Dynamics of magnetized outflows and electromagnetic model of short GRBs

Maxim Lyutikov (Purdue U., CITA)
Jet breaks

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At the afterglow stage **there is no jet, but a non-spherical shock**: dynamics of oblique shocks.
- Post-shock pressure equilibration ≠ spherical (c.f. Kompaneets model for atmospheric shocks)
- Driven $\Gamma \gg 1$ shocks do not “expand sideways”, unless $\Delta \theta < 1/\Gamma^2$ (Lyutikov 2011)
- Kompaneets ~ Laumbach-Probstein in the limit $\Gamma \gg 1$ (also Shapiro 1979)
- Numerical simulations in general agreement (van Eerten talk)
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- Numerous jet-break related calculations need to be reconsidered.
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\[
\Gamma \sim \left( \frac{L}{\rho c^3} \right)^{1/4} r^{-1/2} = 1200 r^{-1/2}_{16} L^{1/4}_{52}
\]

Poynting energy is well transferred to the FS (Lyutikov 2005)

Can FS be used to probe ejecta?

Only for extreme magnetization and only at very early times FS shows a difference between fluid and highly magnetized case

Lyutikov 2011
Magnetized ejecta. 2- Reverse shock

- Reverse shock forms at a finite distance, ~ $10^{16}$ cm for sigma ~ 1.
- **Two conditions** for reverse shock: weak and strong (in 1D compression wave always turns into shock, not necessarily in multi-D)

\[
\gamma_w > \sqrt{\frac{3}{8}} \sqrt{\frac{\rho_0}{\rho_{ex}}} \sqrt{\sigma}, \quad r_{RS, weak} = \frac{1}{\gamma_w^2} \sqrt{\frac{3\sigma L}{2\pi \rho_{ISM} c^3}} = 10^{16} \text{ cm } n^{-1/2}
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\gamma_w > \sqrt{6} \sqrt{\frac{\rho_0}{\rho_{ex}}} \sigma^{3/2}, \quad r_{RS, strong} = \sigma r_{RS, weak}
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- Highly variable optical emission (in fast cooling)?
- Shock corrugation (CD is RT unstable, fast variability)
- Simulations of magnetized ejects must be at least 2D
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\[V_{\text{CD}} < V_{\text{ej}} < V_{\text{CD}} + V_{\text{A}}\]

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Conditions in GRBs: FS & RS

Lyutikov 2012
Conditions in GRBs: FS & RS

Lyutikov 2012
- Dynamics of RS even in mildly magnetized outflows is considerably different from the fluid case.
- Only for extreme magnetization, and at very early times, the FS is sensitive to ejecta content.
BH hair & EM model of short GRBs
NS-NS merger as paradigm for Short GRBS

- Active stage of NS-NS merger takes 10-100 msec, then **collapse into BH**
- Transient NS - 100 msec, **(NOT 100 sec!)**
- Very little mass is ejected, drains out quickly
- Many short GRBs have long 100 sec tails, energetically comparable to the prompt spike.
- Many GRBs have late time flares, $10^5$ sec

100 sec tail has ~ 30 times more energy than the prompt spike
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**BH hair**

100 sec tail has ~ 30 times more energy than the prompt spike
Newly formed isolated spinning astrophysical black holes can keep magnetic fields for times much longer than predicted by the “No hair” theorem, powering an electromagnetic outflow
- Rotating NS - unipolar inductor
  - generate plasma out of vacuum
  - open B-field lines to infinity
- Blandford & Znajek: BHs do the same
- Outside plasma: $E \cdot B = 0$ - frozen-in B-field
- If a BH keeps producing plasma, like a NS, B-field cannot slide off: **field lines that connected NS surface to infinity, has to connect horizon to infinity**

The “no hair” theorem is not applicable to collapse of rotating NSs: high plasma conductivity introduces topological constraint (frozen-in B-field).

Conserved number: open magnetic flux:

$$N_B = e \Phi_\infty / (\pi c \hbar)$$

$$\Phi_\infty \approx 2\pi^2 B_{NS} R_{NS}^3 / (P_{NS} c)$$

Can be measured at infinity: BH hair
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Goldreich & Julian, 1969
BH can only have open field lines: split monopole magnetosphere

- Analytics: time-dependent B-field in Schwarzschild geom.

\[ B_\phi = -\frac{R_s^2 \Omega \sin \theta}{\alpha r} B_s, \quad B_r = \left( \frac{R_s}{r} \right)^2 B_s, \]

\[ E_\theta = B_\phi, \quad j_r = -2 \left( \frac{R_s}{r} \right)^2 \cos \theta \Omega B_s \frac{\alpha}{r}, \]

\[ \Omega \equiv \Omega \left( r - t + r(1 - \alpha^2) \ln(r \alpha^2) \right) \quad \alpha = \sqrt{1 - 2M/r} \]

Take a relativistic object with monopolar B-field, rotate it **arbitrarily** (slowly, \( a \ll 1 \)). The field will remain monopolar.
Simulations (Lyutikov & McKinney, 2011)

- Split-monopole magnetosphere
- Slow balding

\[ \text{BH} \]

\[ z \frac{c^2}{GM} \]

\[ R \frac{c^2}{GM} \]

\[ 10^2 \]

\[ 1 \]

\[ 0.1 \]

\[ 0.01 \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 10^{-8} \]

\[ 10^{-9} \]

\[ 10^{-10} \]

\[ 10^{-11} \]

\[ 10^{-12} \]

\[ 0 \]

\[ 2 \times 10^2 \]

\[ 4 \times 10^2 \]

\[ 6 \times 10^2 \]

\[ 8 \times 10^2 \]

\[ 10^3 \]
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Tuesday, April 16, 2013
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Tearing mode developing

$R \frac{c^2}{GM}$

$z \frac{c^2}{GM}$

$\phi_{EM}$

$t \frac{c^3}{GM}$

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Fields are contained by the equatorial current, just like in BZ, but this current is self-produced

Tuesday, April 16, 2013
The electromagnetic model of short GRBs

- NS-NS merger generates $B \sim 10^{15}$ G in the torus around BH (Rezzolla et al.)
- BH-torus launches a jet along the axis: prompt spike
- After $\sim 100$ msec torus collapse, isolated BH spins down electromagnetically, produces equatorially-collimated flow, $L \propto \sin^2 \theta$: prompt tail
- Tail is more energetic, but de-boosted for axial observer
- Very late re-brightening of the remnant

Rezzolla et al.
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Rezzolla et al

SN-less long GRBs (GRB060505,060614)
Long & short GRBs: similarities

- Both Longs and Shorts are powered electromagnetically, by fast-spinning BHs, ~ Faraday disk
- High polarization of prompt

- Acceleration by reconnection (efficient, highly variable)
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\[ \Omega \]

\[ B\text{-field} \]

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Acceleration by reconnection (efficient, highly variable)
Fast variability from large radii, $R_{em} \sim 10^{15}-10^{16}$ cm

- Emission is beamed in outflow frame
  - really beamed $\Delta \theta_{em} \ll 1$
  - random internal motion of emitters, $\Delta \theta_{em} \sim 1/\gamma_{rand}$

- X-flares and breaks are tails of prompt
- Fast variability
- No need for long central engine activity
- Softening with time, harder spikes
- These are preliminary results: alternatives need to be investigated

$\Gamma_{bulk} = 50$, $\gamma_{rand} = 5$
$\theta_{ob} = \pi/10$, $\theta_{jet} = 3 \theta_{ob}$
Efficiency 10%
Observed emission can be highly variable and with high efficiency, tapping into large $V$

\[ \Gamma_{\text{eff}} = 2\Gamma\gamma_{\text{rand}} \]

\[ \Delta t \sim \frac{c}{R} \frac{1}{8\Gamma^2\gamma_{\text{rand}}^2} \]

Relativistic reconnection **within** the outflow: jets with $\gamma_{\text{out}} \sim \sigma \gg 1$

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**Crab flares inconsistent with stochastic acceleration at shocks: reconnection**

Accelerating E-field < B-field

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

\[ E_p = \frac{27}{16\pi} \eta \frac{mhc^3}{e^2} = 236 \eta \text{ MeV.} \]
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Conclusion: BH hair & short GRBs

- The “no hair theorem” is not applicable to rotating magnetized NSs collapsing into BH: open magnetic field lines are retained
- Isolate BHs spin down electromagnetically
- May explain long prompt tails
- Some long GRBs are mis-identified short, SN-less ones