Resolving Doppler factor crisis in AGNs: non-steady magnetized outflows

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Radio-gamma correlation & TeV-GeV relation

- Radio-gamma correlation is well established
  - Details not clear:
    1. radio or gamma leads, if any; (gamma leads-Pushkarev)
    2. OR radio starts before, but peaks after gamma
    3. is gamma generated within the radio-mm optically thick region or outside?
- TeV-GeV
  - TeV and GeV AGNs are (half) different: TeVs are mostly HBLs, half of GeVs are FSRQs
  - GeV variable on ~ hour, probably cannot do shorter due to low counts (TeV ~ minutes).
Doppler factor crisis in AGNs
Henri & Sauge 2006

• Radiative modeling of TeV flares requires $\delta_{\text{TeV}} \geq 100$
  - Fast variability $\Delta t \rightarrow \Delta t' / \Gamma^2$
  - Compactness parameter $\tau \rightarrow \tau' / \Gamma^6$
  - (I will mix up a bit TeV-GeV data. At least both IC.)
• Direct observations of superluminal radio knots imply $\delta_{\text{knot}} \leq 10$
  - MOJAVE: blobs motion reflects underlying flow (bidirectional motions, no inward moving features, multiple blobs in the same jet with the same speed, correlations of jet speeds with other properties)
• Somewhat similarly (?) GeV photons in GRB 080916C $\rightarrow$ Gamma $\sim 2000$.

Natural resolution: separate radio and GeV-TeV sites:
  - in space (fast spine, slow sheath)
  - time/space (decelerating jets, Georganopoulos & Kazanaz 2003)
  - space: this work: accelerating jets
AGN launching: large-scale B-fields

- AGN (and GRB) jets are magnetically accelerated and collimated (Blandford&Znajek, Blandford&Payne).
- $c_s \sim c$, crossing time of SMBH $\sim$ minutes-hours.
- Relax to **steady state**

Observations indicate non-stationarity, blob ejection etc. Probably related to instabilities of the inner disk
- Clear disk-jet connection in galactic BHs
- Some indication in AGNs (3C 120)
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What are the consequences of non-stationary jet injection?
Acceleration: pressure- & magnetic-driven, Newtonian, Relativistic.

Fluid, non-relativistic:
Stationary:
\[ v_{\text{max, stationary}} = \sqrt{\frac{2}{\gamma_{ad} - 1}} c_{s,0} \sim c_{s,0} \]

Non-stationary:
\[ v_{\text{max, non-stationary}} = \frac{2}{\gamma_{ad} - 1} c_{s,0} > v_{\text{max, stationary}} \]

MHD, relativistic:
\[ \sigma = \frac{B^2}{4\pi \rho c^2}, \quad \Gamma_A = \sqrt{1 + \sigma} \]

There is enough energy to have \( \Gamma \sim \sigma \)

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Most internal energy is converted into bulk.

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In non-stationary magnetically-driven expansion $\Gamma_{max} = 1 + 2\sigma$

Leading edges of non-stationary outflows can accelerate to much higher Lorentz factors and may dominate highly boosted high energy emission.

Steady state: $\Gamma \sim \sigma^{1/3}$
Modern shock-capturing numerical schemes (Godunov) are based on Riemann invariants. Exact non-linear solutions are rare, needed for code testing.

Marti&Muller (1996) found $J_{\pm}$ we found shape of characteristics.
Testing theory and codes

Two (!) curves for density: analytical (Lyutikov) and simulations (Komissarov). Codes can deal with high magnetization, high Lorentz factors, large density contrast.
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$$\sigma = 30$$

$$\Gamma \sim \sigma^{1/3}$$
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Non-stationary jet injection in static corona

At sufficiently large radii,

\[ r_{\text{breakout}} \geq \left( \frac{\xi}{\theta_j} \right)^{2/3} \]

\[ r_{BH} = 2 \times 10^{16} \text{ cm} M_\odot, 9 \xi^{2/3} \theta_j^{-2/3} \]

Variations of launching proceed on time scales shorter than the dynamical time scale across the jet,

\[ t_{dyn} \sim r \Theta_j / c_s \]

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Variations in disk/lifting
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**TeV/GeV flares and radio blobs**

TeV and GeV emission in blazars is produced in the leading expansion edge moving with $\Gamma \sim 100$, while the observed velocities of the radio blobs correspond to the bulk motion with $\Gamma \sim 10$.

**Before breakout**

$$\gamma_w = \left( \frac{L}{\rho_{\text{ex}} c^3} \right)^{1/4} r^{-1/2} \sim 10$$

**After breakout:**

- leading edge: $\gamma \sim 4\gamma_w \sigma \sim 100$
- bulk: $\gamma \sim 2\gamma_w \sigma^{1/3} \sim 10$
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Can accommodate short variability and compactness.
TeV/GeV flares and radio blobs

TeV and GeV emission in blazars is produced in the leading expansion edge moving with Gamma ~100, while the observed velocities of the radio blobs correspond to the bulk motion with Gamma ~10.

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Radio blobs
Predicted correlations

- Cores are optically thick at $r_{\gamma}$, typically $r_c > r_{\text{breakout}}$:
  
  $$r_{\text{core}} \approx 1.4\text{pc} \frac{\zeta_R^{2/3} L_{46}^{2/3}}{R^{1/3} \nu_9}$$
  
  $$r_{\text{breakout}} \geq \left( \frac{\xi}{\theta_j} \right)^{2/3} r_{BH} = 2 \times 10^{16} \text{ cm} M_\odot, 9 \zeta_2^{2/3} \theta_j^{-2/3}$$

- Jet breakout will occur while the jet is still optically thick in radio.
  
  $$\Delta t_{\gamma-R} \sim \frac{r_{\text{core}}/c}{2 \gamma_w^2} \sim \text{weeks} - \text{months}$$
  
  $$\gamma_{\text{Gev}} \sim 4 \gamma_w \sigma \sim 100$$
  
- Gamma-rays correlate with radio leading by $\sim$ weeks
  
  $$\gamma_R \sim 2 \gamma_w \sigma^{1/3} \sim 10$$

- Better correlated (shorter delay) at higher radio frequencies

- Acceleration at large $r$: avoid Compton drag near BH.
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Radio-gamma correlation

Gamma-rays-radio correlation with ~ months delay (Pushkarev et al 2010), radio 15 GHz trailing.
Morphologies

- Jet morphology: higher gamma blobs merge later (e.g. variable jets in FSRQ); low gamma: smooth jets in LBLs).

High Gamma, late merging, knotty jet

Low Gamma, early merging, smooth jets
Predicted correlations

- Fermi-detected have higher Gamma
- Jets of gamma-ray-selected AGNs are more aligned than those in radio-selected (but: mini-jets?)
- Gamma-ray emission is more boosted than radio, shorter variability times

\[
\Gamma = 40
\]

\[
\Gamma = 20
\]

Acceleration on 1-10 pc - observed? (Lobanov)
Conclusion

- Non-stationary outflows can accelerate much more efficiently than stationary ones.
- Beaming in GeV-TeV is different from beaming in radio (prediction)
- Gamma rays generated ~ 0.1 - 1 pc from BH, at blob leading edge, mostly inside optically thick region
- The model is able to accommodate both the requirement of small optical depth for gamma-ray photons, short time-scale variability and slow speeds in radio
- Key prediction: radio-gamma delay, confirmed by Fermi (?)
- We do not specify how emission is generated; Blandford: it does not matter, Doppler beaming dominates
- Exact non-linear solutions to the Riemann problem can be used for code testing (and are cute)
Mini-jets


- HST1 in M87: high r, short variability
- Pic A: knots (~kpc) vary on 1yr
Observed emission can be highly variable and with high efficiency (tapping into most of the proper volume).

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

- Spectrum is harder during flare (Burrows et al. 2005).
- Are flares becoming longer and softer as function of flare time?
- Can some Shorts be “one spike Long”? (failed SN-type)
- Can explain optical -gamma correlations in 080319B? E.g. emitting “blobs” expand, killing both

- Relativistic reconnection: jets with \( \gamma_{\text{out}} \sim \sigma \gg 1 \) (Lyutikov & Uzdenski 2004)

- Not fluid “turbulence”, \( \gamma_{\text{rand}} \sim \sqrt{9/8} = 1.06 \)
- RM & RT instabilities will produce \( vT \ll c \) turbulence


Turbulent reconnection (Lazarian & Vishniac)