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On Lorentz invariants in relativistic magnetic reconnection

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Relativistic reconnection has been extensively studied recenlys, inspired by its potential for understanding of many exotic astrophysical systems dominated by magnetic energy such as pulsar winds, Gamma rays and AGN jets [1-4], as well as recent developments in experiments and numerical simulations of laser induced plasmas with a self-generated Giga-Gauss magnetic field have brought studies of magnetic reconnection into the relativistic regime [5-7]. Especially in the electron diffusion region, where in general the electron Alfvén velocity is ultra-relativistic. Then, the question should be raised if the nonrelativistic description of magnetic reconnection holds rigorously in the relativistic regime. For example, the most important measure of magnetic reconnection is the reconnection rate, directly related to $E_{\parallel}$. However, in a moving frame with a velocity of $\mathbf{v} = (\upsilon, 0, 0)$ perpendicular to the magnetic field on the y-z plane, under the Lorentz transformation $\mathbf{E}' \to \gamma_{\rm v}(\mathbf{E} + \boldsymbol{\beta}_{\rm v} \times \mathbf{B})$, with $\boldsymbol{\beta}_{\rm v} \equiv \mathbf{v}/c$ and $\gamma_{\rm v} \equiv (1-\beta_{\rm v}^2)^{-1/2}$, we have $E'_{\parallel} \to \gamma_{\rm v} E_{\parallel}$. Clearly, the variable $E_{\parallel}$. is not a Lorentz invariant.

In this talk we analyze the relativistically invariant definition for the RMR rate and make related investigations in a Lorentz covariant two-fluid model.

Making use of two basic Lorentz invariants

$$I_1 \equiv \frac{1}{2} F^{\mu\nu} F_{\mu\nu} = B^2 - E^2 , \qquad (1)$$

and

$$I_2 \equiv \frac{1}{4} F^{\mu\nu *} F_{\mu\nu} = \frac{1}{4} \varepsilon^{\mu\nu\lambda\tau} F_{\mu\nu} F_{\lambda\tau} = \mathbf{E} \cdot \mathbf{B} , \qquad (2)$$

we can derive the Lorentz covariant reconnection rates.

(1) For the 2D X-points with a guide-field or 3D separators, we can then get the reconnection rate

$$\Re = \frac{|I_2|_{MAX}\, h_{+0}^{1/2}}{I_{1,MAX}^2 \,\mathrm{Re}\, I_3} , \qquad (3)$$

where the local invariant $I_3 \equiv B + iE = \left(I_1 + 2i|I_2|\right)^{1/2}$, and $h_{+0} = n_0 m_{+0} f(T_+)$ is the enthalpy density of the positively charged fluid, with the effective mass variation rate $f(T) = K_3(m_{+0}/T_+)/K_2(m_{+0}/T_+)$ due to thermal motion, by the modified Bessel function K_n (n = 1, 2, 3, …).

(2) For 2D X-points in the anti-parallel case or 3D magnetic nulls, we can get the reconnection rate

$$\Re \approx \frac{\left(|I_{1,MIN}|\, h_{+0}\right)^{1/2}}{I_{1,MAX}^2} . \qquad (4)$$

They are Lorentz covariant. And for both cases, h_{+0} is measured at the point where I_1 reaches its maximum $I_{1,MAX}$.

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