Astrophysical pair plasmas

Andrei Beloborodov
Columbia University

1. Sites of pair creation
2. Shocks (explosions)
3. Magnetic reconnection
4. Electric discharge
Pair plasma is created in compact objects:

**Persistent sources:**
- accreting black holes
- pulsars, magnetars

**Explosions:**
- magnetar flares
- cosmological gamma-ray bursts (GRBs)
Energy transformation in compact objects

gravity -> kinetic energy -> magnetic fields, heat -> radiation

main ways of particle acceleration

reconnection, shocks, electric gaps
Explosions

Dissipation power up to $10^{54}$ erg/s in a region as small as 10 km.

Thermalized energy density $U \sim aT^4$

Temperatures $kT > m_e c^2 = 0.511$ MeV

Magnetic fields up to $B \sim 10^{16}$ G

Ultra-dense, neutron-dominated, object (a star or an accretion disk) surrounded by pair-dominated magnetized plasma with $kT \sim$ MeV. Powerful outflows/jets.

In the expanding ejecta: further dissipation of magnetic energy and bulk motions.

It is capable of producing high-energy particles and photons.
Main mechanism of pair creation: photon-photon collisions $\gamma + \gamma \rightarrow e^+ + e^-$

- Threshold: $E_1 E_2 > (m_e c^2)^2$
- Cross section near threshold: $\sigma_{\gamma\gamma} \sim 0.1 \sigma_T$
- Optical depth: $\tau_{\gamma\gamma} = \sigma_{\gamma\gamma} n_\gamma s$
- Compactness parameter:
  \[
  \ell \equiv \frac{U_{\text{rad}} \sigma_T s}{m_e c^2}
  \]

Radiative cooling

Compton cooling time $< $ light-crossing time

\[
\frac{t_{\text{cool}}}{s/c} \sim \frac{1}{\ell \gamma_e}
\]
Dissipation processes affected by pair creation

I. Shock waves in GRBs
GRB: opaque heated fireball (cf. big bang)

internal shocks — one of a few possible dissipation processes in the outflow (also magnetic dissipation, n-p friction)
$n_\gamma/n_b \sim 10^5$ \hspace{1cm} radiation mediated shocks

Zeldovich, Raizer 1966
Weaver 1976
Blandford, Payne 1981
Budnik et al. 2010
Levinson 2012
AB 2017

Do shocks generate energetic particles?
Do shocks create e+e- pairs?
ballistic flow: caustic

(rest frame of the caustic)

shock formation

\[ P_{\text{rad}} \propto \tilde{\rho}^{4/3} \]

\[ P_B = \frac{\beta^2}{8\pi} \propto \tilde{\rho}^2 \]
Radiation MHD from first principles: “Photon In Cell”

Fluid motion: Lagrangian grid

Radiation: individual photons
   Monte-Carlo scattering

1D problem: $\sim 10^4$ shells
   $\sim 10^8$ photons
Radiation mediated shock ($B=0$)

Bulk Comptonization, Klein-Nishina, and pair creation

$$n_{\pm} \sim 10^{-3} n_\gamma \quad Z_{\pm} \sim 10^2 \left( \frac{n_\gamma/n_b}{10^5} \right)$$
Shock in a magnetized flow

\[ p = \gamma \beta \]

\[ \log \frac{\rho}{\rho_u} \]

\[ w_u = 0.1 \]

\[ \sigma_u = 0.1 \]
Sub-photospheric shock: e+- dressed

\[ n_\pm / n_b \sim 10^2 \]
Radiation-mediated shock

cold plasma; pair creation without high-energy particles!
Consequences of pair creation:

— shock thickness shrinks
— pairs increase optical depth and give “grip” to radiation
— energy per electron is reduced

Shocks “carry” the photosphere with them. Velocity profile between upstream and downstream is shaped by radiation pressure + collisionless jump

Pairs in the shock are producers of inverse Compton and synchrotron radiation.
Pair creation by GRB radiation in the external medium
GRB 080916C

\( h_{\text{proj}} \left[ 10^{10} \text{ cm} \right] \)

\( (R-R_0) \left[ 10^{10} \text{ cm} \right] \)

\( R_0 = 1.5 \times 10^{16} \text{ cm} \)

\( \gamma = 1 \)

\( \beta = 0 \)

\( Z = 1 \)
shaped by e+e- creation

Hascoet, Vurm, AB (2015); Vurm & AB (2017)
shaped by e+e- creation
Dissipation processes affected by pair creation

II. Magnetic flares near accreting black holes
Self-similar chain of plasmoids: \( r_L < w < 0.1 \text{s} \)

- \( c_{\text{lab}}/L = 0.2 \)
- \( c_{\text{lab}}/L = 0.7 \)
- \( c_{\text{lab}}/L = 1.2 \)
- \( c_{\text{lab}}/L = 1.7 \)
- \( c_{\text{lab}}/L = 2.2 \)

- Uzdensky et al. 10
- Melzani et al. 14
- Sironi, Spitkovsky 14
- Guo et al. 16
- Sironi et al. 16
- Werner et al. 16
Radiative magnetic reconnection:

1. Magnetization: \[ \sigma = \frac{B^2}{4\pi \rho c^2} = \frac{2U_B}{\rho c^2} = 1 - 10^3 \]

2. Compactness: cooling time vs. light crossing time

\[ \frac{t_{IC}}{s/c} = \frac{3}{4\gamma_e \ell_{rad}} \]

\[ U_{rad}c \sim U_Bv_{rec} \]

\[ \ell_{rad} = \frac{U_{rad}\sigma_Ts}{m_e c^2} \]

\[ \ell_{rad} \sim \frac{v_{rec}}{c} \ell_B \]

\[ \ell_B = \frac{U_B\sigma_Ts}{m_e c^2} \sim 10^3 \]
Reconnection in the radiative regime
(high compactness parameter)

\[ \ell \gg 1 \implies \begin{align*}
1. & \text{ Plasmoids are cooled} \\
2. & \text{ Energetic photons (>1 MeV) convert to } e^+e^- \text{ pairs}
\end{align*} \]
Pair creation and optical depth

\[ \dot{n}_\pm \sim \frac{Y f_{\text{HE}} U_B}{t_{\text{res}} m_e c^2} \]

\[ \dot{n}_{\text{ann}} = \frac{3}{8} \sigma_T c n_+ n_- \]

\[ \tau_T \sim \frac{16}{3} \beta_{\text{rec}} \times \begin{cases} u, & u < 1 \\ u^{1/2}, & u > 1 \end{cases} \]

\[ u = (3/16) Y f_{\text{HE}} \ell_B \]

\[ \Rightarrow \quad \tau_T \sim 1 \]
Bulk motion of pair-loaded plasmoids

Magnetic stresses push plasmoids:
\[ f_{\text{push}} = \xi \frac{U_B}{w} \]

Radiation exerts drag:
\[ f_{\text{drag}} \approx \beta \gamma^2 U_{\text{rad}} \sigma_T n_\pm \]

Drag-limited motion:
\[ \gamma \approx \left( \frac{\tau_*/\tau_{\text{pl}}}{\tau_{\text{pl}}} \right)^{1/2} \quad (\gamma \leq \sigma^{1/2}) \]

\[ \tau_* \equiv \xi \frac{U_B}{U_{\text{rad}}} \approx \frac{\xi}{\beta_{\text{rec}}} \]
McConnell et al. 2002

AB 2017
III. Rotation-powered pulsars
- beamed coherent radio emission
- $X/\gamma$-ray emission
- e+-loaded wind
- beamed coherent radio emission
- X/γ-ray emission
- e+-loaded wind

Kuiper, Hermsen 2015
Pulsar magnetosphere: pair dominated

- Where is plasma created?
- How much plasma is ejected in a wind?
- Where are gamma-rays emitted?
- How are coherent radio waves emitted?

New approach to the old puzzle: global PIC simulations

Chen, AB 2014; Philippov et al. 2014, 2015; Cerutti et al. 2015, 2016; Belyaev 2015
First-principle numerical experiment

- Start with a non-rotating star and spin it up. E will be induced.

- Particles lifted from the star will move in the self-consistent electromagnetic field.

- E and B: fixed inside the star, calculated from Maxwell equations outside the star.

- Accelerated particles emit photons.

- High-energy photons convert to e+e-. 

\[
\begin{align*}
\frac{dp}{dt} &= eE + ev \times B / c \\
\frac{\partial B}{\partial t} &= -c\nabla \times E \\
\frac{\partial E}{\partial t} &= c\nabla \times B - 4\pi J
\end{align*}
\]
Method: “Particle in cell” (PIC) + pair creation:

- fields calculated on a grid
- particles followed individually
- photon emission, tracing, and pair creation: Monte-Carlo
Time = 0.08

electric current

Chen & AB 2014
aligned rotator

charge density: - blue    + orange
ion energy

matter/magnetic: $U_m/U_B$
Pair creation rate

\[ \dot{N}_{\pm} = 2\mathcal{M} \frac{I}{e} \]

\[ I \approx \frac{\mu \Omega^2}{c} \]

\[ \dot{N}_{\pm} t = \mathcal{M} N_0 \]

\[ N_0 \sim \frac{c^2 K}{e \mu} \sim 2 \times 10^{44} \mu_{31}^{-1} \]

— falls short for Crab nebula by 1-2 orders

Alternative plasma source for pulsar wind nebula: a compact shock at a young age (months to years):

PWN should contain pair-rich freeze-out
Magnetars
X-ray spectra: two peaks
(luminosity $10^{35}-10^{36}$ erg/s)

emitted by e+-pairs

AXP 4U 0142+61

Den Hartog et al. (2008)
twisted closed magnetosphere: j-bundle formation and slow untwisting

Chen & AB 2017: PIC simulations

e+- discharge controls magnetosphere evolution

\[
\frac{\partial B}{\partial t} = -c \nabla \times E
\]
Over-twisted magnetospheres: flares

Parfrey et al. 2013
Summary

- Energy release in compact sources is accompanied by copious pair creation

- Pair creation regulates the dissipation mechanism and dynamics

- Pairs dominate the plasma and shape its observed emission (synchrotron, inverse Compton)

More observational tests: annihilation line, polarization

Energy dissipation in compact objects: shocks, reconnection, electric discharge

More theory: PIC simulations of e+- ion plasma