Double Layers Do Accelerate Particles in the Auroral Zone

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In response to a recent report [D. A. Bryant, R. Bingham, and U. de Angelis, Phys. Rev. Lett. **68**, 37 (1991)] that makes the claim that electrostatic fields are weak in the auroral zone and that electrostatic fields cannot accelerate particles, it is pointed out that the evidence for electrostatic fields in the auroral zone is overwhelming and that these electrostatic fields often are accelerating electrons to produce aurora. The literature cited in the article above as evidence against double layers (strong electric fields) is reexamined and is found not to be evidence against double layers.

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Recently the case for plasma double layers (strong electrostatic fields) not being particle accelerators in the auroral-zone magnetosphere was presented [1]. In presenting the evidence, it appears that many inaccuracies occurred and several omissions were made. As a result I believe that an incorrect conclusion about the role of double layers in the auroral zone was reached.

Bryant, Bingham, and de Angelis present three major objections to models in which static electric fields accelerate electrons to produce aurora [1]: (1) The closed contour integral in any static electric-field structure must vanish and therefore particles cannot be accelerated by the structure, (2) there is no need for electrostatic potential drops because they have an alternate model that will accelerate auroral electrons, and (3) static-electric-field models for the auroral zone are naive.

Concerning the first point, it is true that the closed contour integral across any electrostatic-potential structure vanishes, but that does not mean that an electrostatic structure cannot accelerate electrons into the atmosphere. What is of interest in the auroral zone is the recent history of those electrons, recent meaning the time interval just prior to their hitting the atmosphere. These electrons recently went from one electrostatic potential to another, gaining kinetic energy in the process. If those electrons were to go back up to their original potential, they would indeed lose the energy they gained, but they do not. It is also true of gravity that the closed contour integral of the force vanishes, yet the gravitational acceleration of a dropping object is a valid and useful concept. To discuss the more-distant history of an electron in the auroral zone, a generator mechanism must be considered in addition to the accelerator mechanism. When researchers depict the equipotential contours of an auroral structure, those contours close upward from the particle-acceleration region and into the opposite hemisphere of the Earth (e.g., [2-11]). This closure in the opposite hemisphere is demanded because (a) the parallel (magnetic-field-aligned) portions of the electrostatic electric field are near the Earth and (b) the occurrence of auroral arcs is conjugate in the northern and southern hemispheres. This closure means that the major portion of an active auroral magnetic-field line is charged negative with respect to neighboring magnetic-field lines and with respect to the atmosphere. Any magnetospheric electron on that field line will be accelerated into the atmosphere if it strays into the parallel electric fields near the Earth. To create and maintain such an electrostatic-potential structure requires a generator mechanism that can supply negative charge to the active field line, which means that the generator transported electrons to a higher state of potential energy in the electrostatic structure. An example of a generator that can charge a field line is a cross-field velocity shear of plasma [12-14] in the equatorial magnetosphere. Another example is the absorption of plasma waves in a layer in the magnetosphere [15], if that absorption were to perpendicularly heat ions and displace them off the active field lines to leave those field lines electron rich.

Concerning the second point, even if there were no need for a static electric-field model, static electric fields are directly measured in the auroral zone [16-23] and particle distribution functions consistent with acceleration by static electric fields are observed there [24-29]. Indeed, when the electric field measured along a satellite's orbit is integrated to obtain a value of ϕ, the characteristic kinetic energy (multi-keV) of the auroral particles is found to be equal to $e\phi$ [30,31]. However, the auroral zone is a temporally dynamic and spatially fine-structured region, and so in every case distribution functions consistent with steady-state acceleration through electrostatic-potential structures are not obtained (e.g., [32-34]): Plasma-wave instabilities can alter the distribution functions, electron backscattering off the atmosphere can mask the primary distributions, high-altitude plasma waves can modulate the flow of electrons into parallel-electric-field regions, and the nonzero time resolution of satellites and rockets can mix the distribution functions from different spatial locations to yield a confusing picture. Additionally, there is strong evidence that a second acceleration mechanism acts at low altitudes to energize ions on auroral field lines [35-38].

Concerning the third point, models of the electrostatic-potential structures in the auroral zone are for the most part simplifications. This is because most of the models are focused on specific aspects of auroral phenomena, and the space-physics-research community is aware of the restrictions of these models. Contrary to the implication made in Ref. [1], the models have *not* been restricted to a single spatial dimension (e.g., [39–45]), and I believe that no researcher *really* envisions a one-dimensional electrostatic structure in the auroral zone. Also, it is accepted in the research community that a generator mechanism is needed, in addition to an accelerator mechanism, before the auroral zone can be understood [46–51], and several generator models are being discussed [52–58]. The authors of Ref. [1] also object to the use of simple circuits to describe a plasma (which involves only a small number of researchers): I would like to point out that this use reflects the natural inclination of scientists to reduce the description of a phenomenon to a simple equation or a simple analogy, which can be an effective method for making progress.

In addition, Bryant, Bingham, and de Angelis [1] raise five "discrepancies" that are said to be part of a catalog of evidence against particle acceleration by electrostatic fields. Looking at these five claims I find that none of them are in discrepancy with a model in which electrostatic-potential structures accelerate auroral particles. I would like to address the five claims as follows. In claim (i) two-satellite observations are cited [28] in which energetic upflowing ions are seen to have a warm distribution and in which downflowing energetic electrons are seen to have a warm distribution and have energies (10–15)% higher than the inferred field-aligned potential drop. As concluded in Ref. [28], these observations are consistent with particle acceleration by electrostatic fields, with some particle heating by plasma waves which are always present on auroral field lines [59]. In claim (ii) it is stated that the frequent occurrence of counterstreaming electrons (citing [60]) and of simultaneously upflowing electrons and ions (citing [61]) is evidence against electrostatic acceleration. The counterstreaming electrons observed in Ref. [60] are of low energy (100's of eV) and are flowing up from the atmosphere out of the loss cone and down toward the atmosphere in the loss cone and are observed at times when energetic electrons are flowing into the atmosphere: These counterstreaming electrons are consistent with energetic electrons that have backscattered off of the atmosphere (hence their source is limited to the atmospheric loss cone and their energies are degraded) and that are trapped below the auroral electrostatic-potential barrier. The simultaneously upflowing electrons and ions cited in Ref. [61] were observed on the dayside [$\sim$9 MLT (magnetic local time)] very high-latitude region above the ionosphere. This is not a region where auroral arcs reside and so it is not a region where electrostatic-potential structures are expected to reside. Hence I do not believe the cited evidence to be relevant to double layers. In claim (iii) it is stated that the observed differences (citing [62,63]) between the energies of upflowing H^+ ions and those of upflowing O^+ ions are evidence against electrostatic acceleration. Both of the observations cited can be explained as ionospheric ions undergoing mass-dependent energization at low altitudes followed by electrostatic acceleration at high altitudes (as interpreted by the authors of Refs. [62] and [63]) or they may be explained by ions undergoing electrostatic acceleration followed by the ion-ion two-stream instability, which would transfer energy from H^+ ions to O^+ ions [64,65]. In claim (iv) the uncorrelated behavior between injected barium ions and auroral arcs is given as evidence against electrostatic acceleration (in Ref. [1] the reader is referred to Ref. [66] for evidence). In Ref. [66] it is stated that sometimes barium has been seen to be upwardly accelerated by electric fields associated with visible aurora (citing [67]) and sometimes it has been seen to be upwardly accelerated by electric fields not associated with visible aurora (citing [68]). Both of these observations are consistent with electrostatic electric fields, since there are believed to be small-scale electrostatic-potential structures associated with the visible auroral arcs that reside within the auroral zone (e.g., [40,45]) and large-scale electrostatic-potential structures associated with the entire auroral zone (e.g., [42,43]). The lack of visible aurora between the arcs is a result of the fluxes of particles to the atmosphere lacking the intensity to produce airglow above the eye's threshold, not because there is an absence of an electric field. Finally, in claim (v) it is stated that there is no evidence for electrostatic structures (double layers) except for insignificant ($\sim$1 V) potential drops, and that those insignificant potential drops may really be Alfvén waves. As pointed out above, the direct observational evidence for substantial (multi-kV) electrostatic potential structures in the auroral zone is plentiful [16–27].

The Earth's auroral zone is far from being fully understood, but observations clearly show that electrostatic-potential structures (called double layers or electrostatic shocks) reside in the auroral magnetosphere and they do accelerate auroral particles. At times other acceleration mechanisms may also operate. This author concludes that the case presented in Ref. [1] is not an accurate representation of the state of auroral physics.

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[1] D. A. Bryant, R. Bingham, and U. de Angelis, Phys. Rev. Lett. **68**, 37 (1991).

[2] P. Carlqvist and R. Bostrom, J. Geophys. Res. **75**, 7140 (1970).

[3] D. W. Swift, H. C. Stenbaek-Nielsen, and T. J. Hallinan, J. Geophys. Res. **81**, 3931 (1976).

[4] J. R. Kan and S.-I. Akasofu, J. Geophys. Res. **81**, 5123 (1976).

[5] M. K. Hudson and F. S. Mozer, Geophys. Res. Lett. **5**, 131 (1978).

[6] S. D. Shawhan, C.-G. Falthammar, and L. P. Block, J. Geophys. Res. **83**, 1049 (1978).

[7] D. W. Swift, Space Sci. Rev. **22**, 35 (1978).

[8] L. P. Block, in *Physics of Auroral Arc Formation*, edited by S.-I. Akasofu and J. R. Kan (American Geophysical Union, Washington, DC, 1981), p. 218.
[9] G. Atkinson, J. Geophys. Res. **87**, 1528 (1982).
[10] J. R. Kan, Space Sci. Rev. **31**, 71 (1982).
[11] J. E. Borovsky, Astrophys. J. **306**, 451 (1986).
[12] G. Rostoker and R. Bostrom, J. Geophys. Res. **81**, 235 (1976).
[13] T. Yamamoto and N. Hori, Planet. Space Sci. **35**, 1009 (1987).
[14] G. L. Siscoe, W. Lotko, and B. U. O. Sonnerup, J. Geophys. Res. **96**, 3487 (1991).
[15] B. G. Harrold, C. K. Goertz, R. A. Smith, and P. J. Hansen, J. Geophys. Res. **95**, 15039 (1990).
[16] D. A. Gurnett and L. A. Frank, J. Geophys. Res. **78**, 145 (1973).
[17] F. S. Mozer, C. W. Carlson, M. K. Hudson, R. B. Torbert, B. Parady, J. Yatteau, and M. C. Kelley, Phys. Rev. Lett. **38**, 292 (1977).
[18] N. C. Maynard, T. L. Aggson, and J. P. Heppner, Geophys. Res. Lett. **7**, 881 (1980).
[19] F. S. Mozer, Geophys. Res. Lett. **8**, 823 (1981).
[20] C. Kletzing, C. Cattell, F. S. Mozer, S.-I. Akasofu, and K. Makita, J. Geophys. Res. **88**, 4105 (1983).
[21] E. L. Bennett, M. Temerin, and F. S. Mozer, J. Geophys. Res. **88**, 7107 (1983).
[22] M. S. Redsun, M. Temerin, and F. S. Mozer, J. Geophys. Res. **90**, 9615 (1985).
[23] D. R. Weimer, C. K. Goertz, D. A. Gurnett, N. C. Maynard, and J. L. Burch, J. Geophys. Res. **90**, 7497 (1985).
[24] P. F. Mizera and J. F. Fennell, Geophys. Res. Lett. **4**, 311 (1977).
[25] D. R. Croley, Jr., P. F. Mizera, and J. F. Fennell, J. Geophys. Res. **83**, 2701 (1978).
[26] J. B. Cladis and R. D. Sharp, J. Geophys. Res. **84**, 6564 (1979).
[27] J. M. Bosqued, C. Maurel, J. A. Sauvaud, R. A. Kovrazhkin, and Y. I. Galperin, Planet. Space Sci. **34**, 255 (1986).
[28] P. H. Reiff, H. L. Collin, J. D. Craven, J. L. Burch, J. D. Winningham, E. G. Shelley, L. A. Frank, and M. A. Friedman, J. Geophys. Res. **93**, 7441 (1988).
[29] C. Gurgiolo and J. L. Burch, J. Geophys. Res. **93**, 3989 (1988).
[30] M. Temerin, M. H. Boehm, and F. S. Mozer, Geophys. Res. Lett. **8**, 799 (1981).
[31] P. F. Mizera, J. F. Fennell, D. R. Croley, Jr., and D. J. Gorney, J. Geophys. Res. **86**, 7566 (1981).
[32] B. A. Whalen and P. W. Daly, J. Geophys. Res. **84**, 4175 (1979).
[33] M. Temerin, J. McFadden, M. Boehm, C. W. Carlson, and W. Lotko, J. Geophys. Res. **91**, 5769 (1986).
[34] B. Hultqvist, J. Geophys. Res. **93**, 9777 (1988).
[35] B. A. Whalen, W. Bernstein, and P. W. Daly, Geophys. Res. Lett. **5**, 55 (1978).
[36] J. E. Borovsky, J. Geophys. Res. **89**, 2251 (1984).
[37] D.M. Klumpar, W. K. Peterson, and E. G. Shelley, J. Geophys. Res. **89**, 10779 (1984).
[38] A. W. Yau, B. A. Whalen, and P. M. Kintner, in *Ion Acceleration in the Magnetosphere*, edited by T. Chang (American Geophysical Union, Washington, DC, 1986), p. 39.
[39] D. W. Swift, J. Geophys. Res. **81**, 3935 (1976).
[40] J. S. Wagner, T. Tajima, J. R. Kan, J. N. Leboeuf, S.-I. Akasofu, and J. M. Dawson, Phys. Rev. Lett. **45**, 803 (1980).
[41] J. R. Kan and L. C. Lee, Geophys. Res. Lett. **7**, 633 (1980).
[42] L. R. Lyons, J. Geophys. Res. **86**, 1 (1981).
[43] Y. T. Chiu, A. L. Newman, and J. M. Cornwall, J. Geophys. Res. **86**, 10029 (1981).
[44] M. K. Hudson and D. W. Potter, in *Physics of Auroral Arc Formation* (Ref. [8]), p. 260.
[45] J. E. Borovsky and G. Joyce, J. Geophys. Res. **88**, 3116 (1983).
[46] G. Atkinson, J. Geomag. Geoelectron. **30**, 435 (1978).
[47] C. K. Goertz, Rev. Geophys. Space Phys. **17**, 418 (1979).
[48] C. K. Goertz and R. W. Boswell, J. Geophys. Res. **84**, 7239 (1979).
[49] T. Sato and T. Iijima, Space Sci. Rev. **24**, 347 (1979).
[50] R. L. Lysak, J. Geophys. Res. **90**, 4178 (1985).
[51] J. E. Borovsky (to be published).
[52] C. K. Goertz, in *Proceedings of the Sixth ESA Symposium on European Rocket and Balloon Programmes* (European Space Agency Report No. SP-183, 1983), p. 221.
[53] D. W. Swift, in *Magnetotail Physics*, edited by A. T. Y. Lui (Johns Hopkins Univ. Press, Baltimore, 1987), p. 199.
[54] K. Watanabe and T. Sato, Geophys. Res. Lett. **15**, 717 (1988).
[55] Y. Song and R. L. Lysak, in *Modeling Magnetospheric Plasma*, edited by T. E. Moore and J. H. Waite (American Geophysical Union, Washington, DC, 1988), p. 121.
[56] Y. I. Galperin and A. V. Volosevich, Can. J. Phys. **67**, 719 (1989).
[57] L. R. Lyons, in *Auroral Physics*, edited by C.-I. Meng, M. J. Rycroft, and L. A. Frank (Cambridge Univ. Press, Cambridge, 1991), p. 195.
[58] J. Birn and M. Hesse, J. Geophys. Res. **96**, 1611 (1991).
[59] D. A. Gurnett, in *Auroral Physics* (Ref. [57]), p. 241.
[60] R. D. Sharp, E. G. Shelley, R. G. Johnson, and A. G. Ghielmetti, J. Geophys. Res. **85**, 92 (1980).
[61] B. Hultqvist, R. Lundin, K. Stasiewicz, L. Block, P.-A. Lindqvist, G. Gustafsson, H. Koskinen, A. Bahnsen, T. A. Potemra, and L. J. Zanetti, J. Geophys. Res. **93**, 9765 (1988).
[62] H. L. Collin, R. D. Sharp. E. G. Shelley, and R. G. Johnson, J. Geophys. Res. **86**, 6820 (1981).
[63] R. Lundin and B. Hultqvist, J. Geophys. Res. **94**, 6665 (1989).
[64] H. L. Collin, W. K. Peterson, and E. G. Shelley, J. Geophys. Res. **92**, 4757 (1987).
[65] I. Roth, M. K. Hudson, and R. Bergmann, J. Geophys. Res. **94**, 348 (1989).
[66] D. A. Bryant, Phys. Scr. **T30**, 215 (1990).
[67] G. Haerendel, E. Rieger, A. Valenzuela, H. Foppl, H. C. Stenbaek-Nielsen, and E. M. Wescott, in *European Programmes on Sounding-Rocket and Balloon Research in the Auroral Zone* (European Space Agency, Neuilly, France, Report No. ESA-SP115, 1976).
[68] H. C. Stenbaek-Nielsen, T. J. Hallinan, E. M. Wescott, and H. Foppl, J. Geophys. Res. **89**, 10788 (1984).