Blazar jets: new clues and old challenges

Fabrizio Tavecchio
(INAF-OAB, Italy)
New clues:
Clues on particle acceleration from X-ray polarization
A stratified shock model for high synchrotron peak BL Lacs

Old challenges:
Extreme blazars: acceleration at recollimation shocks?
Jets: the fundamental questions

Jet dynamics, speed, composition, power

Magnetic fields, dissipation, acceleration and emission mechanisms

Formation, collimation, acceleration

e.g. Blandford et al. 2019
Blackman and Lebedev 2022
Particle acceleration: many places, several processes

Matthews et al. 2020
Jets pointing at us: blazars

SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

\[ L_{\text{obs}} = L' \delta^4 \]
\[ \delta = \frac{1}{\Gamma(1 - \beta \cos \theta_v)} \]

Synchrotron and IC in leptonic models.

Also hadronic scenarios (synchrotron or photo-meson emission)
One zone models

e.g. Tavecchio et al. 1998
Beyond one-zone  An incomplete list ...

Ghisellini, FT & Chiaberge 2005

Chen et al. 2011

Marscher 2014

Kinetic

Magnetic

Comisso, Sobacchi et al. 2020

Zhang et al. 2018, Bodo et al. 2020

Christie et al. 2019, 2020
HBLs: extreme accelerators

- Synchrotron
- Inverse Compton
- TeV energies

Mkn 421

High-energy, freshly accelerated electrons

\[ h\nu_X = 1 - 10 \text{ keV} \]

\[ \gamma_X = \left( \frac{2\pi m_e c\nu_X}{eB\delta} \right)^{1/2} \sim 10^5 - 10^6 \]

\[ ct_{\text{cool}} = 2.3 \times 10^{15} B_{-1}^{-2} \gamma_{X,6}^{-1} \text{ cm} \]

Compact regions

\( t_{\text{var}} = 4 \text{ h} \)

\( t_{\text{var}} = 24 \text{ h} \)

X-rays
One zone modeling: results

- High electron Lorentz factors
- Low magnetic field (subequipartition)
Hints from IXPE (1)

Stratified shock?

Liodakis et al. 2022

Analogue results for: PG 1553+113 (Middei et al. 2023), 1ES 0229+200 (Ehlert et al. 2023), and others in the pipeline
Magnetic fields at shocks

**Compression**
- Shock $\rightarrow$ particle acceleration (DSA/magn. reconnection)
- B-field compression

**Self-generated field**
- Trans-relativistic, nearly parallel, low $\sigma$ shock

- $\Gamma_0 = 1.5$, $\sigma = 0.1$, $\theta_{B,0} = 10^\circ$

**Figures**
- a) Density profile
- b) Amplified B-field
- c) Angle $\theta_B$
- d) Angular distribution

**References**
- e.g. Laing 1980
- Angelakis et al. 2016
- Sironi et al. 2015
- Caprioli & Spitkovsky 2014
- Vanthieghem et al. 2020
Stratified shock: a toy model

\[ \nu_s \propto \gamma^2 B \]

Reminiscent of “X-ray first” behavior in large scale jets? (E. Meyer’s talk)

Tavecchio et al. 2018, 2020
Stratified shock: a toy model

Just two possible realizations! A full exploration of the parameter space is required (MCMC)

$B_\perp(d) = B_{\perp,0} \left[1 + \frac{d}{\lambda}\right]^{-m}$

Phenomenological law for the field
e.g. Lemoine 2013

$\Gamma = 22, \theta_v = 1.3^\circ$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\gamma_{cut} \times 10^5$</th>
<th>$n$</th>
<th>$n_{e,0}$</th>
<th>$B_{\perp,0}$</th>
<th>$B_z$</th>
<th>$r_j \times 10^{15}$</th>
<th>$\lambda$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.5</td>
<td>2.1</td>
<td>20</td>
<td>0.25</td>
<td>0.03</td>
<td>4.3</td>
<td>$5 \times 10^{13}$</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>12.6</td>
<td>2.2</td>
<td>30</td>
<td>0.25</td>
<td>0.03</td>
<td>4.8</td>
<td>$1.2 \times 10^{12}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Stratified shock: a toy model

Electron distribution at different distances

Radiative cooling only

Emission profiles

Tavecchio in prep.

\[ B_\perp(d) = B_{\perp,0} \left[ 1 + \frac{d}{\lambda} \right]^{-m} \]
Shock acceleration?

DSA can work efficiently only in weakly magnetized jets (e.g. Sironi+2015)

This is consistent with SED modeling (e.g. FT+2016)

This is **inconsistent** with jet production models (e.g. Komissarov et al. 2009)
Hints from IXPE: 2) limits to turbulence

The observed steadiness of the polarization effectively limits the level of (macro)turbulence

Magnetic (high magn.)

Kinetic (low magn.)

Zhang et al. 2023

e.g. Marscher & Jorstad 2022
Hints from IXPE: 3) EVPA rotations

Mkn 421

Observed during relatively high states

Di Gesu et al. 2023
See also Kim et al. 2023

\( \Psi \approx 80 \text{ deg/day} \)

\( \Psi \)\non-axysimmetric field (e.g. shock)

Marscher et al 2008, 2010

\( \Psi \)\non-axysimmetric feature (e.g. shock)

Koenigl & Choudhuri 1985
LSP: emission mechanisms and matter content

Constraining lower limits from IXPE (below optical)

Leptonic (SSC) preferred? Yes, but...

(One zone) Hadronic models predicts a relatively large polarization of the raising portion of the high-energy bump (synchrotron from protons and decay products)

Middei et al. 2022

Zhang & Boettcher 2013
LSP:
emission mechanisms and matter content

What about a stratified scenario?

Small volume. Large $\Pi$
$ct_{\text{cool, e}} \sim 3 \times 10^{13}$ cm

Large volume. Low $\Pi$
$ct_{\text{cool, p}} > 1 \text{pc}

B = 10 G
Which kind of shock?

(mildly) relativistic shock  \rightarrow  Sub-relativistic downstream (in the shock frame)

Substantial beaming of the downstream emission  \rightarrow  Large \Gamma of the shock in the observer frame if the shock is of normal incidence

Traveling relativistic shock

$$\Delta z \sim c \Delta t \Gamma_{sh}^2 \approx 1 \text{ pc}$$

in 1 day (observed)

Modeling provides consistent parameters even for very distant epochs (months)

\rightarrow  \text{oblique standing shock?}

Sokolov et al. 2004, 2005
Tagliaferri et al. 2008
Zech & Lemoine 2021
Recollimation shocks

2D simulations
Chain of recollimation shocks

Komissarov & Falle 1997
Bromberg & Levinson 2007

Fichet de Clairfontaine et al. 2021

Costa et al. in prep
Instabilities

**HD jet**

Rayleigh-Taylor/centrifugal + Richtmyer-Meskov instabilities

Matsumoto et al. 2017, 2021
Komissarov & Gougouliotos 2018
Abolmasov & Bromberg 2023

Costa et al. in prep
Instabilities

MHD jet

Sufficiently large B field can stabilize the jet

Low magn.

High magn.

Matsumoto et al. 2021
Extreme BL Lacs

Observed spectrum

Hard de-absorbed spectrum

Hard X-ray spectrum

Small radio flux

Costamante et al. 2001
Review in Biteau et al. 2020

Bonnoli et al. 2015
Stawarz et al. 2004
Zech & Lemoine 2021
Extreme BL Lacs

One zone model
Large minimum electron energy
Very low B

Costamante et al. 2018

<table>
<thead>
<tr>
<th>Source</th>
<th>$\gamma_0$</th>
<th>$n_0$</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$B$</th>
<th>$K$</th>
<th>$R$</th>
<th>$\delta$</th>
<th>$U_d/U_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IES 0229+200$^a$</td>
<td>–</td>
<td>–</td>
<td>100</td>
<td>$1.1 \times 10^6$</td>
<td>2</td>
<td>$10^7$</td>
<td>1.4</td>
<td>3.35</td>
<td>0.002</td>
<td>6</td>
<td>0.8</td>
</tr>
<tr>
<td>IES 0229+200$^b$</td>
<td>–</td>
<td>–</td>
<td>$2 \times 10^4$</td>
<td>$1.5 \times 10^6$</td>
<td>2</td>
<td>$10^7$</td>
<td>2.0</td>
<td>3.4</td>
<td>0.002</td>
<td>$10^3$</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Extreme BL Lacs

Hard electron distribution from multiple shock crossing in a recollimating jet.

\[ \frac{dN_{>}}{d\gamma_{>}} = \frac{(s - 1)^{n+1}}{n! n^{-s} \gamma_{\min}^{-n}} \left( \frac{\gamma_{>}}{\gamma_{\min}} \right)^{-s} \ln \left( \frac{\gamma_{>}}{\gamma_{\min}} \right)^{n}. \]

Stawarz et al. 2004
Zech & Lemoine 2021

But instabilities?
Extreme BL Lacs: low $\sigma$, unstable jets?

Tavecchio, Costa & Sciaccaluga 2022
Extreme BL Lacs: low $\sigma$, unstable jets?
Extreme BL Lacs: low $\sigma$, unstable jets?

But IXPE again…

$\Pi_X = 18\%$  
In the prototype 1ES 0229+200  
Ehlert et al. 2023

The most polarized BL Lac!  
Incompatible with turbulence?
Final thoughts

X-ray polarization of HSP: stratified shock? Need for realistic physical models!

Extreme blazars: acceleration at recollimation shocks? Better characterization of role of instabilities/turbulence in particle acceleration
THANK YOU!
Energizing the particles

Contopoulos 1994
Komissarov et al. 2009
Tchekhovskoy et al. 2009
Magnetic field generation at shocks

Compressed (circularly polarized) Alfven waves self-generated by accelerated protons streaming upstream

Caprioli & Spitkovsky 2014
## Polarimetry in the X-ray band

### Possible alternatives and predictions

<table>
<thead>
<tr>
<th></th>
<th>Optical</th>
<th>Medium-Hard X-Rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock (turbulent)</td>
<td>$\Pi \lesssim 15%$, variable; $\chi$ variable, smooth rotations possible</td>
<td>$\Pi \lesssim 30%$, highly variable highly and rapidly variable</td>
</tr>
<tr>
<td>Shock (self-produced field)</td>
<td>$\Pi \lesssim 20%$, slowly variable, flips by $\Delta \chi = 90\deg$</td>
<td>$\Pi \gtrsim 40%$ substantially constant, constant $\chi = 0$</td>
</tr>
<tr>
<td>Reconnection (kink-induced)</td>
<td>$\Pi \lesssim 20$–$30%$, moderately variable smooth rotations, $\Delta \chi \gtrsim 90\deg$</td>
<td>same as optical as optical</td>
</tr>
</tbody>
</table>

---

Tavecchio 2021
Stratified shock: a toy model

Tavecchio et al. 2018, 2020
Stratified shock: a toy model

For a fixed SED!

\[ \zeta = \Gamma \theta_v \]

\( \zeta = 1 \)
0.8
0.6
0.4
0.2
0

Decreasing angle

Dependence on the observing angle

Tavecchio in prep.