Classical Electrodynamics of charged massless particles

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based on F. Azzurli and K. Lechner, *Electromagnetic fields and potentials generated by massless charged particles*, [arXiv:1401.5721[hep-th]].

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Some issues in classical Electrodynamics for point-like particles I

- Self-interaction not included in Lorentz force $\frac{dp^\mu}{ds} = eF^{\mu\nu}u_\nu$
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- $F^{\mu\nu}(x)$ and $j^\mu(x) = e\int u^\mu \delta^4(x - y(s))ds$ are distributions but the energy-momentum tensor of the EM field

$$T^{\mu\nu}_{em} = F^{\mu\rho}F^{\nu}_{\ \rho} + \frac{1}{4}F^{\rho\sigma}F_{\rho\sigma}$$

is not: $T_{em} \sim \frac{1}{L^4}$, not integrable for $L \sim 0$.

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$\Longrightarrow$ postulate $\mathcal{T}^{\mu\nu}_{em}$

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$$\frac{dp^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{e^2}{6\pi}\left(\frac{d^2u^\mu}{ds^2} + \left(\frac{du}{ds}\right)^2 u^\mu\right)$$

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Can we do the same for massless charges? (and learn some lesson?)

Some notation

For massive particles moving at speed $V < 1$ capital letters

- $Y^{\mu}(\lambda)$ world-line parametrized by λ
- $U^{\mu}(\lambda) = \frac{dY^{\mu}}{d\lambda}(\lambda)$ four-velocity
- $W^{\mu}(\lambda) = \frac{dU^{\mu}}{d\lambda}(\lambda)$ four-acceleration
- $J^{\mu} = e \int u^{\mu} \delta^4(x - y(s)) d\lambda$ four-current

and field with italic letters $F^{\mu\nu}$...

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For massless particles lower case letters for $y^\mu(\lambda)$, $u^\mu(\lambda)$, $w^\mu(\lambda)$, j^μ and calligraphic font for the fields $\mathcal{F}^{\mu\nu}$...

Liénard-Wichert fields

Define retarded time $\lambda_r(x)$ and

$$L^\mu = x^\mu - Y^\mu(\lambda_r(x)) \quad , \underbrace{L^2 = 0}_{light-like} \quad \underbrace{L^0 \geq 0}_{causal}$$

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Coulomb field

$$C^{\mu\nu} = \frac{e}{4\pi} \frac{\left(U^\mu L^\nu - U^\nu L^\mu\right) U^2}{(UL)^3}$$

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Naively set $V = 1$. On

$$\Gamma^\mu(\lambda, b) \; = \; y^\mu(\lambda) + bu^\mu(\lambda), \quad b > 0$$

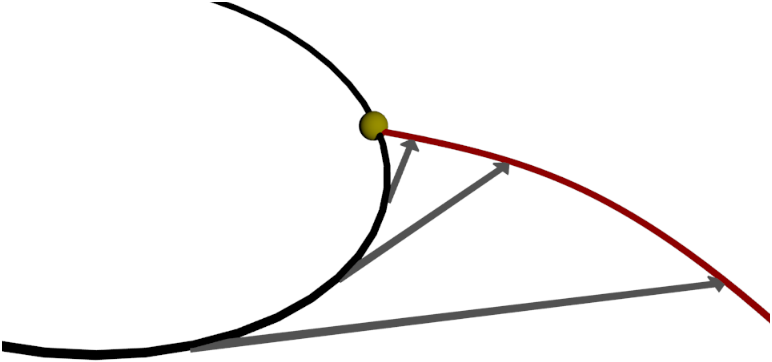
$$l^\mu = \Gamma^\mu - y^\mu \propto u^\mu \implies ul \propto u^2 = 0 \implies \mathcal{C}^{\mu\nu}, \mathcal{R}^{\mu\nu}|_\Gamma \to +\infty$$

Notice: Γ has a border: $l^0 > 0 \implies b > 0$.

String of singularity

Corresponding string at time t (using t as parameter)

$$\vec{\gamma}(b) = \vec{y}(t-b) + b\frac{d\vec{y}}{dt}(t-b)$$



Green function method fails

The method ($V = 1$):

$$\partial_\mu \mathcal{F}^{\mu\nu} = j^\nu, \partial_{[\alpha} \mathcal{F}_{\beta\gamma]} = 0, \quad \Longrightarrow \Box \mathcal{A}^\mu = j^\mu, \quad \partial_\mu \mathcal{A}^\mu = 0$$

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$$\Box G(x) = \delta^4(x) \implies G(x) = \frac{1}{2\pi} H(x^0)\delta(x^2) \longrightarrow \mathcal{A}^\mu = G * j^\mu$$

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For rectilinear uniform motion at $V = 1$ one gets

$$\mathcal{A}^\mu_{RU} = \frac{e}{4\pi} \frac{u^\mu}{ux} H(ux) \notin \mathcal{S}'!$$

Rectilinear uniform motion

$A^{\mu}_{RU} \in \mathcal{S}'$ given by J^{μ}_{RU}, but $\operatorname*{Lim}_{V\to 1} A^{\mu}_{RU} \notin \mathcal{S}'$

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Absorb divergences with gauge transformations:

$$\tilde{A}^\mu_{RU} = A^\mu_{RU} + \partial^\mu \Lambda, \quad \mathcal{A}^\mu_{RU} = \operatorname*{Lim}_{V\to 1} \tilde{A}^\mu_{RU} \in \mathcal{S}'$$

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$$\mathcal{F}^{\mu\nu}_{RU} = \partial^\mu \mathcal{A}^\nu_{RU} - \partial^\nu \mathcal{A}^\mu_{RU} = \underset{V\to 1}{\mathrm{Lim}} F^{\mu\nu}_{RU}$$

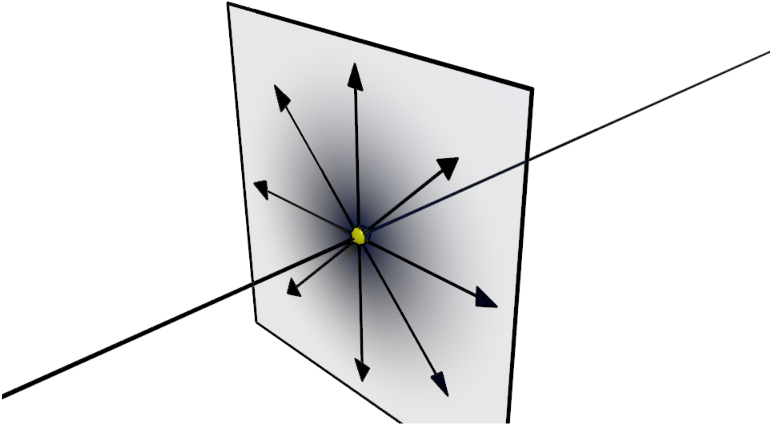
and it solves the Maxwell equation for j^μ_{RU}

$$\partial_\mu \mathcal{F}^{\mu\nu}_{RU} = \partial_\mu \underset{V\to 1}{\mathrm{Lim}} F^{\mu\nu}_{RU} = \underset{V\to 1}{\mathrm{Lim}} \partial_\mu F^{\mu\nu}_{RU} = \underset{V\to 1}{\mathrm{Lim}} J^\mu_{RU} = j^\mu_{RU}$$

The shockwave

Resulting field: the shockwave ($v^\mu = \frac{dy^\mu}{dy^0}$)

$$\mathcal{F}^{\mu\nu}_{RU} = \mathcal{C}^{\mu\nu}_{RU} = \frac{e}{2\pi}\frac{v^\mu x^\nu - v^\nu x^\mu}{x^2}\delta(vx)$$



The four potential

Green function method provides

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$$\mathcal{A}^\mu(\varphi) = \frac{e}{4\pi}\int \frac{u^\mu}{r}\varphi(t + r, \vec{x} + \vec{y}(t))d^4x$$

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Not integrable in region $t \sim -r \to -\infty$ and $\vec{x} \sim -\vec{y}(t) \to \infty$.

Bounded motion

$\vec{y}(t) \overset{t\to-\infty}{\not\to} \infty \implies \mathcal{A}^\mu \in \mathcal{S}' \implies \mathcal{F}^{\mu\nu}$ given by derivatives computed in $\mathcal{S}'$

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Easier to use a regularisation!

$$Y^0(\lambda) = \frac{y^0(\lambda)}{V}, \quad \vec{Y}(\lambda) = \vec{y}(\lambda) \implies \operatorname*{Lim}_{V\to 1} J^\mu = j^\mu$$

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$$\mathcal{Q}^{\mu\nu} = e\int_0^{+\infty} b\,(u^\mu w^\nu - u^\nu w^\mu)\,db \int \delta^4(x - \Gamma(\lambda, b))d\lambda$$

Poincaré dual of $\Gamma^\mu \implies \partial_\mu \mathcal{Q}^{\mu\nu} = j^\nu \implies \partial_\mu \mathcal{P}(R^{\mu\nu}) = \frac{1}{2} j^\mu$

Currents

$$\begin{cases} \partial_{[\mu} C_{\nu\rho]} &= 0 \\ \partial_\mu C^{\mu\nu} &= J^\nu + K^\nu \end{cases}, \quad \begin{cases} \partial_{[\mu} R_{\nu\rho]} &= 0 \\ \partial_\mu R^{\mu\nu} &= -K^\nu \end{cases}$$

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Unbounded motion I

$$\vec{y} \overset{t\to-\infty}{\longrightarrow} t\vec{v}_\infty$$

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$$\vec{\gamma}(b) = \vec{y}(t-b) + b\frac{d\vec{y}}{dt}(t-b)$$

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Same strategy as before

$$\mathcal{R}^{\mu\nu} = \operatorname*{Lim}_{V\to 1} R^{\mu\nu} = \mathcal{P}(R^{\mu\nu}) + \frac{1}{2}\mathcal{Q}^{\mu\nu}$$

Unbounded motion II

This time

$$\partial_\mu \mathcal{R}^{\mu\nu} = -\mathop{\mathrm{Lim}}_{V\to 1} K^\mu = e \int [u^\mu(\lambda)\varphi(\Gamma(\lambda, b))]_{b=+\infty}^{b=0}\, d\lambda = j^\nu - j^\nu_{RU}$$

where j_{RU} current of rectilinear motion along $\vec{v}_\infty$

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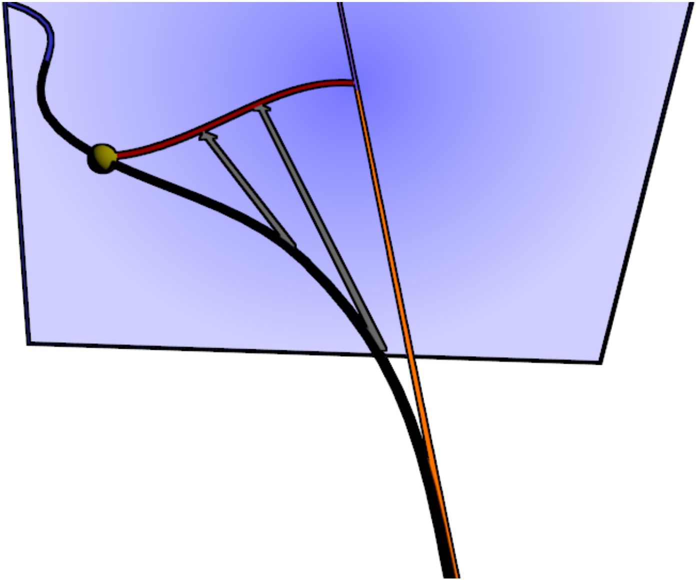
Unbounded motion generate:

1. A radiation field
2. A shockwave
3. A string of singularities that ends on the shockwave



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Thanks for your kind attention.