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Double Layers, Waves and Particle Acceleration

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Abstract

Our conclusions that static potential differences, including those associated with double layers, could not be the cause of auroral electron acceleration, and that resonance with electrostatic wave turbulence provided a possible mechanism were dismissed in a recent publication as being totally incorrect. In this reply we find the criticism to be built upon a number of misconceptions and factual errors which render it invalid. We are, therefore, able to re-affirm our earlier conclusions.

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I INTRODUCTION

Gedalin and Peter [1] claim that our paper [2] showing why we are unable to reconcile the long-held contention that electrostatic double layers are particle accelerators contained a fallacy. Curiously, though, they neither attempt to justify the claim nor do they indicate the nature of the alleged fallacy. The claim appears to be based on a blanket acceptance of a paper by Borovsky [3]. However Borovsky's paper fails to recognize the significance of the conservative nature of potential fields, and contains seriously misleading factual errors [4]. These errors are further promulgated by Gedalin and Peter who go on to criticize what can only be described as a gross misrepresentation of the wavepacket model [5] of the wave theory of auroral electron acceleration.

II DOUBLE LAYERS

We begin with a definition of the main feature under discussion. A double layer comprises two equal but oppositely charged, essentially parallel but not necessarily plane, space charge layers [6]. A double layer may also be seen as a surface covered with dipoles (in the present context, electric) each having its axis in the direction of the normal to the surface [7]. While discussing the frequency invoked potential differences associated with double layers we may safely exclude non-essential additional attributes such as the wave activity that can accompany double-layers in plasmas. We return, though, to this important

aspect later. Note that a double layer *per se* does not include source of particles such as hot filaments or a background of ionizing radiation and a supply of neutral particles.

It follows from Poisson's equation that *in vacuo* the electrostatic potential of a double layer (with or without the above non-essential attributes) at distances large compared with the dimensions of the layer the potential falls off as the inverse square of distance from the layer. In a plasma it falls off faster, within a few Debye lengths. A finite double layer introduces, therefore, only a localized variation of potential, as illustrated in Figure 1. It follows that the net potential difference between any two points remote from the layer is zero, the line integral of the internal field being exactly balanced by the line integral of the weaker but correspondingly more extensive external field. Concepts which require the external field to vanish or which ignore it altogether are inconsistent with Poisson's equation and therefore non physical. Note that a one-dimensional treatment is totally misleading in this vital respect, since here the external field vanishes only because of the double layer's implicit infinite, and therefore non-physical, lateral extent. This often-used treatment is equivalent, therefore, to an analysis of just the central section of Figurel, the disastrously misleading consequences of which are illustrated by Figure 2.

Being essentially localized entities basic double layers, ie ones meeting the definition above, cannot cause net changes in the kinetic, potential or total energy of particles traversing their sphere of influence. They cannon, therefore, be described as particle accelerators in any sense. This will be recognized as a particular example of the general

conservative nature of central forces. This is not to argue, of course, that double layers cannot exist within accelerators or that they cannot form component of accelerators. An example of the former, and to which Gedalin and Peter refer, is a double layer in a discharge tube. Here, acceleration of charged particles moving between the electrodes may well take place primarily within a double layer, if present and of suitably large magnitude, but retardation by its external fields will ensure that the overall effect of the layer is zero. The energy gained is determined simply by the potential difference between the electrodes and is the same whether a (basic) double layer is present or not. Wave activity, which having the vital non-conservative element of time-varying electric fields and which is well known to produce particle acceleration may operate as well within double layers as anywhere else, but such acceleration is then determined by the wave properties, not by the double layer of space charge. Gedalin and Peter specifically exclude this possibility when they describe auroral electron acceleration as a bulk process not relying on resonant coupling between waves and particles. A combination of a double layer and an internal charged-particle source can, of course, constitute an accelerator, but this has not yet, to our knowledge, been invoked for the fully ionized plasma of the auroral acceleration region.

III STATIC ELECTRIC FIELDS

Gedalin and Peter state, as does Borovsky [3], apparently as circumstantial evidence

for potential-difference acceleration, that significant (multi-kV) potential differences have been measured along magnetic field lines. It is clear from the conservative nature of static fields that even if the statement were true these potential differences would be irrelevant to particle acceleration (particles would lose as much kinetic energy in ascending potential barriers as they would gain on re-emerging). The statement, though, is not only irrelevant, it is incorrect. Actual measurements of such potential differences would require probes of dimensions comparable to those of the acceleration region some 10,000km in extent. Measurements are restricted to assessments of potential gradients over distances of the order of a few tens of metres at most. Linear extrapolations over more than five orders of magnitude can hardly be described as a measurement. When the difficulties of measuring relatively weak fields parallel to the local magnetic vector are taken into account, and it is realized that the characteristically fluctuating nature of the acceleration region field argues against the assumption of any degree of uniformity, it is clear that the statement is seriously misleading.

IV ACCELERATION BY WAVES

In their criticism of the wavepacket model of auroral electron acceleration Gedalin and Peter misrepresent the model so seriously that the criticism does not apply to the model itself. In an attempt to clear up any misunderstanding that there may be we briefly summarize the model and contrast its real properties with the alleged ones.

In the model in question [5] electrostatic wave turbulence is represented by an assembly of discrete wavepackets. The wavepackets serve as moving potential barriers to charged particles. Particles with velocities not too dissimilar to the phase velocity within a wavepacket (ie resonant particles) have their velocities reflected in the wave frame, as Newton's third law requires for elastic collisions. Resonant particles gain energy and momentum in a frame in which they are seen to be overtaken by a wavepacket. Energy and momentum flow the other way if the particle overtakes the wave. The process is dynamically equivalent to second-order Fermi acceleration and, indeed, to the sport of ocean surfing, to which acceleration by waves in plasmas is often likened. Particles moving much faster or much more slowly than the phase velocity lead to a randomization of velocities of some resonant particles. This introduces and element of heating in addition to the systematic interaction just described. The characteristics of this stylized interaction, as illustrated in figure 1, are remarkably similar to those obtained by detailed numerical simulation [7].

The effect of velocity reflection on an initially steeply falling particle velocity distribution is to cause a migration of the large numbers of particles at the lower limit of resonance to higher velocities where they create a peak. At first, far fewer particle migrate in the opposite direction since there are fewer to start with at higher velocities. If the process were to continue indefinitely a broad plateau would be produced throughout the resonant velocity range. the precess may thus be seen as large-amplitude Landau damping. If it

does indeed occur in the auroral acceleration region it could be seen as a natural enactment of current drive in tokomaks in the laboratory, even to the extent of the same waves, lower-hybrid waves, being involved.

Gedalin and Peter have incorrectly represented this model in a number of ways. Energy transfer does not require a difference between phase and group velocities. In fact, the precess is at its most effective when there is no dispersion. The wavepacket concept is not an assumption. It is inevitable that incoherent wavelets will combine in beats of wavepackets. The phenomenon known as 'wave collapse', by which the volume occupied by wavepackets shrinks and the waves grow in amplitude [9] gives further cause to treat electrostatic turbulence as discrete wavepackets. Wavepackets need not remain coherent indefinitely. To be effective a wavepacket needs to last only for the duration of a single interaction.

Gedalin and Peter liken wavepackets to double layers. There is indeed a generic link. A wavepacket may be seen as a travelling multiple double layer whose velocity, not the (zero) net potential difference, holds the key to their accelerating ability. Static (relative to keV-electron velocities) double layers by the same token may be seen as degenerate, ineffectual wavepackets.

It could not be further from the truth to suggest, as Gedalin and Peter do, that the unique properties of acceleration by wave particle interactions seem to rule these

mechanisms out in the auroral region. The facts are that all approaches to the problem, whether they be stylized stochastic as in the wavepacket model [5], deterministic [10], or particle-in-cell simulation [11], lead to undeniably realistic results, in particular, the part played by resonance, which the criticism dismisses for the aurora, appears to be exhibited very clearly in the relative invariance of the low velocity region of the auroral electron distribution.

V CONCLUSIONS

No "fallacy" has so far been revealed in the conclusion that double layers *per se* are not particle accelerators. This conclusion follows directly from Poisson's equation and is simply a particular manifestation of the conservative nature of central forces. No shortcoming has been identified in the wave theory of auroral electron acceleration or in its wavepacket model. To this extent the theory provides a viable explanation of the phenomenon. If it is indeed correct, the aurora may be understood as a spectacular natural demonstration of the process of current drive employed to great effect in tokamaks in the laboratory. Mutually beneficial exchanges of experience and ideas between the space and laboratory areas of plasma physics become therefore, a real and very promising option.

VI REFERENCES

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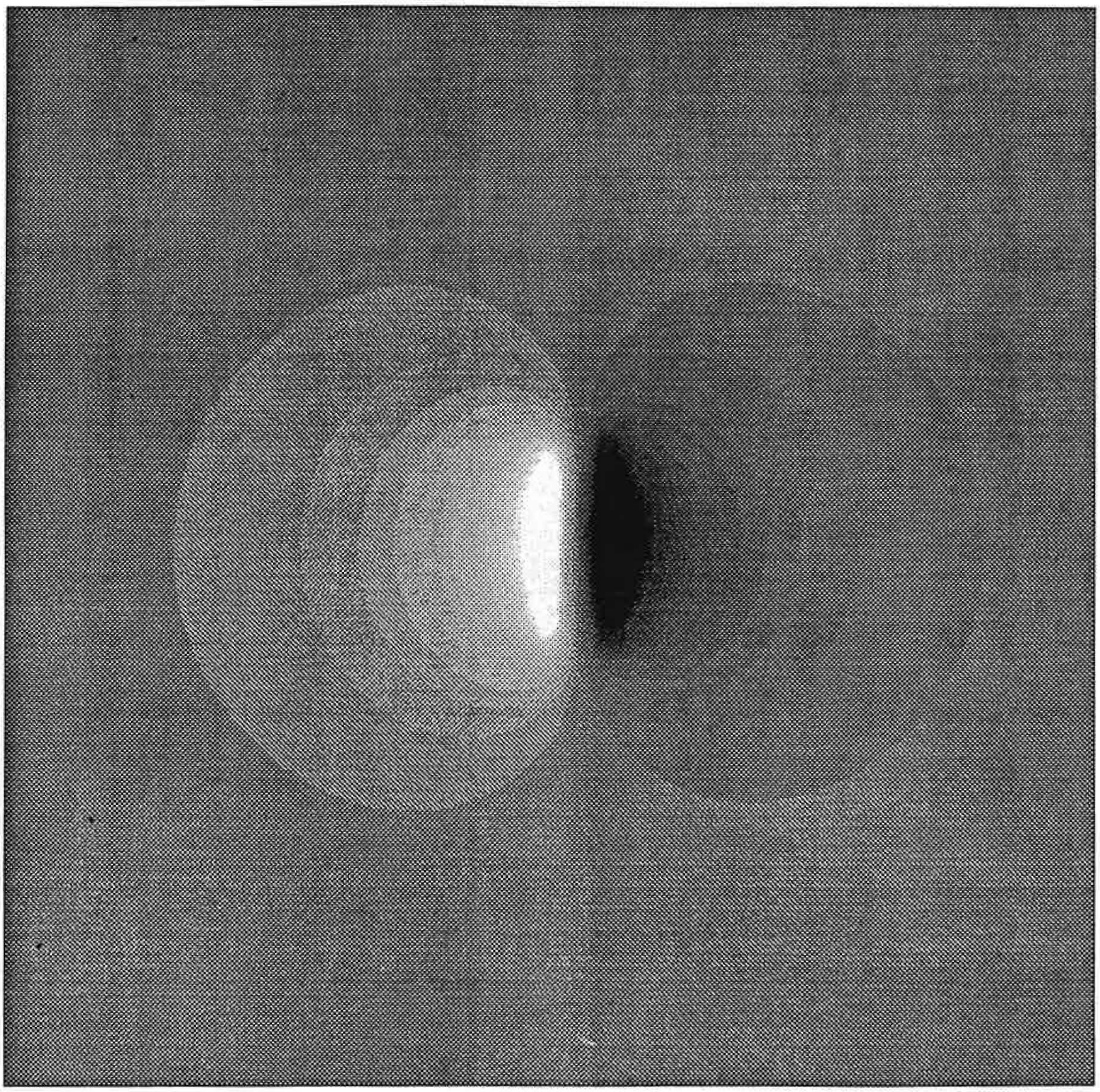

Figure 1: Electrostatic potential distribution of a double layer composed of positive and negative disks of space charge. Potentials are shown on a linear grey scale in a plane containing the axis of rotational symmetry which is horizontal and central. The positive and negative disks appear as black and white. The purely localized nature of the perturbation from the mean (mid grey) is evident.

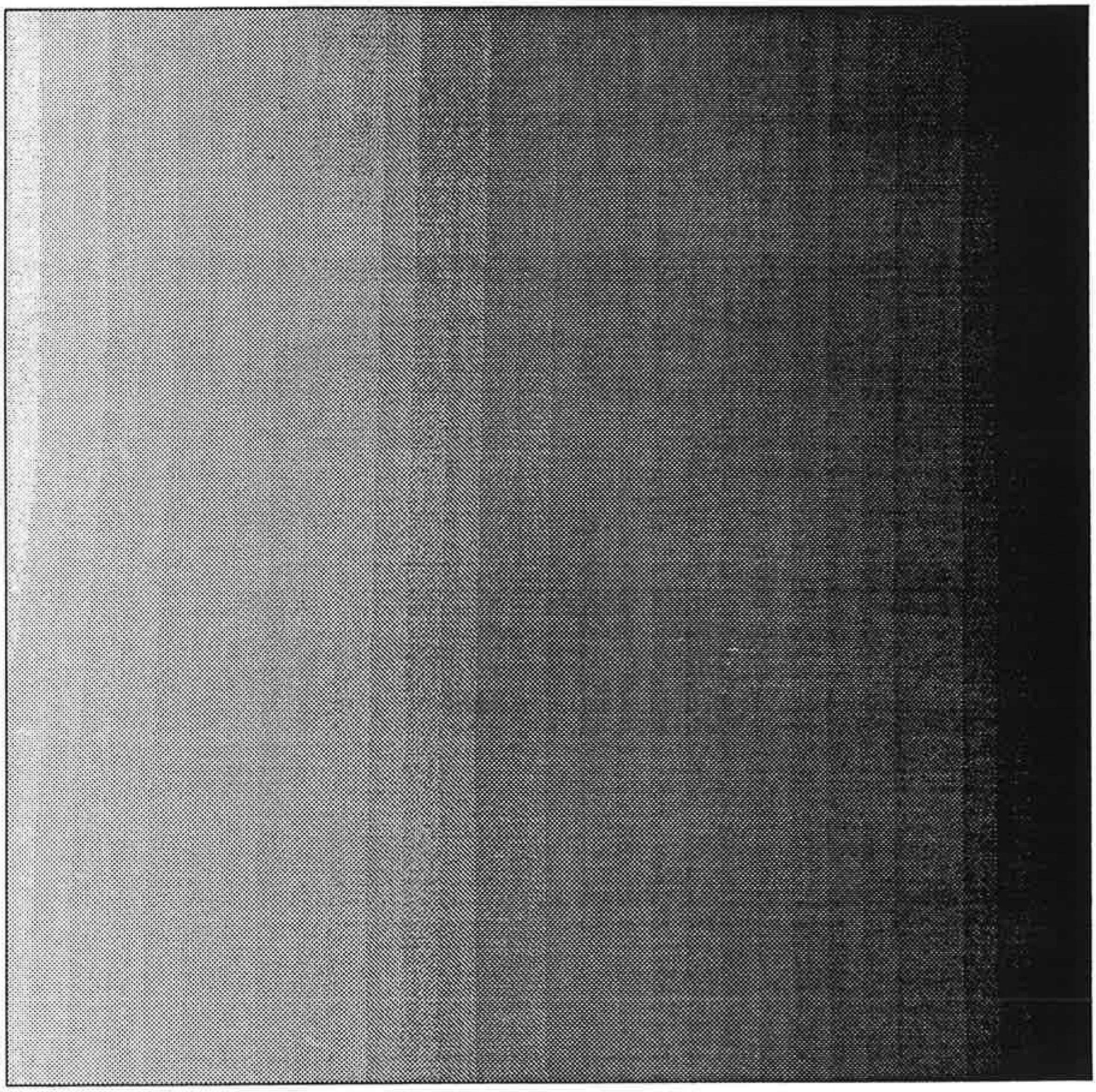

Figure 2: The central region only of figure 1, equivalent to a one-dimensional analysis in which the external field is neglected, giving a false impression of a net potential difference across the layer.

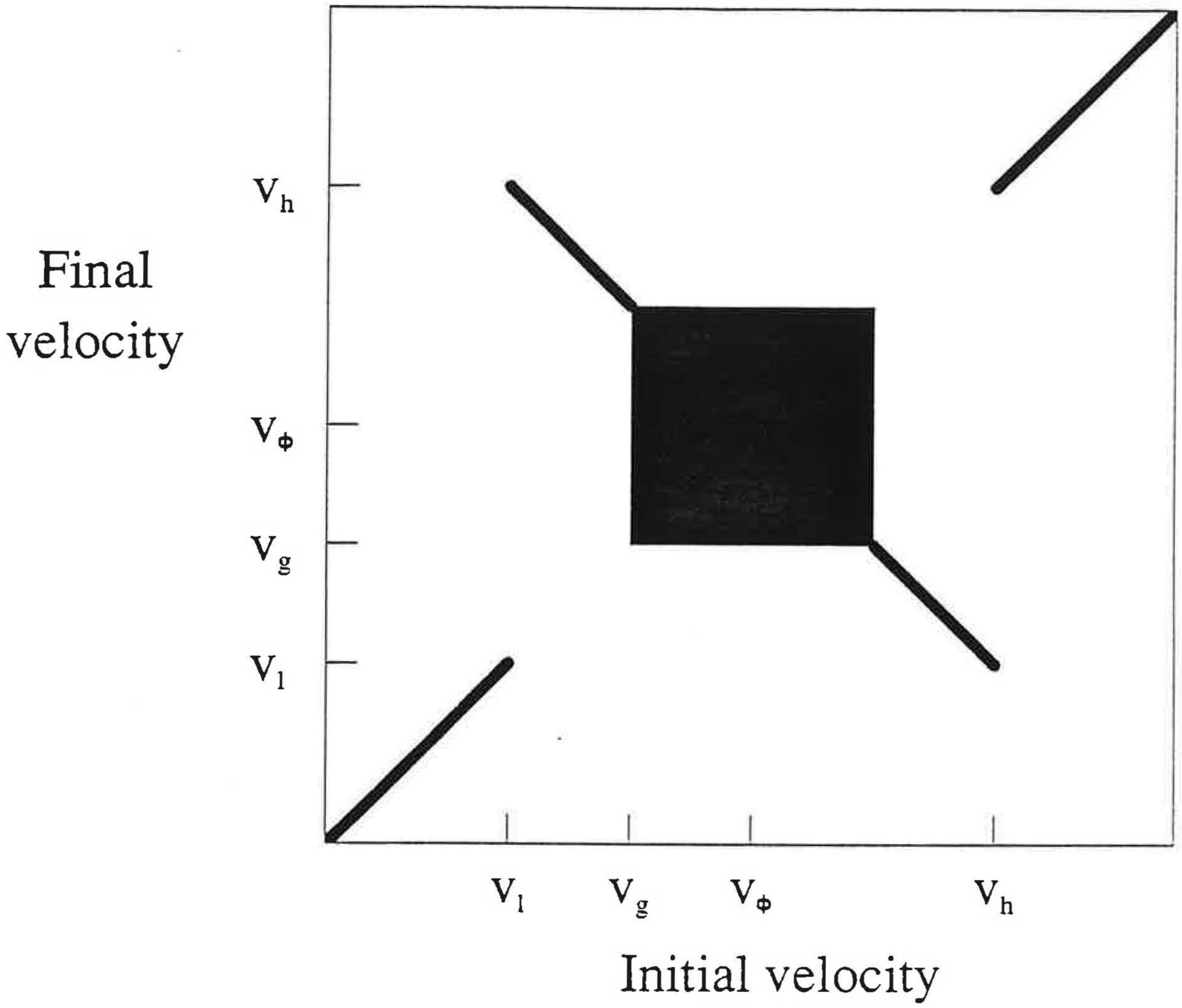

Figure 3: Relation between initial and final velocities, v_i and v_f for an interaction with a wavepacket of central phase and group velocities v_ϕ and v_g and maximum potential Φ. There is a net change of velocity only for $v_1 < v_i < v_h$, where $v_1 = v_\phi - \sqrt{2e\Phi/m}$ and $v_h = v_\phi + \sqrt{2e\Phi/m}$. When $|v_i - v_\phi| > v_\phi - v_g, v_f$ is a reflection of v_i about v_ϕ, as indicated by the negative diagonal lines. When resonance is very close, v_f lies in the range v_g to $2v_\phi - v_g$, as indicated by the central shaded area, its value within this range depending upon phase during the encounter.