Emission of compact jets powered by internal shocks

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Evidence for compact radio jets in the hard state

Cygnus X-1
(Stirling et al. 2001)

Flat/inverted radio spectra
(Fender 2001)
Observed Spectral Energy Distribution of Compact Jets

Black hole
(GX 339-4)

Neutron star
(4U 0614+091)

see also Corbel & Fender 2002, Chaty et al. 2011; Rahoui et al 2012; Russell et al. 2013...
Standard conical jet emission model (Blandford & Koenigl 1979)

Synchrotron radiation from a population of relativistic leptons travelling down the jet
\[ n_e(\gamma_e) \propto \gamma_e^{-p} \]

Energy losses neglected:
⇒ constant specific internal energy:
\[ \tilde{\varepsilon}(z) = \tilde{\varepsilon}_0 \]

\[ B^2 \propto n \propto E_{\text{int}} \propto V^{-1} \propto r^{-2} \]

\[ F_\nu \propto \nu^\alpha \Rightarrow \alpha_{\text{thick}} = 0 \]
\[ \alpha_{\text{thin}} = \frac{1 - p}{2} \]
What about adiabatic expansion losses?

Pressure work against external medium as flow expands in conical geometry

\[ d\tilde{W} = Pd\tilde{V} = (\gamma_a - 1)m\tilde{e}\frac{d\tilde{V}}{\tilde{V}} \approx \frac{2m\tilde{e}}{3}\frac{dR}{R} \]

⇒ Specific internal energy decreases: \( \tilde{\varepsilon} \propto R^{-2/3} \)

\[ \Rightarrow \alpha_{\text{thick}} = \frac{2p + 13}{4p + 18} \approx 0.65 \]

Spectrum is strongly inverted: need to compensate for losses
Jet = ‘shells’ ejected at time intervals $\sim t_{\text{dyn}}$ with randomly variable velocities.

- Faster shells catch up with slower shells and collide.
- Shocks, particle acceleration, and emission of synchrotron radiation.
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Velocity fluctuations of smaller amplitudes and longer time-scales merge (and dissipate) at larger distances

Aim: study how results depend on the properties of Fourier PSD of fluctuations

Combining two approaches:
- Monte-Carlo simulations
- Analytical/Semi-analytical model
Response to sinusoidal fluctuations

$$\Gamma_t(t) = \Gamma + \sqrt{2} \Gamma_{\text{rms}} \sin(2\pi f_i t)$$

$$f_i = 1 \text{ Hz} \quad \Gamma = 2 \quad \Gamma_{\text{rms}} = 0.3$$

\[ \Rightarrow \text{Dissipation at distance} \]

$$z_d = \frac{\Gamma^3 \beta^3 c}{4 \Gamma_{\text{rms}} f_i}$$

after that $$\tilde{\epsilon} \propto z^{-2/3}$$

\[ \Rightarrow \alpha_{\text{thick}} = \frac{2p + 13}{4p + 18} \sim 0.65 \]
Response to white noise fluctuations

PSD of Lorentz factor fluctuations

Dissipation profile

Spectral energy distribution

Specific energy profile

\[ \Rightarrow \alpha_{\text{thick}} = \frac{2p + 13}{4p + 18} \sim 0.65 \]

\[ \tilde{\epsilon} \propto z^{-2/3} \]
\[ P(f) \propto f^{-\alpha} \]

\[ \Rightarrow \alpha_{\text{thick}} = \frac{(2p + 13)(1 - \alpha)}{4p + 18 - \alpha(10 + 2p)} \]

\[ \tilde{\epsilon} \propto z^{-\frac{2(1-\alpha)}{3-\alpha}} \]
Application to black hole binaries

\[ P(f) \propto \frac{1}{f} \quad \text{for} \quad 10^{-3} < f < 50 \quad \text{Hz} \quad \text{rms} = 30\% \]

\[ P_{kin} = 0.01L_E, \quad \Gamma = 2, \quad \phi_j = 1^o, \quad + \text{equipartition} \]
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- Base of emitting region: \( z_0 \sim 10^{10}\text{cm} \)
- Magnetic field at base: \( B_0 \sim 10^4 \text{G} \)
- Flux of flat component: \( F_{v0} \sim 84 \frac{\delta^2}{D_{\text{kpc}}^2} \text{mJ} \)
- High frequency break: \( \nu_T \sim 2 \times 10^{13}\text{Hz} \)
- Low frequency break: \( \nu_s \sim 1 \text{GHz} \)
Fast Jet Variability

Observations of GX 339-4

Optical

Infrared

Gandhi et al. 2010

Casella et al. 2010
Model

Fast Jet Variability

Malzac et al. in prep.
IR /X-ray correlation

Observations

GX 339-4

Casella et al. 2010
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Observations

GX 339-4
Casella et al. 2010

Simulation

Assuming X-ray flux $\propto 1/\Gamma$
Malzac et al., in prep
Why flicker noise?

Accretion disks may produce 1/f noise (Lyubarskii 1997; King et al. 2004; Mayer & Pringle 2006)

\[ P(f) \propto f^{-1.3} \] at low frequencies

+ band limited (Lorentzians) at high frequencies in HS

X-ray power spectra of X-ray binaries close to flicker noise:

- Cyg X-1
- Cyg X-2

Gilfanov 2010
Using observed X-ray PSD as input PSD of jet Lorentz factor fluctuations
Conclusions

Internal shocks can account for the canonical SED of compact jet provided the power spectrum of injected fluctuations is close to $P(f) \propto f^{-1}$.

Internal shocks produce strong, frequency dependent, variability similar to that observed.
Thanks !