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Problems with Double Layers as Particle Accelerators

D A Bryant R Bingham and U de Angelis

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D A Bryant, R Bingham, and U de Angelis[(a)]

Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, United Kingdom OX11 0QX

Abstract

It is pointed out that the continuing advocacy of electrostatic double layers as particle accelerators in the aurora and other space and astrophysical plasmas is fundamentally unsound. It is suggested furthermore that there is little reason to invoke static or quasi-static electric fields as the cause of auroral electron acceleration. Stochastic acceleration by wave turbulence appears to present a natural explanation for electron acceleration in collisionless plasmas in general. This report is an expanded version of a recent paper [1] on this subject, taking into account subsequent comments and discussions held at the present meeting and elsewhere.

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INTRODUCTION

Double layers — "two equal but oppositely charged, essentially parallel but not necessarily plane, space charge layers"[2] — have long been advocated[3] as accelerators for charged particles in the aurora[4], solar flares[5] and, by implication, other space and astrophysical plasmas. We wish to point out, however, that double layers (at least, as so defined) cannot, in fact, serve as particle accelerators, in the sense of providing energy, since the electric fields associated with any static configuration of space charge are conservative. Furthermore, since the line integral of the electric field outside such a double layer exactly balances the line integral inside, (equipotential contours being closed surfaces) it cannot even promote a net (ie more than a temporary and local) exchange of potential and kinetic energy, and is thus not an accelerator in this limited sense either.

The Tower of Pisa, invoked by adherents of acceleration by potential differences, can be considered an accelerator for stones falling from its top only if we are not interested in how the stones ascended the Tower in the first place. But if we start with all the stones on the ground our problem is to explain how some of them were raised to the top, before we can consider the Tower of Pisa combined with a lifting mechanism (perhaps even Galileo himself) as an accelerator. After all, Isaac Newton's apple wasn't accelerated by the tree! It should be stressed here that the term "particle acceleration" is used as a synonym of "particle energization" in the literature on plasmas[6] and in the context of high-energy particle acceleration in general. Nothing is learned, to employ another example, if the kinetic energy at the mid point of the swing of a pendulum is attributed simply to the potential energy at the extrema, when we wish to know what set the pendulum swinging.

Any model advocating potential differences (arising from double layers or any other source) to explain the measured kinetic energies of auroral particles must, therefore, solve the real problem of particle energization; or, if the model restricts itself just to the exchange of potential for kinetic energy, it should not be claimed to be an explanation of the aurora.

ORIGIN OF POTENTIAL-DIFFERENCE THEORY

Let us attempt to trace the steps by which the belief summarized in the opening sentences, so at variance with basic physics, appears to have arisen and why it continues to be promulgated, as the solution to the problem, fifty years after the "serious energy difficulty"[7] with this type of theory was pointed out. The pioneering observation was that the electrons responsible for producing a bright active auroral arc were concentrated within such a narrow band of energies that they were termed "monoenergetic"[8]. Since, at that time, acceleration processes of a statistical nature were thought to be incapable of generating a peak in a distribution function, an acceleration process involving (static) electric fields seemed to be the only possibility. However, measurements from higher flying rockets with more advanced detectors were able to demonstrate that velocity-space densities of the electron streams responsible for auroral arcs and other forms of discrete aurorae rise again towards low energies[9], making the original description of the distribution no longer apt. The term continues to be used in some quarters to describe the peak alone, though this is inappropriate, even misleading, when the peak-to-valley velocity-space-density ratio is typically of order 2 only[10], and there is commonly as much as a factor of 2 in velocity between the peak and the valley on the low-velocity flank. On occasions there is only a plateau or even just an inflexion (note that the earliest examples of "monoenergetic" distributions[11], when translated from count rate to velocity-space density were actually of this last type). The prime reason for seeking a process that could create a monoenergetic distribution has, therefore, long disappeared.

Most of the current literature advocating double layers in the aurora seems to concentrate on the trivial role of these structures to transform energy from potential to kinetic, whereas a prerequisite for any interpretation of particle acceleration by double layers, or any other quasi-static potential structure, is a quantitative model for a "dynamo" or "generator" that is also consistent with observations. This aspect of the problem is clearly recognized[12], and a model for an magnetohydrodynamic dynamo has recently been presented[13], but it is only barely sketched, and exhibits a number of inconsistencies[14].

PROBLEMS WITH THE POTENTIAL-DIFFERENCE THEORY

Conflict with Observations

Despite these developments many observations have been, and continue to be, put forward as revealing, directly or indirectly, the presence of static or quasi-static (relative to particle transit time) electric fields, both parallel and perpendicular to the local magnetic field. In the absence of information to the contrary, we understand that these fields should be treated as naturally occurring and not spacecraft induced. It is clear, incidentally, from the tens-of-minutes durations of moderate and active aurora[15] — a class including auroral arcs, from the lack of periodic oscillations or reversals in the acceleration process, and from the relative stability of the magnetic field, that induction can be neglected, at least as a primary agent. What evidence there is for a significant potential difference is at best highly equivocal, with a wide range of ad hoc assumptions being necessary to account for individual discrepancies. Taken together these create a substantial catalogue of evidence against the hypothesis[16]. Among the more telling are (i) a significant difference between the energies gained by electrons and positive ions travelling in opposite directions through the acceleration region[17], (ii) the frequent occurrence of counterstreaming electrons[18], and simultaneously upward flowing electrons and positive ions[19], (iii) a factor of up to 5 between energies gained by upward flowing ions of different mass (H^+ and O^+) though carrying the same charge[20], (iv) a lack of association between the behaviour of Ba^+ ions introduced, in active experiments, into the acceleration region and the aurora directly below[16].

The claim[21] that the characteristic kinetic energy is found to be equal to the potential difference obtained from electric field measurements has no foundation whatsoever, since the measured electric fields relate, in the model used, to potential differences *below* the spacecraft, and the observed electron distributions, in the same model, to potential differences *above* the spacecraft[22,23]. Moreover, even the estimation of potential drops below the spacecraft from measurements along the path is strongly qualified in the references cited by the declarations that "Experimental problems such as electric field saturation effects, threshold limitations, and sensitivity difficulties make this conclusion tentative at best"[22], and "...it is to be expected that the energy of maximum ion flux would be only a rough indicator of the potential below the satellite"[23]. Reservations have been expressed, too, about the quality of fit between observed and predicted velocity-space-density contours of electrons flowing upward in and near the so-called widened loss cone[16,24].

External Field

Many analytical studies of double layers in space plasmas have been restricted effectively to a single dimension in which the charge sheets are treated as being infinite in lateral extent[3]. This simplification is able to overlook the vital fact for a real double layer of an external as well as as internal field and, consequently, the vanishing line integral. Reference to double layers as "regions of a single electric field polarity"[25], a definition as "strong electric fields"[21], and an assessment that they behave as loads[12], all seem to indicate neglect of the external field. The view that numerous 'weak double layers' in series would add to produce a significant combined potential difference[12] also requires the external field to vanish (in the same way that the potential difference across a row of batteries or capacitors becomes the sum only when the external fields are removed with conducting linkages). Note that a definition requiring a vanishing electric field on each side of the layer[26] does not satisfy Poisson's equation.

The same restrictions apply, of course, in the laboratory. Within a discharge tube a charged particle may, of course, exchange potential for kinetic energy to a degree determined by the boundary conditions. A double layer will help to determine where the exchange takes place, but cannot, of course, affect its magnitude[27,28]. The discharge tube as a whole could be considered to be an accelerator, but only in the same sense as the charged dome of a Van de Graaff generator. Energy is provided in these instances by the battery, or equivalent source of energy, across the discharge tube, and by the mechanically driven charging belt of the generator. The net potential difference resulting from the one-dimensional treatment does not, therefore, apply in practice.

'Generators' and 'Dynamos'

Related and equally disqualifying shortcomings are to be found in the many models that appeal to open-ended representations of electrostatic equi-potentials[29]. If they are closed, eg in the opposite hemisphere, the potential well has to be replenished, and the fundamental generator problem, mentioned above, immediately arises. Theories[30], and numerical simulations[31] that simply endow electrons with the potential energy later to appear as kinetic energy must be considered just as unsatisfactory. The solution to the problem of an energy source for particle acceleration in space cannot, we think, be solved either by drawing a few lines and calling them a "cosmic dynamo" with no indication of, or reference to the crucial non-conservative element, or to the mechanical constraints and intricacies of real dynamos (this is the state of affairs in current publications on the subject, decades after Alfvén made the then original and intriguing suggestion[4] before the advent of in-situ space observations). It should also be added, that almost fifty years of research have established beyond any doubt that a plasma can choose its behaviour from a near infinity of possibilities, the least likely being emulation of a simple circuit[32].

Length of Acceleration Region

A further major problem has been made even more acute recently by the announcement at this meeting[33] that typical inferred potential drops across double layers are $\approx 0.1V$ (rather than the previous $\approx 1V$). The double layers are estimated[12] to have a vertical extent of $\approx 100m$, which, together with the published data, implies a vertical separation of $\approx 2.5km$. The number of such double layers needed to give the characteristic $\approx 10keV$ peak energy (assuming that they could add) is then $\approx 10^5$. Since only 1 in 5 of these potential structures is deduced to have a non-zero potential difference[12], the total number required is $\approx 5 \times 10^5$. At the above spacing the length of the series of layers is, then, $\approx 1.25 \times 10^6 km$, or approximately 200 Earth radii. This is to be compared with the $\approx 10^4 km$, of order 2 Earth radii, length of the acceleration region confirmed from numerous satellite measurements. Even if the double layers are packed tightly with no spacing, the region would need to be 8 Earth radii in extent. This hardly seems a viable option. We would also have to accept that there is a high probability for hundreds of thousands of double layers to be generated synchronously along the electron paths. We think it more likely that this probability is negligibly small.

WAVE THEORY

Waves are well known to be very effective agents for transferring energy between different components within collisionless plasmas. It is also well established that the auroral region is turbulent and that it exhibits waves and wave-particle interactions of many kinds[34]. For such reasons it has been suggested for many years[35] that auroral-electron acceleration is due to wave-particle interactions. If a configuration of space charge is in motion, eg. as an electrostatic wave packet, or even a double layer moving at a suitable (resonant) velocity, reflexion of a charged particle by a potential barrier, although conservative in the wave frame, is accompanied by an energy exchange $\pm mv\Delta v$, where m is the mass of the reflected particle, v is the wave-packet velocity, and Δv is the velocity difference. This will be recognised as a (non-relativistic) electrostatic form of Fermi acceleration[36]. The same principle is used in celestial mechanics to speed a spacecraft as it passes a moving planet. When $v \to 0$ we recover the degenerate, conservative case. Consistent and characteristic features of the auroral acceleration region are highly irregular or "spiky" electrostatic fields[37] and broadband electrostatic waves[38]. When these are treated as an ensemble of electrostatic wave packets of the lower-hybrid type, and the constraints set by phase velocity, group velocity and amplitude governing stochastic interaction with electrons are taken into account in a Monte-Carlo model, the characteristic peak is found to evolve naturally[39]. Lower-hybrid turbulence is readily generated in a plasma whenever ion beams, ion conics, or ring distributions are present[32], or where there are inhomogeneities in the plasma[40]. Such waves are renowned for their effectiveness in accelerating or heating the electron component, by acting as the energy-transfer mechanism[41]. Other waves with similar electric-field properties would be equally effective[42], as a recent analysis of the effect of Alfvén waves confirms[43]. Acceleration of electrons is thus an expected consequence of turbulence on auroral field lines.

It should be mentioned at this point that double layers in the laboratory (to date the only well documented double-layers) are always associated with instabilities, wave activity and even turbulence[44]. This was pointed out by Alfvén when he wrote that noise in double layers is so important that "... theories which do not take it into consideration run some risk of being irrelevant"[45]. Had this timely caution been heeded, a double layer would have been seen to be a most unlikely candidate for the source of potential gradient supposed to be responsible for what was once thought to be an ordered particle acceleration. Given the great variety of situations where wave-turbulence energizes charged particles, a wave-particle interaction seems to be the natural first choice in a wide range of applications[46]. The electron accelerator in space plasmas may thus be seen, not as the equivalent of a Van de Graaff generator with unspecified drive mechanism, but as a stochastic linear accelerator governed by fundamental properties of the plasma[39].

CONCLUSION

We suggest, therefore, that there is no further reason to credit double layers, or any other source of static or quasi-static electric field, with the acceleration of electrons in the aurora or other space or astrophysical plasmas. All present evidence is overwhelmingly in favour of acceleration by electrostatic wave turbulence of the lower-hybrid or equivalent type.

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