds (plasma density enhancements) where eq. (5) and (6) were utilized. (Note: In this case the minus signs in eq. (15) would become plus signs.) Indeed, eq. (4) or (6) can be thought of as the case of a dielectric immersed in a uniform electric field. However, the plasma depletion is analogous to the case of a cavity immersed in a dielectric with a uniform field (since the field is enhanced inside a depletion). The solution of the potential eq. (4) or (6) for the general elliptical shape can be found in Smythe [1950]. For the case of a plasma depletion described by eq. (4), with $\underline{g} \times \hat{b}$ in the y direction, we have for the polarization (induced) electric field

$$-\frac{\partial \phi}{\partial y} = \frac{\Omega}{v_{in}} \frac{Mg}{e} \left(\frac{a \frac{\delta n}{n_o}}{b + a \left(1 - \frac{\delta n}{n_o} \right)} \right) \quad (16)$$

with the attendant bubble rise velocity given by

$$v_B = \frac{g}{v_{in}} \left(\frac{a \frac{\delta n}{n_o}}{b + a \left(1 - \frac{\delta n}{n_o} \right)} \right) \quad (17)$$

(Note: In arriving at eq. (16) we have assumed v_{in} to be a constant. This is a good approximation so long as the size of the depletion is small compared with an atmospheric scale height).

Now we will examine eq. (17) with respect to different shapes. For the case $b \ll a$, i.e., the sheet geometry, we obtain

$$V_B = \frac{g}{v_{in}} \frac{\frac{\delta n}{n_0}}{1 - \frac{\delta n}{n_0}}$$

which is eq. (14) as it should be. For $a/b \rightarrow 0$, i.e., a slab case (uniform in the direction of $\underline{g} \times \hat{b}$), $V_B \rightarrow 0$ since the induced electric field goes to zero. When $a = b$ (cylindrical case), we have

$$V_B = \frac{\frac{\delta n}{n_0}}{2 - \frac{\delta n}{n_0}} \frac{g}{v_{in}} \quad (18)$$

For $\delta n/n_0 \ll 1$ eq. (18) yields $V_B = 1/2 (g/v_{in})(\delta n/n_0)$ which is half the value given by the linear perturbation model (see eq. (12)). With $\delta n/n_0 = 1$ (100% depletion), eq. (18) yields $V_B = g/v_{in}$. Fig. 5 shows the vertical bubble rise velocity for a cylindrical shape (as given by eq. (18)) and Fig. 6 exhibits the bubble rise velocity for an elliptical shape ($a/b = 5$) as a function of altitude for various values of $\delta n/n_0$, using values of v_{in} depicted in Fig. 2.

III. DISCUSSION AND SUMMARY

Figures 3-6 depict vertical bubble (plasma depletion) rise velocities for various bubble models (shapes), for equatorial Spread F geometry, as a function of altitude and percentage depletions. Exceedingly high velocities can be attained, especially for the severely elongated models (e.g., sheet model in Fig. 4 and the elliptical model with a 5:1 axial ratio in Fig. 6). Table 1 shows the bubble rise velocity, in units of g/v_{in} , as a function of fractional depleted plasma density for various bubble shapes. For all values of $\delta n/n_0$ (except at 1.0) the non-linear cylindrical model gives a smaller velocity (see also eqs. (12) and (18)) than the linear model. The table also shows that the cylindrical bubble velocity for a given $\delta n/n_0$ is attained by the sheet model for a value of $1/2 \delta n/n_0$ (see also eqs. (14) and (18)). An elliptical model with 10:1 axial ratio is also shown in Table 1. Except for $\delta n/n_0 = 1$, it has already become fairly sheet-like. A common feature to all models is that the higher the altitude and/or the higher the density depletion, the higher the vertical rise velocity. This result is consistent with the recent satellite in situ measurements described by McClure et al. [1977].

The models described by Fig. 3-6 essentially assume that the bubble does not change its shape. For real bubbles, where the depletion density changes inside the bubble, the bubble should elongate in the vertical direction (steepening on the topside of the bubble) and become narrower in the east-west extent. This is in agreement with the radar

observations (Woodman and La Hoz, 1976) and the numerical simulation of rising equatorial Spread F bubbles (Scannapieco and Ossakow, 1976). Therefore, in modeling a changing bubble by one of constant shape we are employing somewhat of an artifact. However, using this technique Linson [1972] has shown (using optical data) that evolving barium clouds (plasma density enhancements) tend to be more cylindrical than sheet-like. Using the constant shape approach and the simulation results of Scannapieco and Ossakow [1976], where $V_B \sim 10$ m/sec and $\delta n/n_0 \sim 40\%$ for an altitude of 350 km, the cylindrical bubble shape is favored (although the simulation pictures show an elongated bubble). More data and simulation results are needed to ascertain which model fits best.

All of the models described in this paper, based on collisional Rayleigh-Taylor type equations, show that the vertical bubble rise velocity is of the form

$$V_B = \frac{g}{v_{in}} f\left(\frac{\delta n}{n_0}\right) \quad (19)$$

where $f(\delta n/n_0)$ is some function of $\delta n/n_0$. The factor g/v_{in} should not be too surprising since the growth rate (γ) for the collisional Rayleigh-Taylor instability, neglecting recombination effects, is $g/v_{in} L$ (Hudson and Kennel, 1975; Scannapieco and Ossakow, 1976), which is a velocity divided by the electron density gradient scale length. This of course is similar to the growth rate ($\gamma = cE_0/BL$) for barium cloud striations

due to $\underline{E}_0 \times \underline{B}$ gradient drift instability (Simon, 1963; Linson and Workman, 1970). This similarity between the gravitational and the electric field terms has been shown in eq. (11). In eq. (19), the factor g/v_{in} favors high altitude because v_{in} decreases as a function of altitude (see Fig. 2). The factor f increases with increasing $\delta n/n_0$ (see Fig. 3-6). At least according to linear theory, $\delta n/n_0$ increases with altitude and decreasing bottomside electron density gradient scale length ($\gamma = g/v_{in} L$). These ideas indicate that there is a range of bubble vertical rise velocities (in accord with McClure et al., [1977]), but these rise velocities depend on ambient equatorial F region ionospheric conditions (e.g., height of the F peak and bottomside gradient scale length). Recent numerical simulations (S. Ossakow, S. Zalesak and B. E. McDonald, private communication, 1977) support these ideas. Also, it should be pointed out that for $\delta n/n_0 = 0$, i.e., for bubbles which have the same density as the background ionosphere, the induced (polarization) electric field (which causes the bubble to rise through $\underline{E} \times \underline{B}$) becomes zero (with all models, as it should), as does the attendant vertical bubble rise velocity. This simply states that a bubble created on the bottomside of the F region will rise until its density equals the topside background ionospheric density.

It should be pointed out that our vertical velocity result for cylindrical bubbles does not agree with Ott's [1977] result. In his analogy with bubbles in a fluid, Ott found only a cylindrical solution. For the collision dominated regime he found $V_B = 1/2(g/v_{in})(\delta n/n_0)$, in

our terminology; whereas, our result shows $V_B = 1/2(g/v_{in})(\delta n/n_0) \cdot (1 - 1/2(\delta n/n_0))^{-1}$. For the case where the bubble density is negligibly small ($\delta n/n_0 \approx 1$) compared with the density in the ionosphere outside, Ott's result yields $V_B = 1/2(g/v_{in})$; whereas, our result yields $V_B = g/v_{in}$.

Finally some comments about the various upward and westward bubble velocities presented by McClure et al. [1977] and the tilts of the plumes seen by the Jicamarca radar measurements (Woodman and La Hoz, 1976). Equations (1) and (2), used by Scannapieco and Ossakow [1976], or eqs. (3) and (4) for that matter produce only vertical bubble rise. These equations only admit of a horizontal polarization electric field (eastward) caused by the $\underline{g} \times \hat{b}$ term such that depletions rise and enhancements fall with respect to the ionosphere. Inclusion of an ambient background horizontal electric field (eastward or westward) in the equations could only cause additional vertical (upward or downward) motion of the bubbles. Since the ionosphere moves mainly downward at night (westward electric field; see McClure et al., 1977) this could slow down the bubbles at low altitudes and have a negligible effect at higher altitudes (see eq. (11)). Vertically the bubbles move more slowly at lower altitudes and/or small values of $\delta n/n_0$. Thus there exist conditions whereby the bubbles do not move vertically with respect to the ionosphere. McClure et al. [1977] and Woodman and La Hoz [1976] have stated that the ionosphere moves mainly eastward at night. This would mean an ambient electric field pointing downward. Inclusion of such an

electric field in the equations would cause bubbles to move eastward. Thus the westward motion of the bubbles must be caused by introducing an asymmetry into the eq. (1) and (2) (or (3) and (4)) which causes a vertical (upward) electric field. Such an effect can be produced by an eastward directed neutral wind which would essentially polarize the bubble to produce an upward polarization electric field and account for the westward motion of the bubble (and tilts of the radar plumes). This last idea has also been set forth by Woodman and La Hoz [1976] and Ott [1977].

Recalling our discussion about the electric field, $E^* \equiv E_0 + (\Omega/v_{in}) \cdot (M/e) \underline{g} \times \hat{b}$, after eq. (6), all of our vertical bubble rise velocities can take account of horizontal motions. The general bubble velocity is then just $\underline{v}_B = (c/B) \underline{E}^* \times \hat{b} f(\delta n/n_0) = ((c/B) \underline{E}_0 \times \hat{b} - \underline{g}/v_{in}) f(\delta n/n_0)$. This clearly shows how the directionality of $\underline{v}_B$ is formed. In this case for the elliptical shape a is in the direction of $\underline{E}^* \times \hat{b}$, etc. and non-constant density depletions will steepen and elongate in this direction.

Recent results from the Wideband associated equatorial experiments performed at Kwajalein (August 1977) lend credence to this notion (S. Ossakow and J. Clark, private communication, 1977). Backscatter irregularity (~ 1 meter) measurements (performed by D. Towle) have shown that these patches rise and appear westward when neutral wind measurements (Fabry-Perot interferometer measurements performed by M. Biondi and D. Sipler) show strong west to east winds (~ 160 m/sec) earlier in the evening. As the evening progresses the neutral winds die down (~ 10 - 20 m/sec) and the radar shows the irregularities appearing eastward.

IV. ACKNOWLEDGMENT

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Table 1. Bubble rise velocity (in units of g/v_{in}), V_B' , as a function of fractional depleted density, $\delta n/n_0$, for various bubble shapes.

V_B' \ $\frac{\delta n}{n_0}$	.25	.5	.75	.9	1
Linear	.25	.5	.75	.9	1
Sheet	.33	1	3	9	∞
Cylindrical	.14	.33	.6	.82	1
Elliptical (5:1)	.26	.71	1.67	3	5
Elliptical (10:1)	.29	.83	2.14	4.5	10

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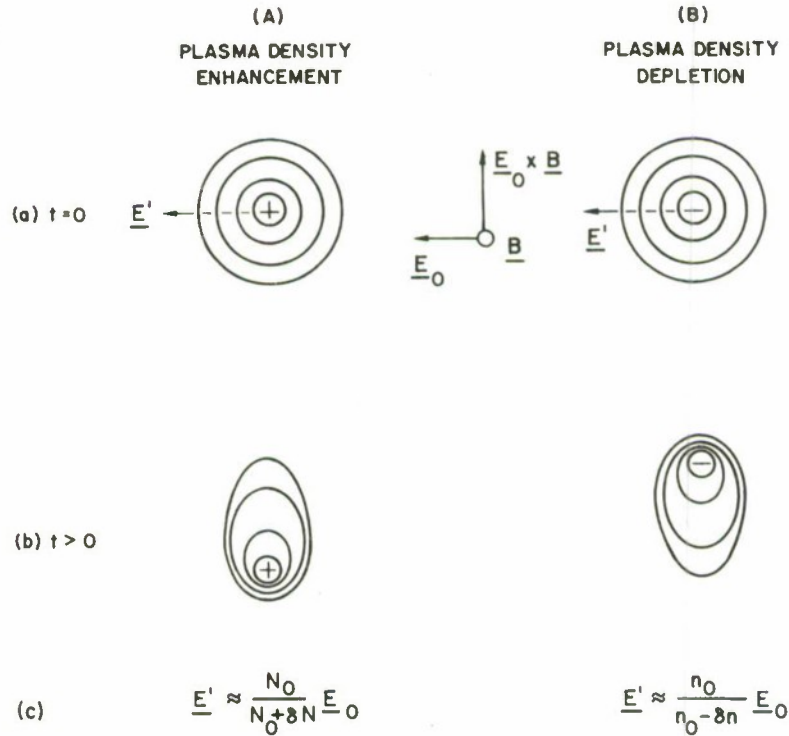


Fig. 1 — Deformation of (A) a plasma density enhancement (e.g., a barium cloud) and (B) a plasma density depletion (e.g., equatorial Spread F bubble or artificially created “hole”) in crossed electric ($\underline{E}_0$) and magnetic ($\underline{B}$) fields (representative of equatorial geometry). (a) Initial ($t=0$) cylindrical isodensity contours with largest enhancement (+) and depletion (-) values in the center and falling off away from these values to an ambient level n_0 outside. $\underline{E}'$ represents the total electric field inside the enhancement or depletion and $\underline{E}_0$ is the ambient field outside. (b) Qualitative evolution of the isodensity contours. (c) Approximate values for the initial electric field ($\underline{E}'$) inside the enhancement or depletion.

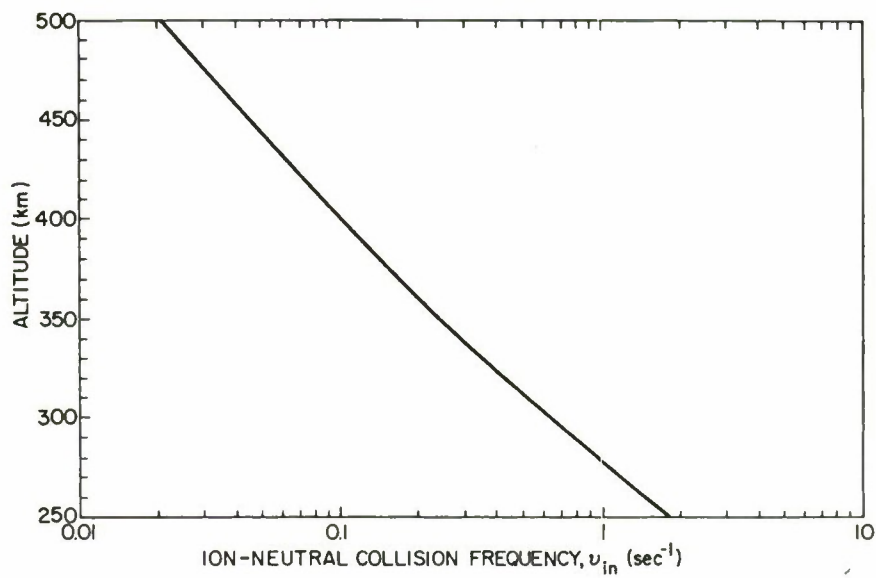


Fig. 2 — Ion-neutral collision frequency, ν_{in} , as a function of altitude

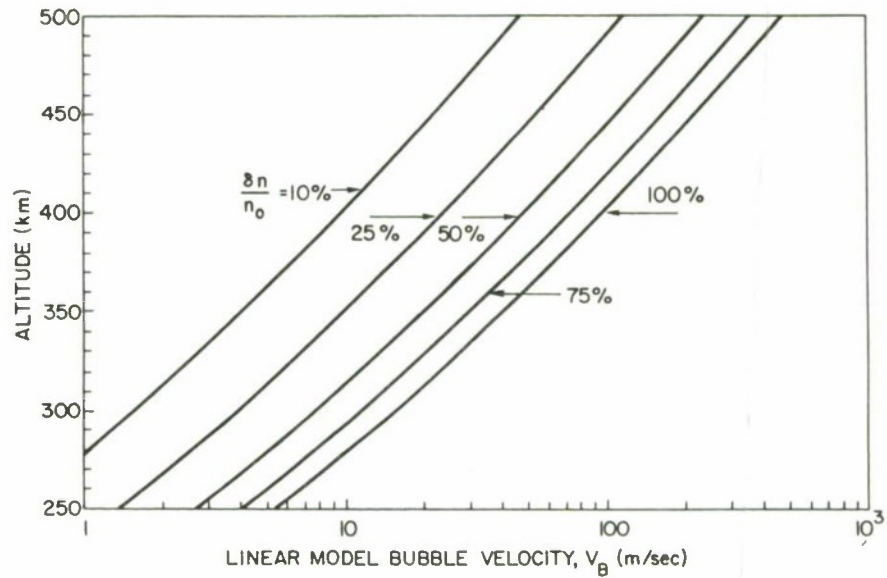


Fig. 3 — Depletion (bubble) vertical rise velocity, V_B , as a function of altitude for various values of the percentage depletion, $\delta n/n_0$, for the linear bubble model, i.e., $V_B = (g/v_{in})(\delta n/n_0)$

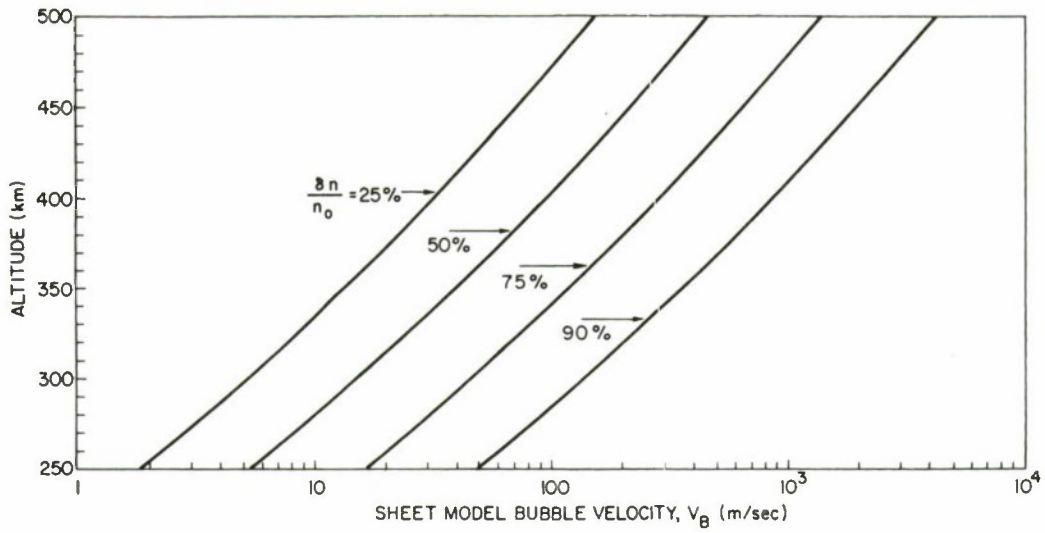


Fig. 4 — Same as fig. 3, but for the nonlinear sheet bubble model, i.e., $V_B = (g/v_{in})(\delta n/n_0)(1-\delta n/n_0)^{-1}$

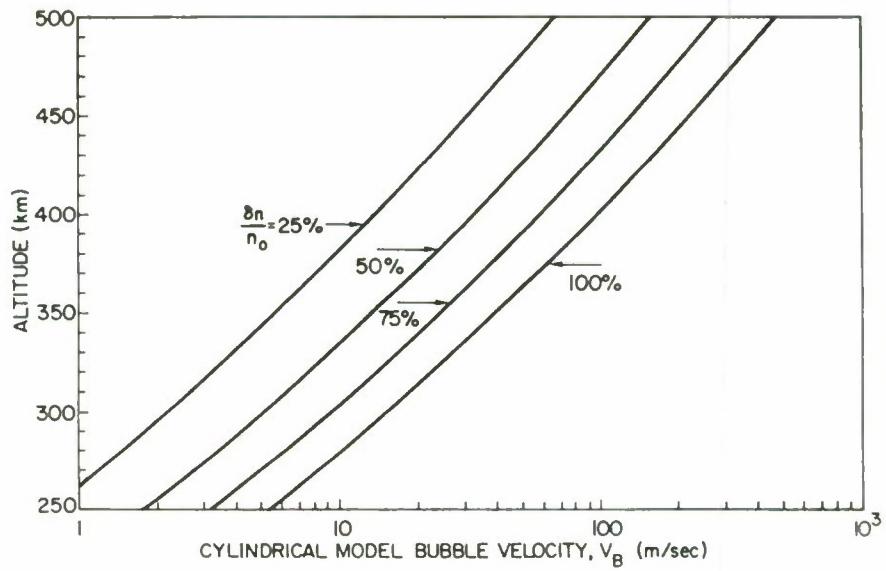


Fig. 5 — Same as fig. 3, but for the nonlinear cylindrical bubble model, i.e., $V_B = (g/v_{in})(\delta n/n_0)(2-\delta n/n_0)^{-1}$

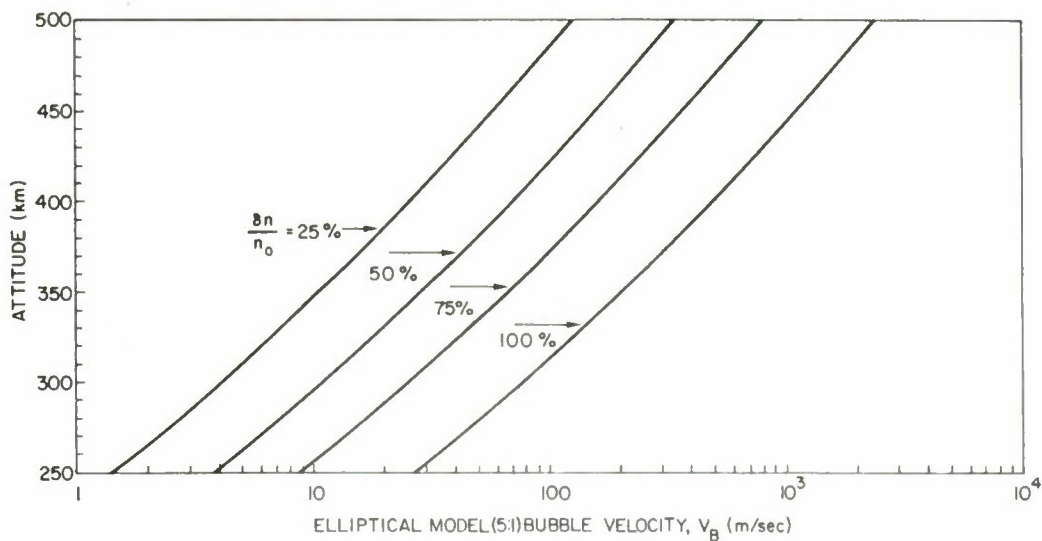


Fig. 6 — Same as fig. 3, but for the nonlinear elliptical bubble model (with the vertical dimension five times the horizontal dimension), i.e., $V_B = (g/v_{in})(5 \delta n/n_o)(6-5 \delta n/n_o)^{-1}$

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