Extreme particle acceleration in reconnection layers and gamma-ray emission in the Crab Nebula

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1. Abstract:

The gamma-ray flares recently discovered in the Crab Nebula by *Fermi* and *Agile* challenge classical models of particle acceleration. We argue that the sudden release of magnetic energy *via* reconnection of magnetic field lines in the nebula powers the flares and accelerates electrons to ultra-high energies (PeV) in a milli-Gauss magnetic field.

2. Puzzling properties of the flares:

→ Observed synchrotron photon energy **>100 MeV exceeds the classical limit** ($\varepsilon_{sync} < m_e c^2/\alpha \approx 70$ MeV) given by the balance between the electric force e**E** and the radiation reaction force, assuming that E is smaller than the magnetic field B.

→ The **variability timescale is < 1 day**, *i.e.* a tiny part of the nebula ($L < 10^{16}$ cm << 0.1 pc) radiates most of the high-energy gamma-ray flux.

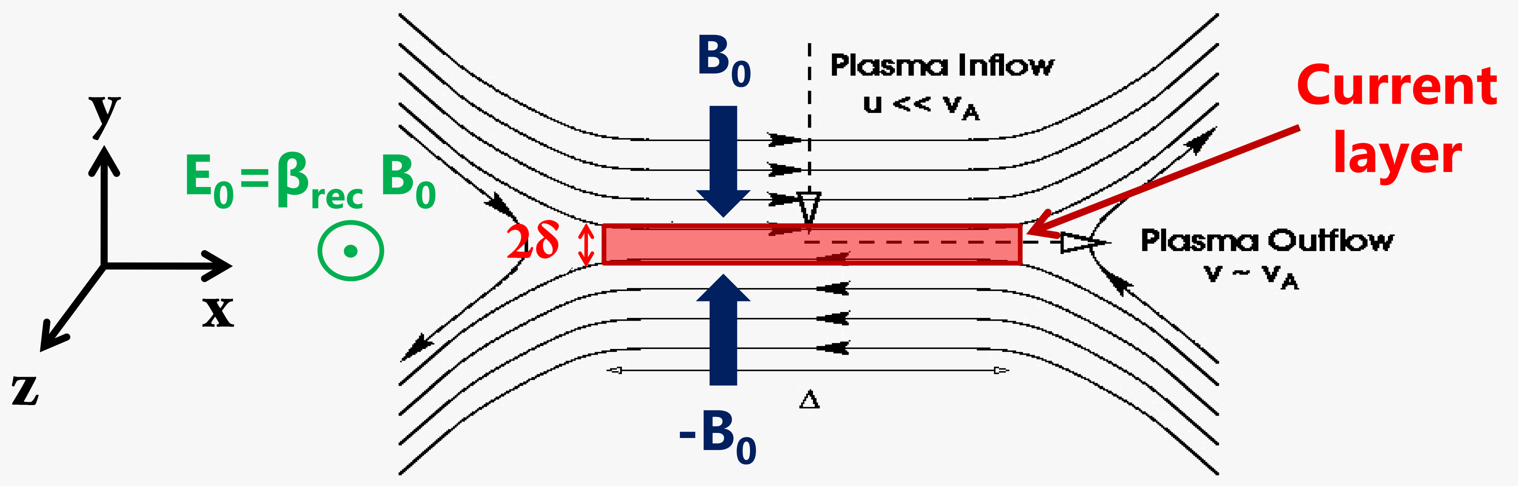
3. Single electron's trajectory in a magnetic reconnection layer:

We calculate the orbit of an ultrarelativistic electron in the electromagnetic field (**E**,**B**) of the reconnection layer, and include the radiation reaction force.

- Lorentz force: $\mathbf{F_L} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c)$

- Radiation reaction force: $\mathbf{F_{rad}} = -(P_{rad}/c^2)\mathbf{v}$, where P_{rad} is the radiated synchrotron power.

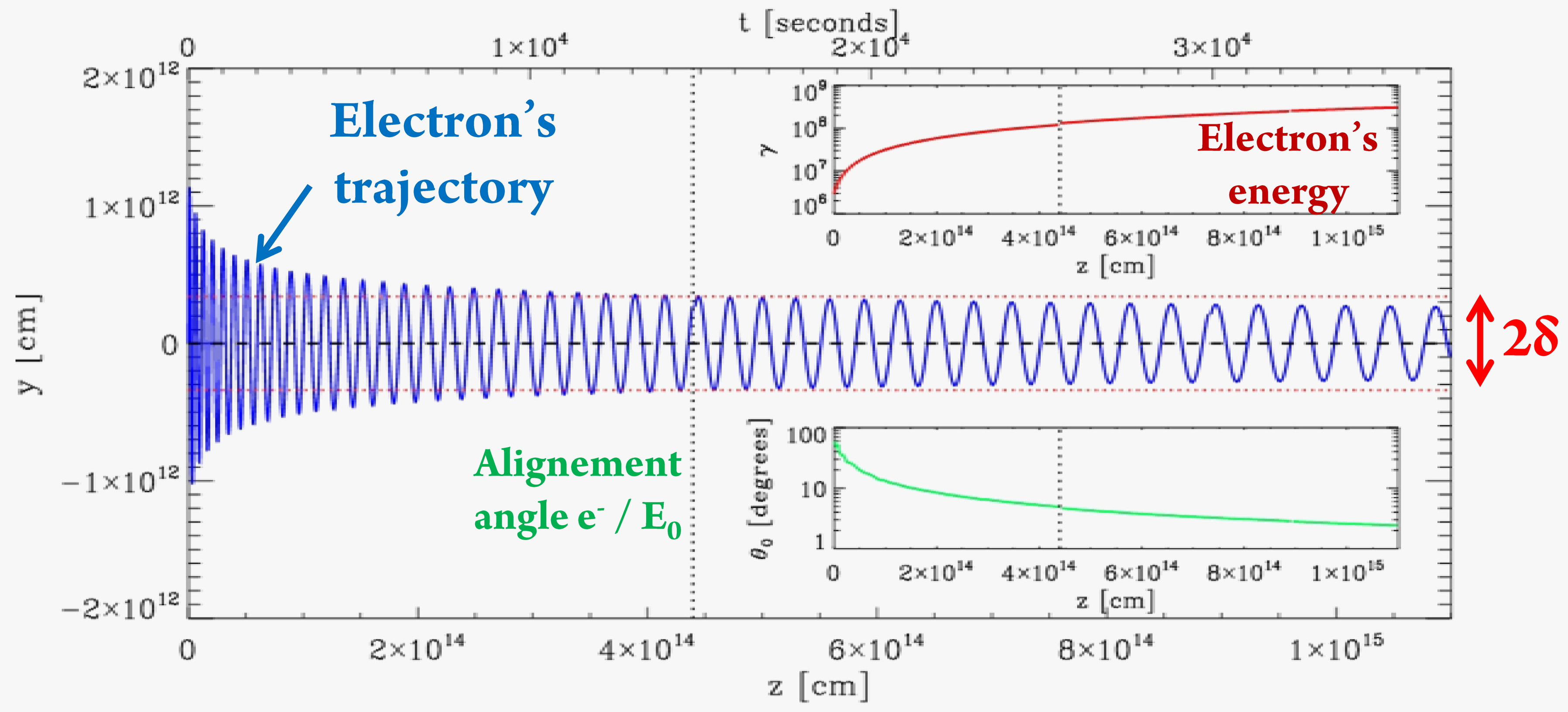
Magnetic reconnection geometry:



Adapted from © http://mrx.pppl.gov/

Example of an orbit (relativistic Speiser orbit)

Parameters: $B_0 = 5$ mG, $\beta_{rec} = 0.1$, $\gamma_{inj} = 3\times10^6$, $\theta_{inj} = 90°$



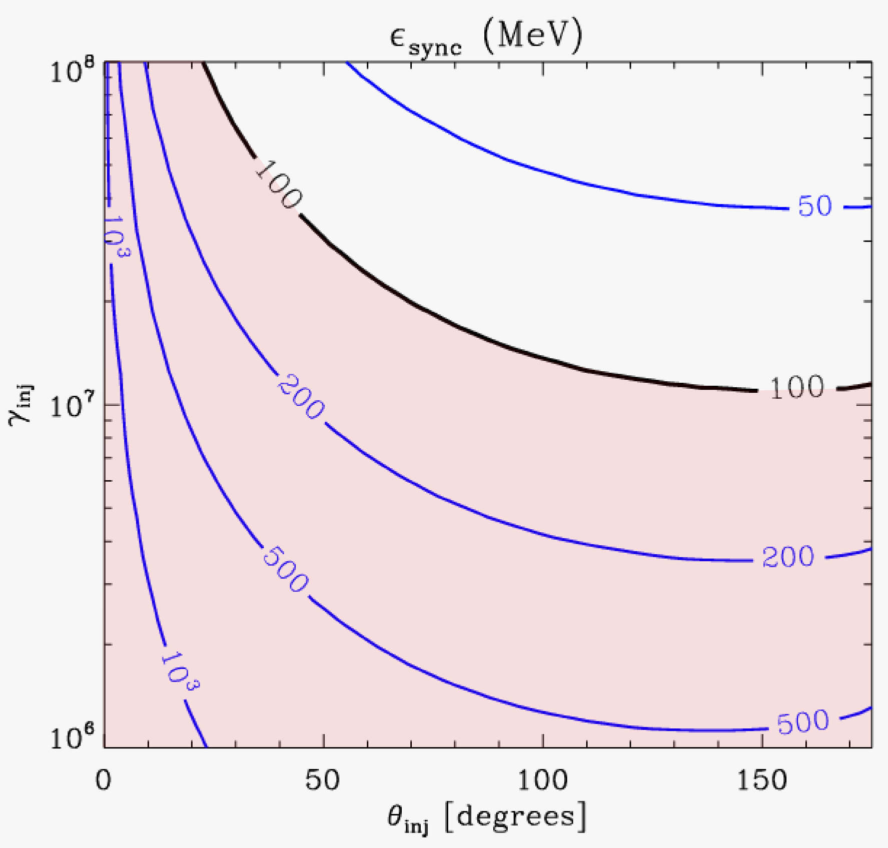
[Uzdensky, Cerutti & Begelman, submitted 2011]

Results: The electron's orbit is **trapped** and **shrinks** deep into the reconnection layer where the magnetic field is small. Radiative losses decrease and the electron can reach **ultra-high energies.**

4. Extreme synchrotron emission

After 4 days of acceleration in the reconnection layer, electrons are focused into a narrow beam of a few degrees and pile up at PeV energies.

The critical synchrotron photon energy is $\varepsilon_{sync} = (3/2)\gamma^2 \hbar\omega_c$ (with $\omega_c = eB_0/m_e c$), and can exceed 100 MeV depending on the electron's initial parameters γ_{inj} and θ_{inj}.



5. Conclusions

→ Synchrotron photons >100 MeV are emitted by PeV electrons **accelerated deep inside the reconnection layer** where the reconnecting magnetic field is small.

→ PeV particles are **focused** into a **narrow beam**. Flares would be observed when the beam points towards us.

→ This mechanism could be at work in other astrophysical objects (AGN jets, pulsar winds) *[see Kirk, PRL 2004]*

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