Relativistic reconfinement shocks

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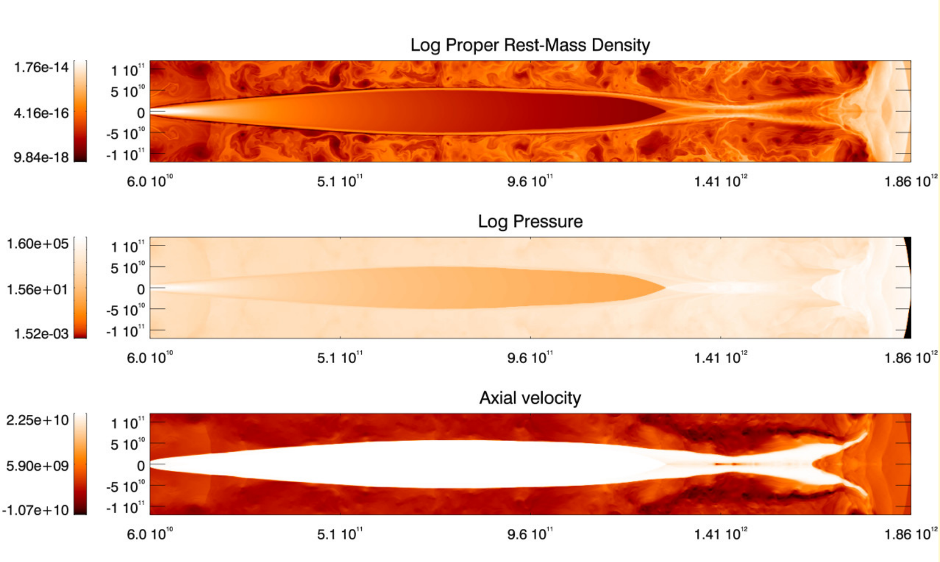
Outline

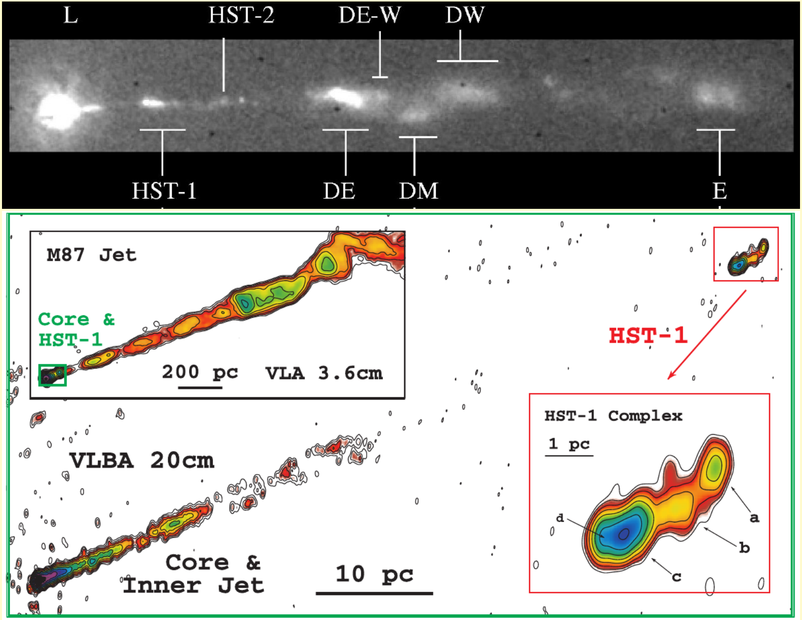
- HST-1
- 2005 outburst of 3C 454.3
- energy dissipation efficiency
- polarization

Basic concept

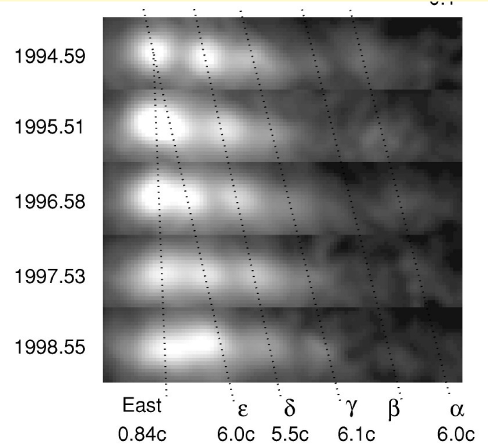


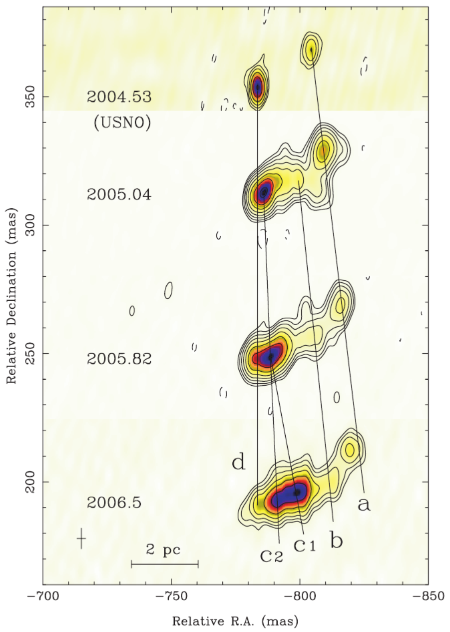
(Perucho & Bosch-Ramon 2008, A&A, 482, 917)

HST-1


L
HST-2
DE-W
DW
HST-1
DE
DM
E
M87 Jet
Core &
HST-1
200 pc
VLA 3.6cm
VLBA 20cm
Core &
Inner Jet
10 pc
HST-1
HST-1 Complex
1 pc
a
b
c
d

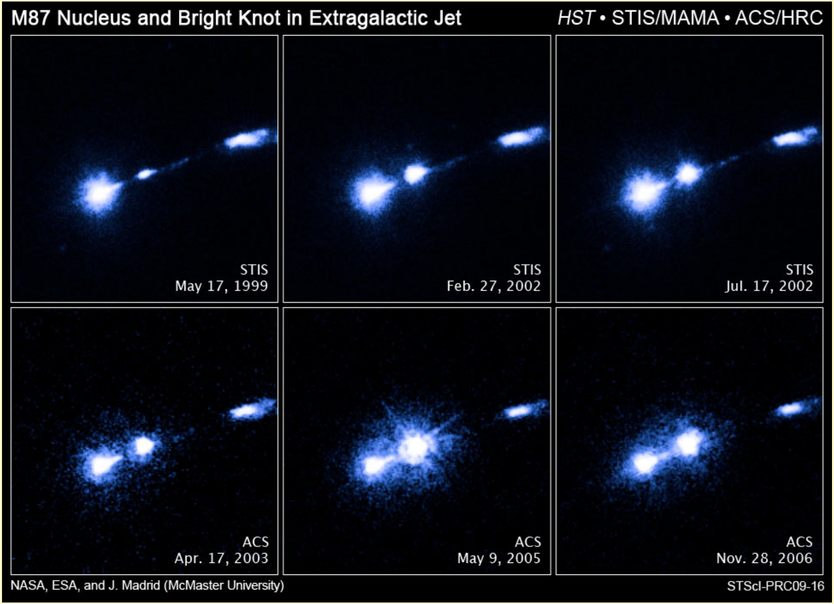
The knot itself appears stationary, but it emits superluminal features.



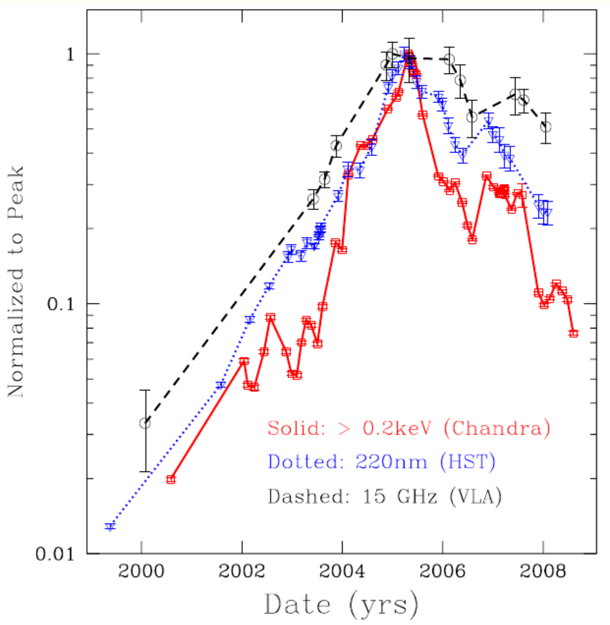


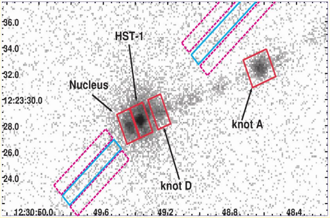
(*Biretta et al. 1999, ApJ, 520, 621*)
(*Cheung, Harris & Stawarz 2007, ApJL, 663, 65*)

HST-1


M87 Nucleus and Bright Knot in Extragalactic Jet
HST • STIS/MAMA • ACS/HRC
STIS
May 17, 1999
STIS
Feb. 27, 2002
STIS
Jul. 17, 2002
ACS
Apr. 17, 2003
ACS
May 9, 2005
ACS
Nov. 28, 2006
NASA, ESA, and J. Madrid (McMaster University)
STScI-PRC09-16

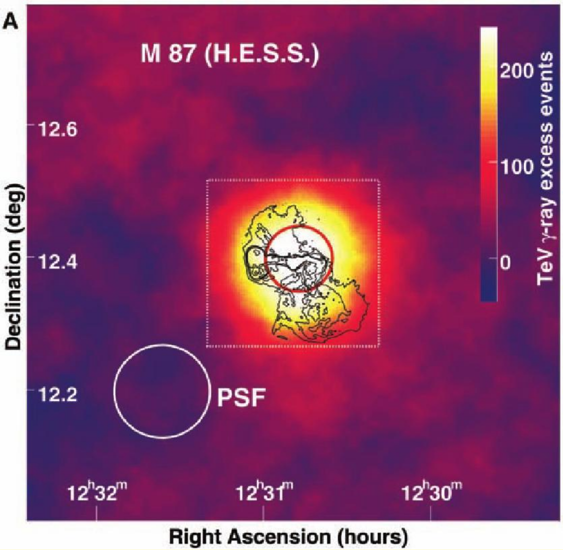
HST-1

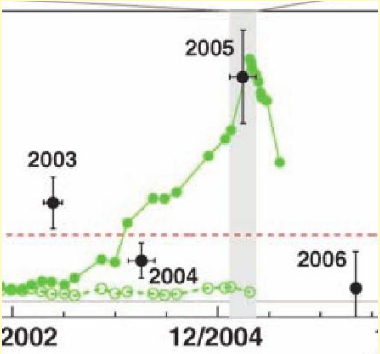




(*Harris et al. 2009, arXiv:0904.3925*)

HST-1





(HESS Collaboration 2006, Science, 314, 1424)

Is TeV emission coming from HST-1?

- Separation between HST-1 and the nucleus of M87 is $0.8''$ (projected distance 62 pc).
- This is not a blazar ($\theta_{obs} \sim 30^\circ$), hence limited Doppler boosting.

Constaints on the size of flaring region:

- From VLBI imaging: $0.15\ \mathrm{pc}$,
- From X variability timescale: $0.02\mathcal{D}\ \mathrm{pc}$,
- From TeV variability timescale: $0.002\mathcal{D}\ \mathrm{pc}$,

(*Cheung, Harris & Stawarz 2007, ApJL, 663, 65*)

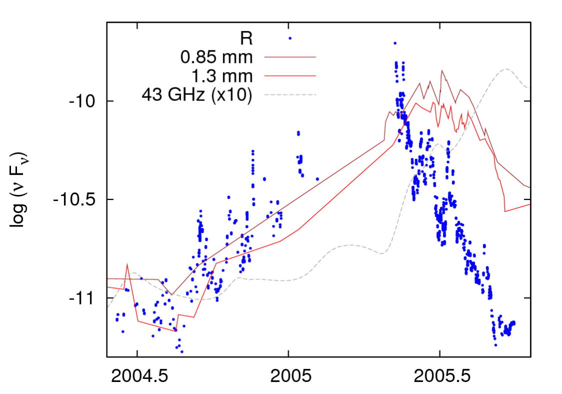
Mechanism behind the radiation origin:

- Simultaneous flare in radio, optical and X-rays strongly suggests common, i.e. synchrotron origin.
- The TeV flare could be produced by IC scattering of ambient photons on synchrotron-emitting electrons.

(Stawarz et al. 2006, MNRAS, 370, 981)

Other possibility is that it originates in the vicinity of SMBH.

2005 outburst in 3C 454.3

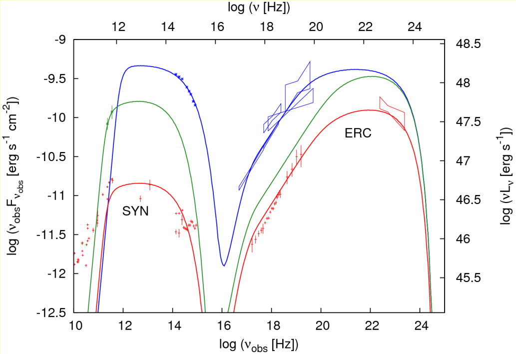


We compared the light curves in the optical (from WEBT) and mm (from IRAM) bands:

- The growing parts are very similar, the flux doubles on time scale $\sim$ 3 months;
- We see a 3-month plateu around the mm maximum, but there are no data indicating a similar feature in optical light curve;
- The decay is much faster, with mm light curve lagging $\sim$ 2 months behind the optical one.

We argue that the data are consistent with a cospatial emission in mm and optical bands.

2005 outburst in 3C 454.3



The data were fitted with a one zone model consisting of Synchrotron and External-Radiation-Compton (where the soft photons is the hot dust thermal emission) components. The Synchrotron-Self-Compton component is low, due to large Lorentz factor $\Gamma = 20$.

The spectral index between the two mm bands is $\alpha_{mm} \sim -0.2$ ($F_\nu \propto \nu^\alpha$), which is between optically thin spectrum ($\alpha = -1$) and self-absorbed spectrum ($\alpha = 5/2$), thus we have secure estimate for the characteristic self-absorption frequency (which corresponds to $\tau \sim 1$):

$$\nu_{abs} \sim 190 \frac{[\nu_{abs} L_{SYN}(\nu_{abs})]^{2/7} B^{1/7}}{R^{4/7}} \ \mathrm{MHz}$$

This gives us the size of the emission zone $R_{mm} \sim 1.5 \times 10^{18}$ cm and it's position $r_{mm} \sim \Theta_j R_{mm} \sim R_{mm}/\Gamma \sim 2.8 \times 10^{19}$ cm $\sim$ 10 pc.

2005 outburst in 3C 454.3

Note that in 3C 454.3 10 pc corresponds to $5 \times 10^4\ R_g$ ($M_{bh} \sim 4 \times 10^9\ M_\odot$).

The variability timescale is determined by the light travel time across the blob:
$t_{mm} \geq R_{mm}/\Gamma c \sim 1$ month.

We argue that the emission zone is much further than in models involving Comptonization of the Broad Emission Lines ($r_{mm} \sim 3 \times 10^{16}\ \mathrm{cm}$).

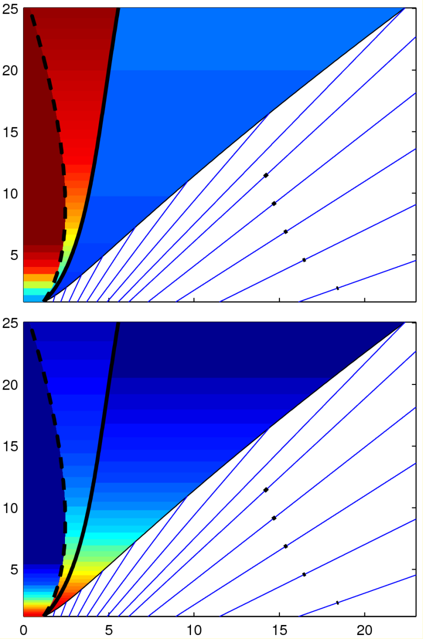
Dissipation model based on internal shocks provides an order-of-magnitude estimate for the location, where the collision takes place:
$r_0 \sim \Gamma^2\ R_g \sim 400 R_g \sim 3 \times 10^{17}\ \mathrm{cm} \sim 0.1\ \mathrm{pc}$.

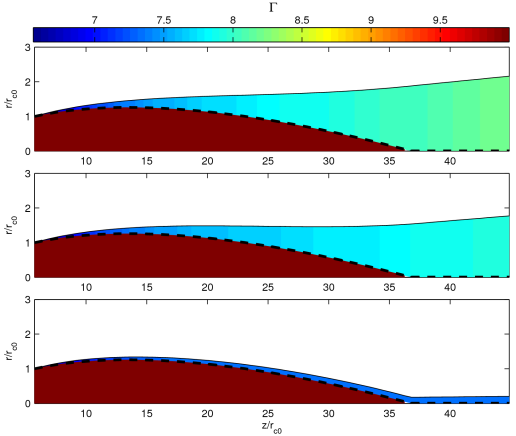
The dissipation process responsible for the outburst could be due to a reconfinement shock, since they are expected on scales similar to the one inferred from the emission zone radius.

A faster flux variability ($\sim$ 10 days) is seen in mm data. This can be explained by internal shocks, since the variability timescale at r_0 is
$t_{var} \geq R_0/\Gamma c \sim 7\ \mathrm{h}$.

(Sikora et al. 2008, ApJ, 675, 71)
(Nalewajko 2007, MSc Thesis)

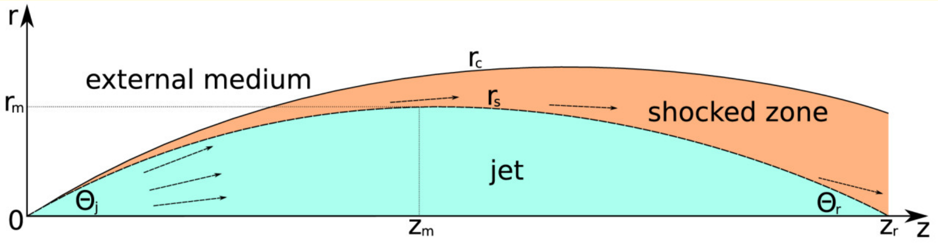
Semi-analytical modeling





(Bromberg & Levinson 2007, ApJ, 671, 678)
(Bromberg & Levinson 2009, arXiv:0810.0562)

Semi-analytical modeling



- dynamical:
  - Γ_j – jet Lorentz factor
  - L_j – jet total power
  - $p_e(z)$ – external pressure
- geometrical:
  - $r_s(z)$ – shock front
  - $r_c(z)$ – contact discontinuity
  - Θ_j – half-opening angle
  - Θ_r – half-closing angle
  - z_r – position of the recollimation nozzle
  - r_m – maximum jet radius

- exact relativistic shock jump equations
- approximate treatment of shocked zone taking into account transverse pressure gradient
- synchrotron emissivity proportional to local energy dissipation rate
- linear polarization from compressed chaotic magnetic field according to *Hughes et al. 1985, ApJ, 298, 301*

Position of the recollimation point

Position of the recollimation nozzle can be estimated analytically for a power-law profile of external pressure $p_e(z) = p_0(z/z_0)^{-\eta}$:

$$z_r \sim z_0 \left(1 + \delta \frac{\Lambda}{z_0}\right)^{1/\delta} ,$$

where $\delta = 1 - \eta/2$ and

$$\Lambda \sim 0.7\sqrt{\frac{L_j}{p_0 c}} \sim 0.9\sqrt{\frac{L_{j,46}}{p_{0,-2}}}\,\mathrm{pc} .$$

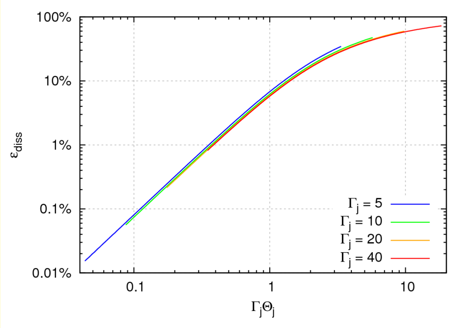
Recollimation is possible for $\eta < 2$.

(Komissarov & Falle 1997, MNRAS, 288, 833)

Energy dissipation efficiency

Fraction of kinetic energy dissipated at the shock front:

$$\epsilon_{diss} \equiv \frac{F_{kin(j)} - F_{kin(s)}}{F_{kin(j)}} \simeq \frac{\Gamma_j - \Gamma_s}{\Gamma_j - 1}$$



In the case of internal shocks (two blobs with Lorentz factors Γ_1 and Γ_2 collide):

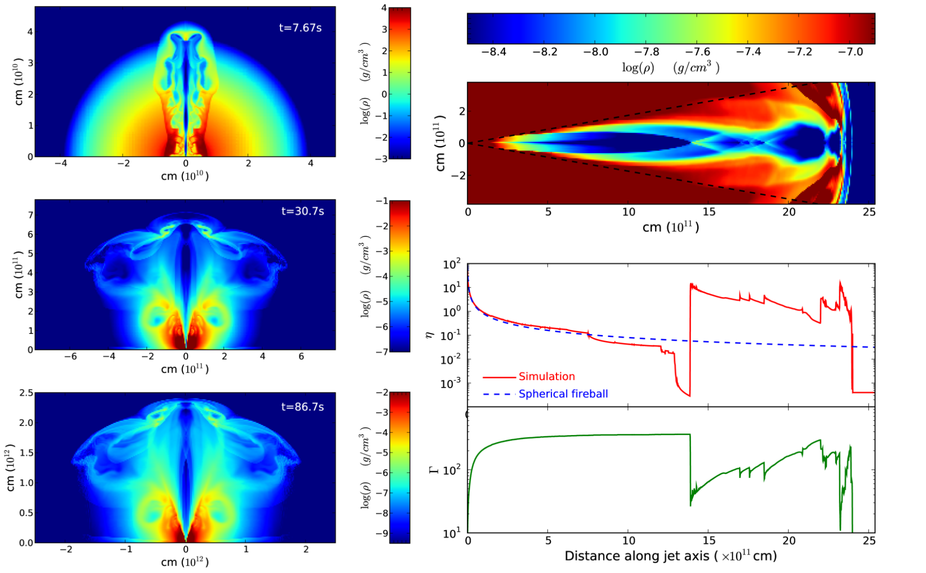
$$\epsilon_{diss} \sim \frac{\left(\sqrt{\Gamma_1} - \sqrt{\Gamma_2}\right)^2}{\Gamma_1 + \Gamma_2}$$

For $\Gamma_2/\Gamma_1 = 2$: $\epsilon_{diss} \sim 6\%$,
for $\Gamma_2/\Gamma_1 = 4$: $\epsilon_{diss} \sim 20\%$.

For $\Gamma_j\Theta_j < 1$ we have $\epsilon_{diss} \sim 6\%(\Gamma_j\Theta_j)^2$.

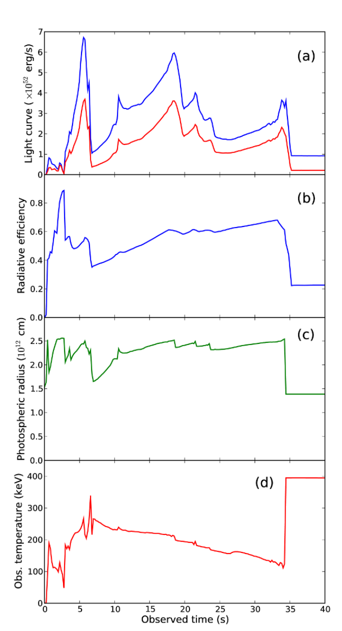
(Nalewajko & Sikora 2009, MNRAS, 392, 1205)

Very high efficiency (GRBs)



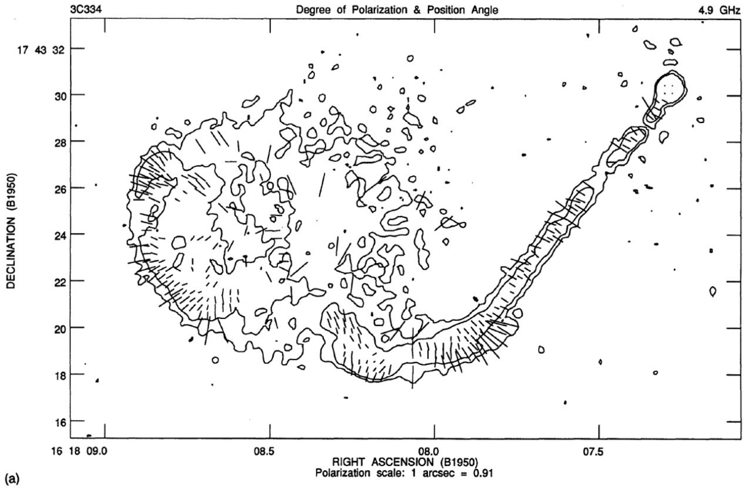
(Lazzati, Morsony & Begelman 2009, arXiv:0904.2779)

Very high efficiency (GRBs)



Polarization of kpc-scale jets

"Specific geometrical and kinematical structures of reconfinement shocks are expected to be reflected in polarization properties, provided that magnetic fields are dominated by the shock compressed random field (Laing 1980; Cawthorne & Cobb 1990). This may explain the polarization electric vectors in the radio knots of AGN kiloparsec scale jets perpendicular to the jet direction (Bridle et al. 1994)."



The problem of perpendicular polarization

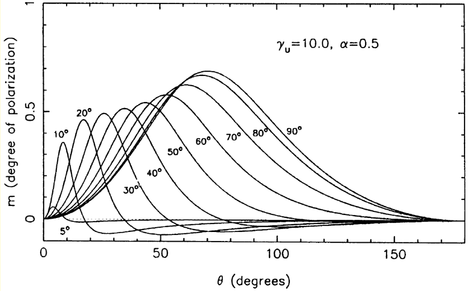
In an expanding jet carrying different magnetic field components conservation of the magnetic energy flux implies:

- parallel component $B_{\parallel} \propto R^{-2}$,
- perpendicular component $B_{\perp} \propto R^{-1}$.

Thus, on large scales the magnetic field in jets should be dominated by perpendicular component and polarization of synchrotron emission should be parallel.
(Begelman et al. 1984, RvMP, 56, 255)

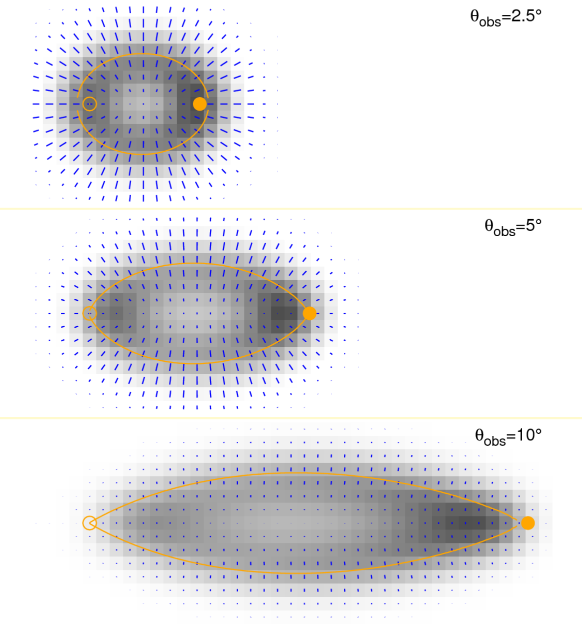
Since we observe perpendicular polarization on both kpc and pc scales, a component of parallel (poloidal) magnetic field is needed, usually associated with a velocity shear.
(Laing 1981, ApJ, 248, 87)
(Cawthorne 2006, MNRAS, 367, 851)

Polarization from initially chaotic magnetic fields compressed at conical shocks is almost always parallel to the jet axis. If perpendicular, the polarization degree is less than 10%.



(Cawthorne & Cobb 1990, ApJ, 350, 536)

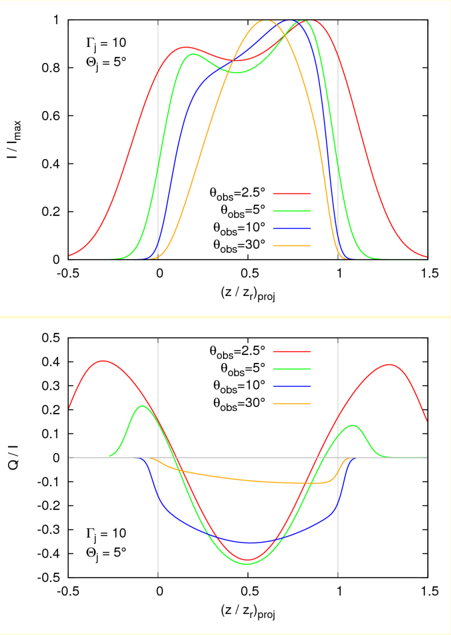
Polarization



- Total intensity (gray) and electric vectors (blue) predicted for a reconfinement shock with $\Gamma_j = 10$ and $\Theta_j = 5^\circ$, as seen by different observers.
- At shock outline (orange) the polarization vectors are perpendicular to it, and polarization degrees reach their local maxima.
- Total intensity is edge brightened and strongly affected by doppler boosting.

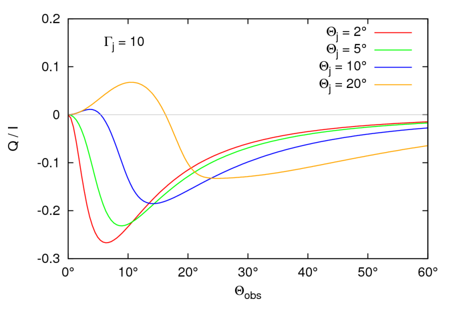
(Nalewajko 2009, MNRAS, 395, 524)

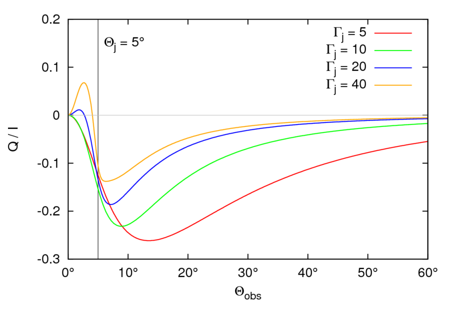
Polarization (longitudinal profiles)



- Since our model is axisymmetric, Stokes parameter $U = 0$, so $|Q/I|$ measures the polarization degree. $Q > 0$ for parallel polarization.
- At large viewing angles all portions of the shock produce perpendicular polarization.
- At small viewing angles regions close to the structure endpoints give parallel contribution and are strongly affected by Doppler boosting.
- Note very high degree of perpendicular polarization obtained around the shock midpoint for a range of viewing angles.

Polarization (averaged)

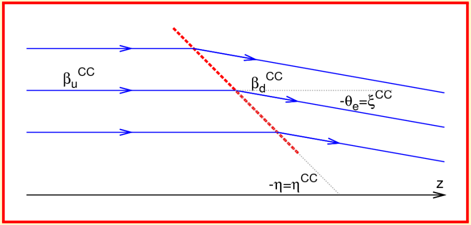


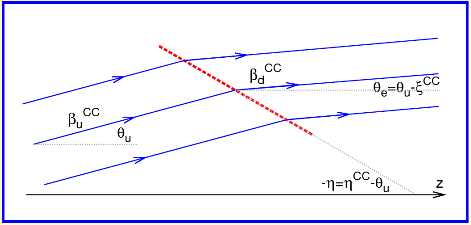


- Spatially averaged polarization is perpendicular in almost all cases.
- Highest polarization degrees are observed at viewing angles slightly larger than the opening angle.
- Perpendicular polarization degree is not higher than 30%. The maximum value decreases with increasing Γ_j and Θ_j.

The effect of flow divergence

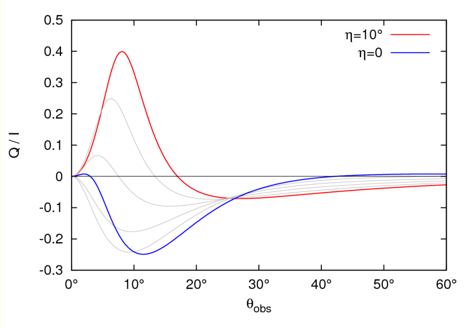
In the model of conical shocks in Cawthorne & Cobb (1990) it was assumed, that the upstream flow is parallel to the jet axis.





In our model the upstream flow is expanding spherically, thus it diverges.

We consider a conical shock section with a constant upstream and downstream Lorentz factors and flow inclination angles. A simple rotation of the shock front can describe a transition between a CC90 model (red) and a midpoint section of the reconfinement shock (blue).



Summary

- Reconfinement shocks may be responsible for energy dissipation in powerful blazars.
- Energy dissipation efficiency can be very high in most relativistic shocks ($\Gamma_j \Theta_j > 1$), e. g. in GRBs.
- Synchrotron emission from reconfinement shocks with chaotic magnetic fields is perpendicular, unless $\Gamma_j \Theta_j > 1$ and $\Theta_{obs} < \Theta_j$.
- Oblique shocks compressing chaotic magnetic fields can produce perpendicular magnetic fields with degrees higher than 10%: up to 30% for conical shocks and even higher in spatially resolved structures.