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Comment on "Can gamma radiation be produced in the electrical environment above thunderstorms"

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In a recent letter Chang and Price [1995] (subsequently referred to as CP) set forward the claim that runaway electron acceleration followed by runaway discharge [Gurevich, 1961; Connor and Hastie, 1975] can take place at the altitude of about 70 km in the ionosphere in the presence of a vertical laminar electric field E of the order of 500 V/m. Furthermore, they speculate that the γ–ray flashes observed when the Compton γ–ray observatory overflies the equatorial region [Fishman et al., 1994] and the short-pulse radio bursts detected by the ALEXIS satellite [Massey and Holden, 1995] can be attributed to such a runaway discharge occurring at an altitude of 70 km corresponding to neutral density of 7×10^{14} #/cm^3. The purpose of this comment is to demonstrate that the conclusions of the CP paper are based on physical principles inconsistent with the fact that for the relevant ionospheric parameters the electron mean free path is much longer than its gyroradius.

It is easy to see that for runaway electrons the mean free path is far larger than the gyroradius. For example, a 1 MeV electrons in the Earth's magnetic field has a gyroradius of approximately 80 m, while the mean free path at 70 km is tens of kilometers. The CP paper states that an acceleration distance of 3.7 km is required for the electrons to reach 1 MeV. This is forty times longer than the relevant gyroradius. As noted by Papadopoulos and Milikh [1994] and Book et al. [1995], for mean free paths longer than the gyroradius proper analysis requires inclusion of the magnetic field in the equations of motion. The problems with the CP model become apparent by a simple physics analysis which considers acceleration of an electron in the presence of an electric field perpendicular to a magnetic field. Such a configuration is expected for runaway acceleration over thunderstorms in the equatorial region.

We study the runaway acceleration of a test electron in crossed static electric and magnetic fields by transforming the equations of motion to a reference frame moving with the velocity βc relative to the ionospheric frame in which the transformed fields $\mathbf{E}'$ and $\mathbf{B}'$ are parallel. In this frame the electrons can be treated as unmagnetized.

Following Jackson [1975], the electric and magnetic fields in the moving frame are

$$\mathbf{E}' = \gamma(\mathbf{E} + \beta \times \mathbf{B}) - \frac{\gamma^2}{\gamma^2+1}\beta(\beta \cdot \mathbf{E}), \qquad (1)$$

$$\mathbf{B}' = \gamma(\mathbf{B} + \beta \times \mathbf{E}) - \frac{\gamma^2}{\gamma^2+1}\beta(\beta \cdot \mathbf{E}), \qquad \gamma = 1/\sqrt{1-\beta^2}, \qquad (2)$$

with

$$\mathbf{E}^2 - \mathbf{B}^2 = \mathbf{E}'^2 - \mathbf{B}'^2, \quad \mathbf{E} \cdot \mathbf{B} = \mathbf{E}' \cdot \mathbf{B}'. \qquad (3)$$

We determine the value of β required to have $\mathbf{E}'$ parallel to $\mathbf{B}'$. Note, however, that the problem has infinite number of solutions. If there is a frame in which $\mathbf{E}' \parallel \mathbf{B}'$ then every frame parallel to this direction will also preserve it. Consider a reference frame moving at right angles to **E** and **B**, so that

$$\beta \cdot \mathbf{E} = \beta \cdot \mathbf{B} = 0, \qquad (4)$$

$$\mathbf{E}' \times \mathbf{B}' = 0. \qquad (5)$$

From (1) and (2) taking into account (4) we obtain

$$(\mathbf{E} + \beta \times \mathbf{B}) \times (\mathbf{B} - \beta \times \mathbf{E}) = 0. \qquad (6)$$

From (6) using (4) and (5) we can find the relative velocity β of a moving frame in which $\mathbf{E}' \parallel \mathbf{B}'$.

$$\beta = \mathbf{E} \times \mathbf{B}\,\frac{\mathrm{E}^2 + \mathrm{B}^2 - \sqrt{(\mathrm{E}^2 - \mathrm{B}^2)^2 + 4(\mathbf{E} \cdot \mathbf{B})^2}}{2(\mathbf{E} \times \mathbf{B})^2}. \qquad (7)$$

From (1), (2) we then express $\mathbf{E}'$ and $\mathbf{B}'$ in terms of **E, B**

$$\mathrm{E}'^2 = \frac{1}{2}\left[\mathrm{E}^2 - \mathrm{B}^2 + \sqrt{(\mathrm{E}^2 - \mathrm{B}^2)^2 + 4(\mathbf{E} \cdot \mathbf{B})^2}\right], \qquad (8)$$

$$\mathrm{B}'^2 = \frac{1}{2}\left[\mathrm{B}^2 - \mathrm{E}^2 + \sqrt{(\mathrm{E}^2 - \mathrm{B}^2)^2 + 4(\mathbf{E} \cdot \mathbf{B})^2}\right]. \qquad (9)$$

Notice that if **E** and **B** are perpendicular $(\mathbf{E} \cdot \mathbf{B} = 0)$, there are two limits. If E > B there is a frame in which $\mathrm{B}' = 0$ and $\mathbf{E}' = \sqrt{\mathbf{E}^2 - \mathbf{B}^2}$. If B > E then $\mathrm{E}' = 0$ and $\mathbf{B}' = \sqrt{\mathbf{B}^2 - \mathbf{E}^2}$. As a result there is no electron acceleration in crossed static electric and magnetic field for E < B.

In the above equations the values E, E$'$, B, B$'$ are given in Gaussian units. In SI units B will be replaced by the characteristic electric field $\mathrm{E_B}\left(\frac{\mathrm{kV}}{\mathrm{m}}\right) = 7.5\left(\frac{\mathrm{B}}{0.25\mathrm{G}}\right)$, where B is the value of the local magnetic induction. In fact, for an equatorial magnetic field B = 0.25G, and $\mathrm{E_B}$ corresponds to 7.5 $\frac{\mathrm{kV}}{\mathrm{m}}$ which is by more than an order of magnitude larger than the one found in CP. This threshold value is independent of altitude as long as the gyroradius is smaller than the mean free path which for runaway electrons occurs at altitudes as low as 20 km [Longmire, 1978; Papadopoulos and Milikh, 1994]. A similar analysis for electric fields oblique to the magnetic field [Book et al., 1995] indicates that the above results are modified by less than a factor of two, except for high latitudes, where giant thunderstorms do not occur.

Before closing we should note that in addition to the issue discussed above, the paper has additional deficiencies, which

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invalidate the analysis even if the electric field is parallel to the magnetic field. Just two examples: first, CP state that above the runaway threshold the entire electron distribution runs away. This is incorrect, since during the acceleration to relativistic energies an electron produces mostly low-energy, non-runaway electrons, and only one approaching energy one-half that of the ionizing electron [Longmire, 1978]. A complete analysis of this problem applied to tokamaks can be found in Connor and Hastie [1975]. Second, the electron runaway breakdown triggered by fast cosmic secondaries [Gurevich et al., 1992; Roussel-Dupre et al., 1994] could be a much better candidate for the production of gamma ray bursts than thermal runaway, since it has the threshold electric field of almost two orders of magnitude lesser. However, CP rejected possibility of the runaway breakdown, commenting that the coincident occurrence of a positive lightning flash with a cosmic ray above the anvil of a thunderstorm is very small. This is not correct, since based on Fig. 3 from Daniel and Stivens [1974] the flux of let us say 2 MeV electrons is $\sim 1\frac{particle}{m^2 s\ ster}$ at about 35 km,. That is, a region of a few km^2 area irradiated by the electric field due to low altitude lightning will be intersected by a fast particle each μsec, which can trigger runaway breakdown.

In conclusion, we have shown that several errors in the CP paper invalidate the results even for the case of unmagnetized interaction. A detailed analysis of the problem including the role of oblique incidence will be presented elsewhere.

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