Relativistic jets from XRBs and AGNs

Stéphane Corbel
(Université Paris 7 & CEA Saclay)
Outline (last time)

- Introduction on relativistic jets
- Accretion and spectral states in XRBs
- Relativistic ejections in microquasars and AGNs: illustrations of relativistic effects
- Compact cores in the hard state
- Relativistic jet production and X-ray spectral states: a unified view
Compact jet on m.a.s. scale  
Discrete ejection on arcsec scale
Outline (today)

- Relativistic Jets in neutron star binaries
- Large scale jets and radio nebula
- Ultra Luminous X-ray sources (ULX)
- Active Galactic Nuclei (AGN)
- Open questions and perspectives
Relativistic jets in neutron star binaries

1: Transient ejections
2: Self-absorbed jet
Relativistic jets from Sco X-1

At least three components associated with the jet
1. Core flares (1st acceleration)
2. Invisible, highly relativistic beam (Γ>2)
3. `Lobes' energised by beams and moving at ~ 0.4c

The observed radio knots are only tracers of an underlying (unseen) ultra relativistic flow: 2 flows (also Cir X-1 and SS433)

1-1999 Jun 11 at 02:47

Fomalont et al. (2001a,b)
An ultra relativistic jets in Cir X-1

Neutrons star binary with periodic outburst (16.6 days) at periastron.

X-ray flare → core flare → A and then B brighten over 5 days → $\beta_{\text{app}} > 400$ mas/d

Mildly relativistic radio-emitting knots are ‘energised’ by an ultrarelativistic ($\Gamma > 15$) unseen outflow following each outburst…

Jet inclined within 5° of the i.o.s.  Fender et al. (2004)
Most ultra-relativistic jets is from a NS: “escape velocity” paradigm is not valid.

Properties unique to BH are not necessary for the production of jets.

Jet velocity increases with increasing $L_X$
Relativistic jets in neutron star binaries

1: Transient ejections
2: Self absorbed jet
Atoll and Z sources

(Fender 2001)

**'Atoll' sources**
- B (surface) \( \sim 10^8 \) G7
- \( m \sim 0.01 - 0.1 \) Edd

**'Z' sources**
- B (surface) \( \sim 10^{10} \) G7
- \( m \sim 0.5 - 1.0 \) Edd

- Z: 6 srces close to \( L_{\text{edd}} \), similar to GRS 1915+105?
- HB: flat spectrum \( \rightarrow \) compact jet
- NB: transient ejection
- HB \( \rightarrow \) NB: jet line ?? Continuously crossed?
- FB: quenching?

Migliari & Fender 2006
Properties of atoll NS (Migliari & Fender 06)

- Sample of atoll + Z sources + low B XRP + BH
- Fit atoll + Z sources: \( L_R \propto L_X^b \) avec \( b = 0.66 \pm 0.07 \)
- Positive correlation between radio and X-ray luminosities (only) over one order of magnitude in X-rays.
- Fit atoll 4U 1728-34 (hard): \( L_R \propto L_X^b \) avec \( b = 1.40 \pm 0.25 \)
- Fit avec 2 u.l. (0614 and 1608): \( b > 1.60 \pm 0.27 \)
  - The radio/X-ray luminosity correlation is steeper in NS compared to BH (\( \Gamma \sim 0.7 \))
Comparison with black holes

- Hard state (below ~0.1 $L_{\text{edd}}$): BH and atoll seems to make steady self-absorbed compact jets. However poor measure of NS radio spectra.
- Above: optically thin radio flare
- Steeper relation in NS vs. BH
- No quenching in NS soft states
- The NS are less radio loud for a given X-ray luminosity (regardless of mass correction). At $L_x = 2\% \ L_{\text{Edd}}$, ratio is ~30
Hard state
(Thermal state)

Soft state

Very–High state
(Steep Power–Law state)

$L_8.5\,\text{GHz (x10^{26} \, \text{erg/s})}$

$L_{2-10\,\text{keV (x10^{36} \, \text{erg/s})}}$

BHs

NSs
Jet dominated advection flow?

- The total power output $L_{\text{tot}}$ is a combination of the radiative luminosity of the flow ($L_X$ directly observed as X-rays) and the jet power ($L_J$, indirectly traced by e.g. radio flux density):

$$L_{\text{Tot}} = L_X + L_J$$

- Conical jet model $\rightarrow$ $L_{\text{Rad}} \propto L_J^{1.4}$

- $L_{\text{Rad}} \propto L_X^b$ with $b_{\text{BH}} \approx 0.7$ and $b_{\text{NS}} \approx 1.4$:

  $\text{BH: } L_J \propto L_X^{0.5}$

  $\text{NS: } L_J \propto L_X$

- BH: $L_{\text{Tot}} = L_X + A_{\text{BH}} L_X^{0.5} = A^{-2} L_J^2 + L_J$ Normalization $A$ ??

- NS: $L_{\text{Tot}} = L_X + A_{\text{NS}} L_X$
- \( L_J / L_X > 0.05 \) (GX 339-4, Corbel & Fender 02) or > 0.2 (XTE J1118, Fender 01) \( \Rightarrow A_{BH} \sim 0.1 \) and \( A_{NS} \sim 0.01 \) in Eddington units (Fender; M; vK et al. 05)

- Assuming that \( L_{Tot} \) is proportional to mass accretion rate: \( \dot{m} \) (eq. to no advection): \( L_X \propto \dot{m} \) for NS

\( \rightarrow \) NS systems will never reach a jet dominated state (\( L_X \) always > \( L_J \))
If we assume same LX, relation for NS and BH
Æ different LJ / LX relations in NS/BH may imply a different coupling between accretion rate and jet power

- Otherwise you could also assume same coupling between LJ and \( \dot{m} \), but different LX, \( \dot{m} \) relation)

\[
\begin{align*}
\text{BH: } L_J & \propto L_X^{0.5} \quad L_{Tot} = L_X + A_{BH} L_X^{0.5} \\
\text{NS: } L_J & \propto L_X \quad L_{Tot} = L_X + A_{NS} L_X \\
\text{Migliari & Fender 06}
\end{align*}
\]
Assuming also that NS are radiatively efficient (solid surface) and same $L_J, \dot{m}$ coupling

- **NS:**
  \[ L_J \propto L_X \propto \dot{m} \]  
  (what we found before)

- **BH:**
  \[ L_J \propto \dot{m} \propto L_X^{0.5} \Rightarrow L_X \propto \dot{m}^2 \]
  ~indicative of radiatively inefficient inflow (~e.g. ADAF or jet : $E_{pot}$ away )

Possible explanation for different $L_X/L_R$ correlations: NS are in a “X-ray dominated state” and BH in a “Jet dominated state”

Can also explained the difference in quiescent luminosity of BH and NS: jet removing most of the liberated gravitational potential in the quiescent BH (not in NS). ADAF not required.
Large scale jets in microquasars
SS 433

- Large scale X-ray jets (but no motion observed)
  Non thermal emission poss related to jet/ISM interaction
- Relativistic (0.26c) ejection on arcsec scale
  Associated thermal X-rays (Marshall et al. 01, Migliari et al. 02)
6.5 arcsec ~ 0.15 pc at 5 kpc

Migliari et al. 2002
Bremsstrahlung continuum:
- East: $kT \sim 5.0$ keV
- West: $kT \sim 4.6$ keV

(Power law continuum:
- East & West: $\Gamma \sim 2.1$)

Gaussian emission lines:
- East: $E = 7.3 \pm 0.2$ keV
- West: $E = 6.4 \pm 0.1$ keV

The data are consistent with a hot ($>10^7$ K) plasma at large distances from the core moving with the same velocity as the core jets ($\sim 0.26c$)
Large-scale, decelerating relativistic jets from XTE J1550-564

\[ M_{bh} = 10.5 \pm 1.0 \, M_\odot \; ; \; d \sim 5 \, \text{kpc} \; (\text{Orosz et al.} \; 2002) \]

- 20 Sept. 1998: Strong and brief X-ray flare
- Relativistic ejection imaged with VLBI (Hannikainen et al. 2001)
New radio source to the West of the BH in 2002 + another to the East in 2000: aligned with the axis of the VLBI jets

*Corbel et al., Science (2002), 298, 196*

*Kaaret et al., Tomsick et al. 2003*

Moving X-ray sources associated with the radio lobes
Jet deceleration

Direct evidence for gradual deceleration in a relativistic jet

- Smooth deceleration over four years: from $\beta_{\text{app}} > 1.7$ to $\beta_{\text{app}} \sim 0.3$
- Implies $>50\%$ of kinetic energy ($>10^{34} \text{ erg/sec}$) been lost... but only about $1\%$ of this has been observed: $>99\%$ has been dumped into the ISM
Emission mechanism

- SED consistent with a PL of spectral index $\alpha = 0.66 \pm 0.01$
- Same morph. radio/X

Synchrotron emission from the same electron dist.

If synchrotron + Equipartition: $B_{eq} = 0.3$ mG

X-ray emitting electrons: Lorentz factor $\gamma_e > 2 \times 10^7$ (TeV electron)

$N_e = 10^{45}$ electrons; if one p/e, mass = $10^{21}$ g

if mass accretion rate = $10^{18}$ g/s, then injection time $\sim 1000$ s
A large scale relativistic jets in H1743-322!!

- Initially discovered in 1977
- Radio flare on April 8
- High frequency QPOs
- Likely a black hole
- Radio observation during decay: a compact jet?
ATCA radio observations of H 1743-322

- No radio source at the location of H1743
- A weak and varying radio source few arcsec to the East
Exp. rise time
~ 45 days

Exp. decay time
~ 28 days

Chandra

Radio flux density (mJy)

Time after radio flare (days)

Nov. 2003

June 2004

Exp. rise time
~ 45 days

Exp. decay time
~ 28 days
New large scale X-ray jets in H1743-322

Similar properties to the X-ray jets of XTE J1550-564, but decay much faster (Corbel et al. 2005).
A jet/ISM collision?

For XTEJ1550 or H1743: ejection of few relativistic plasmoids
adiabatic expansion --> decay of radio emission

Undetectable for months to years and then re-brightening

Evidence than radio through X-rays is synchrotron emission

• Internal shocks?: internal instabilities, varying flow speed
• External (reverse) shocks?: interactions with denser ISM

Particle *in-situ* acceleration powered by bulk deceleration

Beamed X-ray emission !!!
Large scale jets are common (radio and X-ray)

- **GX 339-4**: large scale transient 12” radio jets. No X-ray jets detected, cf Chandra obs too late (Gallo et al. 04). Similar radio decay rate than H 1743-322.
- **4U 1755-33**: large scale persistent X-ray jets (Angellini & White 03)
- **XTE J1748-248**: transient large scale radio jets (Hjellming, unpublished).
- **XTE J1650-500 ?** (Corbel et al. 04)
- **GRS 1915+105 ?** (Kaiser et al. 04)
- **Cyg X-1** (Gallo et al. 2005)
- **SS 433**: thermal + non-thermal X-ray jets (Migliari et al.
A fossil X-ray jets in 4U 1755-33

- XMM newton observations of 4U1755 in 2000 (in quiescence since 1995)
- Large (7') scale two-sided X-ray jets
- Diffuse emission (Park et al. 05)
- X-rays = synchrotron (Kaaret et al. 06) \( \rightarrow \) 60 TeV e- 
- BHC active for > 25 years
- If v\( \sim \)c, it would have taken 13 yrs to extend to its current length

Angellini & White(2003)
Jet-blown bubbles in the ISM: Cygnus X-1

Gallo et al. 2005

$E_{\text{min}} \sim 10^{48} \text{ erg}$
- Large scale (5pc) radio ring inflated by the inner radio jet
- Bremsstrahlung emission from the shock that develops at the location where the collimated jet strikes the ISM
- ISM = effective jet calorimeter \( \rightarrow <8 \times 10^{35} \text{ to } 10^{37} \text{ erg/s}> \)
- Total power carried by the compact jet of Cyg X-1: \( 9 \times 10^{35} \text{ to } 10^{37} \text{ erg/s} \)
- The total power dissipated by the jets in the form of kinetic energy can be as high (6 to 100%) as the bolometric X-ray luminosity
- Power output of low-luminosity of stellar BH is dominated by the kinetic energy of dark outflows

Gallo et al. 05
Ultra Luminous X-ray sources (ULX)
Ultra Luminous X-ray sources

- Apparent isotropic luminosities > a few $10^{39}$ erg/s
- 2 Fdl questions: beamed or isotropic emission?
- Intermediate mass BH?
  - How are IMBHs formed?
- See more details in lectures by Fabbiano…
Radio counterpart of an ULX: NGC 5408

Kaaret et al. 2003

HST image
Chandra
ATCA (Contour radio)

- X-ray spectrum + radio and X-ray counterparts properties: relativistic beamed jet emission (angle < 10 degrees):
  - Radio: synchrotron emission
  - X-rays: inverse comptonization of photons from a massive companion star by the jet (cf Georganopoulos et al. 2002)

Microblazar ???
Further radio observations (Soria et al. 06)

- Confirm steep radio spectrum: $\alpha \sim -1$
- Constant radio flux density, marginally resolved ($\sim 30$ pc)
- Not a compact jet, flaring jet or beamed jet (if extrapolate XRB)
- Radio source consistent with a radio lobe powered by a jet from the BH (similar to SS433) + faint HII region
- Expansion of a jet-powered $e^-/e^+$ plasma bubble (minimum energy approximation) $\Rightarrow$ average jet power of $7 \times 10^{38}$ erg/s ($0.1 L_{\text{Edd}}$), age $\sim 10^5$ yr
- If lobe origin = compact jet in LHS ($< 0.03 L_{\text{Edd}}$) $\Rightarrow$ require $L_{\text{Edd}} > 2 \times 10^{40}$ erg/s or $M_{\text{BH}} > 150 M_\odot$
Holmberg II

- Only other unambiguous ULX/radio source association
- Resolved (~ 50 pc) and associated with He II nebula
- Beaming scenario → inconsistent with data => $M_{\text{bh}} > 25$ to $40 \, M_\odot$
- Optically thin radio spectra, but not as steep as NGC5408
- Supernova unlikely → synchrotron bubble powered by ULX jet?
- ~ same size as SS433 and 10x brighter
- Same radio to X-ray ratio as NGC 5408

Kaaret et al. (2005); Miller et al. (2005)
Active Galactic Nuclei (AGN)

1: Morphology and ingredients: lobe and jet emission
2: The fundamental plane of BH activity: compact core
3: Accretion – ejection coupling

See lectures by A. Fabian
Active Galactic Nuclei (AGN)

1: Morphology and ingredients: lobe and jet emission
2: The fundamental plane of BH activity: compact core
3: Accretion – ejection coupling
A prototypical radio galaxy: Cyg A

- Any size: from kpc to Mpc
- First order similar radio morphology (but differences depending on radio power, optical luminosity & orientation)
- Typical radio power $10^{23}$ to $10^{28}$ W/Hz
A prototypical radio galaxy: Cyg A

A jet can be separated into three regimes:

- Lobes (steep spectrum)
- Core (flat spectrum)
- Jet (opt thin)
The morphology of a radio galaxy may depend on different parameters:

- **radio power** (related to the power of the AGN?)
- orientation of the radio emission
- intrinsic differences in the (nuclear regions of) host galaxy
- environment
Two main flavors

Edge-brightened
high radio power

Fanaroff and Riley type I and II

Edge-darkened
lower radio power

Court. R. Morganti
Unification of AGN type

- AGN =
  - Central engine = black hole with an accretion disk (UV + X-ray radiation)
  - Torus of dust and cold gas which absorb most of disk em + radiation in IR
  - BLR: gas cloud at high velocity (confined in torus)
  - NLR: gas cloud. Slower + broader distribution
  - Pair of jets: emission radio to γ

- Appearance of AGN depends of viewing angle + obscuration by torus + Doppler boosting
Observers in A see:
- IR emiss from torus + narrow lines
- Jet emission
- Do not see accretion disk and BRL

AGN type
- Radio quiet: Seyfert II, LINERS, buried quasars
- Radio loud: FRI + FRII
Observers in B see:
- IR emiss from torus + narrow lines
- Jet emission
- Accretion disk and BRL

AGN type
- Radio quiet: Seyfert IIs (low lum) radio quiet quasars
- Radio loud: radio loud quasar, broad line radio galaxies
Observers in C see:
- Same objects as B if weak jet emission
- Otherwise, see mainly jet emission with possibly $\gamma$-ray emission (IC)
- Accretion disk and BLR if bright

Type:
- Radio quiet: same as B
- Radio loud: BL Lac, OVV
Observations at different resolution

Centaurus A Radio Source
Australian VLBI Network

$D = 3.4$ Mpc; $1 \text{ mas} = 0.02\text{ pc}$

See lecture 1 for superluminal motion.
M87
radio emission at different frequencies and resolutions
Often the radio emission is more symmetric on the large scale and asymmetric on the small scale.

Jets remains self similar over many order of magnitudes.

The core is defined based on the spectral index: flat ($\alpha \sim 0$).

[to find which component is the radio core is not always easy: free-free absorption can complicate the story!]

---

Jet core
Chandra has shown that many radio jet have also an X-ray counterpart.
Almost identical morphology from the radio to X-ray band: the optical, UV and X-ray data (and spectral indices) are consistent with synchrotron emission.

The electrons must have high $\gamma (10^7)$ and very short life-time ($\ll$yrs).

Universal acceleration mechanisms?

Other possibility: inverse Compton effect

Relativistic electrons in a radiation field. Because of the interaction with the photons, the electrons loose energy while the outcome are photons with higher energy. This interaction can take place between the relativistic electron producing the radio emission and either the radio photons or the photons from the cosmic micro-wave background (prop to $(1+z)^4$).
Active Galactic Nuclei (AGN)

1: Morphology and ingredients: lobe and jet emission
2: The fundamental plane of BH activity: compact core
3: Accretion – ejection coupling
Power unification of compact cores

- Supermassive bh equivalent to soft state XRBs:
  - Higher luminosity sources with strong disk signature (related to different inclination angle):
    - FRII radio galaxies
    - Radio loud quasars
    - Blazars
  - Radio quiet sources:
    - Seyfert galaxies
    - Radio-quiet quasars
    - ? Radio–intermediate quasars ?
- All of these AGN varieties show direct or indirect evidence for emission from a standard accretion disk
Many AGNs do not show evidence for (strong) emission from the accretion disk to hard state:
- BL Lacs
- FR I radio galaxies
- LINERs
- Sgr A*

They all have relatively prominent radio jets or compact radio cores.

Is their entire SED dominated by non-thermal jet-emission?

The basic shape of the broad-band jet spectrum is (relatively) invariant to changes in black hole mass and accretion rate.

Simple scaling laws with $M_{\text{dot}}$ can be derived analytically.

Assumption $P_{\text{jet}} \propto M_{\text{dot}}$!

Radio/optical/X-ray ratio depends on $M_{\text{bh}}$ and $M_{\text{dot}}$!

Smaller black holes peak at higher frequencies (observed in XRB).

Increasing $M_{\text{dot}}$ increases flux density non-linearly.

Scaling laws for Blandford & Königl jet cores.

Remember the radio X-ray correlation in XRBs

Radio/X-ray correlation for GX339-4

non-linear slope:
jet-theory: 1.39
obs: 1.40

\[
\log F_x \propto \frac{17}{12} \cdot \log F_{\text{radio}} = 1.39 \cdot \log F_{\text{radio}}
\]

Corbel et al. (2003), Markoff et al. (2003)

- Obviously the mass does not change - only the accretion rate.
- Jet scaling laws reproduce radio-x ray slope perfectly

Radio/X-ray correlation for sample of XRBs

Gallo, Fender & Pooley 2003
Fundamental Plane: two illustrations
Radio, X-Rays, and Mass

Merloni, Heinz, Matteo (2003)

→ ADAF/Jet model


→ Jet only model

Corrected for mass
Refining the FP: Statistics or Varying the Sample: low & high-state obj. (e.g. quasars)

Fitting function: \[ \log L_X = \xi_R \log L_R + \xi_M \log M + b_X \]

Edited MHDM sample

Körding, Falcke, Corbel (2006)
Statistics - Varying the Sample:
XRBs, LLAGN, FRIs, BL Lacs

Körding, Falcke, Corbel (2006)

$\sigma = 0.38$ dex

$\sigma = 0.12$ dex if XRB, Sgr A* and LLAGN

Körding, Falcke, Corbel (2006)
Summary of FP

- **KFC confirm statistically the existence of a FP**
- However, correlation depends strongly on sample and assumed errors \( \rightarrow \) intrinsic errors = intrinsic scatter besides measurement errors: beaming, non-simult, peculiar, ...(derived from the scatter in the correlation)

- **KFC sample**: only hard state sources:
  - Also X-ray emission estimated from optical fluxes \( \rightarrow \) not affected by cooling or cut-off
  - Correlation consistent with uncooled “jet only” model.
  - The sub-sample XRB+LLAGN is surprisingly tight (\( \sigma_{\text{int}} \sim 0.12 \) dex)

- **MHDM sample**: all kind of AGNs:
  - Sample affected by synchrotron cut-off + high state objects
  - Only jet model not applicable
  - Consistent with ADAF/jet model
AGNs show the same spectral state phenomenology and related disk-jet coupling as the stellar mass accreting black holes.

Maccarone, Gallo, Fender 03
Active Galactic Nuclei (AGN)

1: Morphology and ingredients: lobe and jet emission
2: The fundamental plane of BH activity: compact core
3: Accretion – ejection coupling
Accretion and jet connection in 3C120

Marscher et al. Nature 2002
Superluminal motion ejections follow X-ray dips + hardening of X-ray spectra

Similar to GRS 1915+105

Red points = dips
Blue arrows = ejection

Marsher et al. 2002
Mirabel et al. 1998
Conclusions

- Relativistic jets – Three aspects:
  - Compact core: self absorbed compact jet (flat radio spectra)
  - Relativistic transient ejection events (opt thin radio spectra)
  - Impact of the jets on the ISM or IGM: formation of radio lobes with steep spectra
- All of these three aspects are found in AGN and XRB (ULX?)
- Start to be quite well understood in XRB
- High energy emission of jets:
  - Compact jets at low $L_{\text{Edd}}$: AGN + XRB (?) with similar coupling
  - Lobes: AGN + XRB
- Similar morphology, but also probably same physics on different timescale. Cool for PhD student lifetime 😊.
Open questions (1)

- All XRB = microquasars?
- Unifying accretion – ejection properties among all types of compact objects:
  - Larger sample of galactic BHs
  - Neutrons stars
  - Unifying all AGNs → new fundamental plane for all sources?
- Fraction of total inflow energy in jets?
- Lorentz factor?
- Linking the timing properties to jet properties? QPO in AGNs?
- Composition of jets? Discrete plasmons or semi-continuous flows with internal and / or external shocks
- What is the mechanism(s) that launches the jets?
Open questions (2)

- Nature of the high energy emission in microquasars?
- Microquasars = sources of high energy radiation for HESS or Glast?
- Where are the microblazars?
- Interaction of jet with ISM: in–situ reacceleration at large distances: power estimate, cosmic rays and neutrinos production?
- Extragalactic microquasars? ULX?
- Unifying all jet or shocked sources (at least understanding their properties)? PWN, SNR, YSO, GRB, SGR, shocks, etc…
- Role of BH spin?
- Role of magnetic field?
Some materials used or further informations in these lectures online

- Radiation processes:
  - Geoffrey Bicknell: HEA Course
  - Robert Laing: HEA Course
    http://www-astro.physics.ox.ac.uk/~pfr/hea/

- Compact cores: International Summer School Nijmegen 2003: Heino Falcke’s lectures:
  http://nijmegen03.hef.kun.nl/

- Radio galaxies: Raphaella Morganti’s lecture at NOVA school:
  http://www.astron.nl/~morganti/

- General: Phil Armitage Course AST3880:
  http://jilawww.colorado.edu/~pja/
Bibliography

- “High energy astrophysics”, volume 1+2, M.S. Longair, Cambridge U.P.
- “Beams and jets in astrophysics”, P.A. Hughes, Cambridge A.S.
- “The physics of extragalactic radio sources”, D. De Young, Cambridge
- “Compact stellar X-ray sources”, 2006, see review paper by Fender on astro-ph/0303339
- “Accretion power in astrophysics”, Frank, King & Raine