Explosive Reconnection and Particle Acceleration in Relativistic Plasma

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- JPP, 2017abc
Two related topics

- Structure of pulsar winds (Crab Nebula)
- Particle acceleration in relativistic astrophysical plasmas
High energy sources: non-thermal particles, fast variability (= very fast acceleration)

Mrk 421

GRB light curve

blazar PKS 2155-304
Part I: The Crab wind and Nebula
Crab flares

- Few times per year
- Random
- Flux increase by 40
- 100 MeV - 1 GeV
- lasts for a day (<< dynamical time)

The synchrotron limit

\[ eEc = \eta eBc = \frac{4e^4}{9m^2c^3} B^2 \gamma^2 \]

\[ \hbar \omega_s \approx \hbar \gamma^2 \frac{eB}{m_ec} = \eta \frac{m_\text{e} \hbar c^3}{e^2} \approx 200 \eta \text{ MeV} \]

Nearly monoenergetic!

Diffusive Shock acceleration is excluded

Tavani + 2011
High sigma model of pulsar wind nebulae (Lyutikov 2010)

- Lyutikov (2010): 100 MeV is still too much.
- Ideal flow in the bulk, dissipation on boundary
- “We propose that [...] the excessive magnetic flux is destroyed in a reconnection-like process“

High sigma model of PWNe
- No shocks! (Acceleration in reconnection)
- Relativistic bulk motion of emitting plasma

Two possible reconnection sites
Flares from Crab Inner Knot?

\[ L_w \propto \sin^2 \theta \]

Komissarov & Lyutikov 2011

Lyutikov +, 2012
Crab Inner knot

Scales ~ 0.5” (light day)
In the knot sigma is small!  

\[ \sigma = 0 \quad \sigma = 1 \quad \sigma = 10 \]

Lyutikov + 2016

Bogovalov 1999
Polarization
Inner knot: surface of relativistic shock

- **Location**: The knot is on the same side of the pulsar as the Crab jet, along the symmetry axis, on the opposite side as the brighter section of the Crab torus.
- **Size**: The knot size is comparable to its separation from the pulsar. Only models with $\sigma < 1$ agree.
- **Elongation**: The knot is elongated in the direction perpendicular to the symmetry axis. Only models with $\sigma < 1$ agree.
- **Brightness peak**: The observations indicate that the brightness peak is shifted in the direction away from the pulsar.
- **Polarization**: The knot polarization degree is high, and the electric vector is aligned with the symmetry axis.
- **Luminosity**: Taking into account Doppler beaming, the observed radiative efficiency of the inner knot is fairly low $<< 1\%$.
- **Variability**: The knot flux is anticorrelated with its separation from the pulsar.
  
  Not a sight of gamma-ray flares.
Wind properties

- Knot: Thermal (!) spectrum, $\gamma_w = 3 \times 10^4$

Porth +, 2017
PIC simulations of termination shock in striped wind

- Reconnection-mediated shock

Only relativistic shocks with sigma < 10^{-2} can accelerate non-thermal particles
Large-scale torus structure

Komissarov & Lyutbarksy 2003

sigma << 1
Pulsar winds: coming together of theory, simulations and observations

Highly magnetized wind
Reconnection mediated acceleration at Mach belt, $B_{\text{eff}} \sim 0$, like sigma=0

High sigma regions, flares
Reconnection mediated termination shock

Striped equatorial zone

Just thermalization, $B_{\text{eff}} \sim$ large

Prediction: Inner not will not be seen in radio

Bogovalov 1999
Komissarov+ 2003
Porth+ 2014
Sironi +, 2011
Lyutikov+, 2016
Yuan + 2016
Conclusion 1

We made an important progress in understanding pulsar winds

- Equatorial sigma << 1 flow - shock acceleration in a narrow equatorial wedge
- Only thermalization at intermediate latitudes
- High sigma >> 1 polar flow - location of flares
- Origin of radio/optical particles
  - Nano-flares in the bulk?
  - Fermi-II in the bulk?
Part II: What about flares?

- Explosive reconnection and particle acceleration in relativistic plasmas
Crab flares: very demanding conditions on acceleration

- Acceleration by $E \sim B$ (energy gain & loss on one gyro radius)
- **on macroscopic scales $>>$ skin depth**
  - acceleration size $\sim$ thousands skins
  - acceleration size $\sim 0.1 - 1$ of the system size (in Crab)
- Few particles are accelerated to radiation-reaction limit - gamma $\sim 10^9$ for Crab flares (**NOT** all particles are accelerated)
- Slow accumulation of magnetic energy, spontaneously triggered dissipation
- (relativistic bulk motion)

Explosive Reconnection in relativistic plasmas
Dissipation in relativistic force-free plasma: resistive tearing mode

- Resistive force-free
  \[ j_\parallel = \frac{E_\parallel}{\eta} \]

- Formation of magnetic islands, just like in non-relativistic case

- Growth like in non-relat.:
  \[ \Gamma \sim \sqrt{\tau_\eta \tau_A} \]

- Fast, but not fast enough!

- Collisionless - fast on skin, slow on macroscopic scales

Reconnection driven by large scale uncompensated magnetic stresses
Large scale simulations

- Toroidally-dominated B-fields are unstable to large-scale kinks
- Formation of current-tubes

- Parallel currents attract. Can flux merger be the source of Crab flares?
2D force-free state with $\alpha - \text{constant}$

\[ B = \{-\sin(\alpha y), \sin(\alpha x), \cos(\alpha x) + \cos(\alpha y)\} B_0 \]  (A type of the “ABC” flow)

Is it stable?

- Detailed investigation of stability using analytical, relativistic fluid-type and PIC simulations (Lyutikov, + 2016)
Collapse of stressed magnetic X-point in force-free plasma (a la Syrovatsky)

Dynamics force-free:
- infinitely magnetized plasma:
- currents & charges ensure $\mathbf{E} \cdot \mathbf{B} = 0$, no particle inertia

$$\sigma = \frac{B^2}{4\pi \rho c^2} \gg 1$$

$$\mathbf{B} = \left\{ \frac{a^2}{\lambda^2}, \frac{y}{L} B_\perp, \frac{x}{L a^2} B_\perp, B_0 \right\}$$

$$\mathbf{E} = \left\{ \frac{y B_0}{c}, \frac{x B_0}{c}, -\frac{x^2 \lambda^2 + y^2 a^4}{c L \lambda^2 a^2} \right\} \partial_t \ln a$$

$$\partial_t^2 \ln a = A \left( \frac{a^4 - \lambda^2}{\lambda^4} \right), \quad A = \frac{c^2}{L^2} \frac{B_\perp^2}{B_0^2}$$

- **explosive dynamics** on Alfven time
- slow initial evolution
- Starting with smooth conditions
- Finite time singularity
- Driven by large-scale stresses
Theory, fluid and PIC simulations

Lyutikov +, 2017abc JPP

1-$E^2/B^2$ in force-free simulations
Can produce power-laws

PIC simulations by Sironi
Acceleration in X-point collapse: charge starvation

- Highly efficient acceleration by $E \sim B$
- Driven by large scale magnetic stresses - **wide-open X-point** (not like in tearing mode - flat X-point)
- Acceleration starts abruptly, when reaching **charge starvation.**
  - During collapse current density grows
    \[
    J_z \approx \frac{c}{4\pi} \frac{B_\perp}{L} a(t)^2
    \]
  - But $J < 2 n_e c$ - not enough particles to carry the current
  \[
  \text{curl} \mathbf{B} = \frac{4\pi}{c} J + \partial_t \mathbf{E}/c
  \]
  - E-field grows
  - Condition for charge starvation: $a(t) > \sqrt{\frac{L}{\delta} \frac{1}{\sigma^{1/4}}}$ (not too demanding for Crab)
Collapse of an ABC system of magnetic islands

Two stages:
- Fast acceleration, not much B-field dissipated (X-point collapse)
- Slower acceleration, dissipation (island merger)
Current attraction: two stages: "Free-fall" and "slow-resistive"

Initial attraction due to large-scale stresses
Quasi-steady (repulsion by the current sheet) - slow resistive reconnection
Two stages of particle acceleration: fast-impulsive and slow-resistive.
Merger of zero-current flux ropes

- No total current: no overall attraction force.
- First, resistive effects "eat out" the envelopes (slow)
- After ||-current learn of each other - large scale attraction
The problem with $\gamma_{\text{max}}$

- Average magnetic energy $\gamma \sim \sigma$
- Need $10^9$ - cannot accelerate all
- Evidence for high energy bump, presumably generated at the X-point collapse
- Even for $\sigma \sim 100s$, $p \sim 1.5$ can reach $10^9$

![Electron Spectrum](image)

![Ion Spectrum: time76](image)

If $\sigma \leq 100 \rightarrow p > 2$

$\gamma_{\text{max}} \gg \sigma$!
Flare statistics: isotropic flares

- Flares can be on top of persistent emission, OR
- all emission are flares – small ones average out

Clausen-Brown, Lyutikov 2012

\[ \rho(F)dF \propto F^{-\frac{q+1}{q}} dF \approx \frac{1}{F} dF \]

- average flare flux is dominated by bright rare flares.

Power-law from shot noise!
Where in Crab and AGNs?

\[ \epsilon_{\text{m,x}} \sim \Gamma \epsilon_{\text{m,eq}} \]

\[ \Gamma \sim \frac{1}{\theta} \]

- oblique shock, inner knot

Dissipation zone @ r < 1pc (approximately where

\[ B_\phi' \sim B_p' \]
Reconnection in magnetically-dominated plasma

- can proceed explosively
- efficient particle acceleration
- the explosive stage - X-point collapse - produces (seems to) a separate accelerated component
- is an important, perhaps dominant for some phenomena, mechanism of particle acceleration in high energy astrophysical sources.