LOFAR Constraints on Weakly Accreting Black Hole Jets

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Jets appear in many astronomical objects

SUPERMASSIVE BLACK HOLES
- Virgo A (M87)

 STELLAR-MASS BLACK HOLES
- GRS 1915+105

FORMING STARS
- HH 30

DYING STARS
- PN M2-9
- Cas A

DEAD STARS
- R AQUARIII
- CRAB PULSAR
- SS 433

GRB
Fundamental Questions

- Why do jets form? What are the conditions near the black hole leading to jet creation, collimation etc.? Does the black hole play a special role or could it be anything in there?

- Jet structure/geometry/bulk velocity

- Jet intrinsic physics: Matter (e⁻p vs e⁺e⁻) vs. Poynting flux dominated?

- Is BH physics generic? If yes, should scale predictably between stellar/galactic systems
Accreting BHs with Jets - Mass (Size) Scales

QUASAR (AGN)       MICROQUASAR (XRB)

(Mirabel et al. 92,98)
Comparing accretion across the mass scale

QUASAR (AGN)  MICROQUASAR (XRB)

$10^{4-5}$ yrs!  1 day

(Mirabel et al. 92, 98)
XRB accretion states

(Homan & Belloni 2004)
(BH) XRB Accretion States

**Soft State**
- (no jets)
- $\approx L_{\text{Edd}}$
- $\sim 1$ keV

**Hard State**
- (jets)
- $\ll L_{\text{Edd}}$
- $\sim 100$ keV
Fundamental plane of BH accretion!

\[ \text{Lg} \ L_x \text{ erg/s} \]

\[ \text{Lg} \ L_R \text{ erg/s} \]

Falcke, König & Markofff 2004
Merloni, Heinz & d’Mattia 2003
Fundamental plane of BH accretion!

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Fundamental plane of BH accretion!

Observed

Mass “corrected”

Jet structure/plasma flow

- Measuring lags between frequencies, and amplitude/shape decay/evolution of flare events
- Gives information about plasma velocities and internal physics, e.g., Cyg X-1: (Wilms et al. 2007)
Model Components

(Markoff, Nowak & Wilms 2005)
Radio/Xray only: Cyg X-1 spectrum

Jet model $\chi^2 = 1.04$

(Markoff & Nowak 2004; Markoff, Nowak & Wilms 2005)
Radio/Xray only: Cyg X-1 spectrum

Jet model $\chi^2 = 1.04$

(Markoff & Nowak 2004; Markoff, Nowak & Wilms 2005)
New constraints from IR/Optical II: A0620-00

(Gallo et al. 2007)
M81* simultaneous campaign

All observations

(Markoff et al. 2007)
“Multimessenger” = multiwavelength

★ If protons accelerated in the jets, additional contribution from hadronic interactions

\[ pp \text{ or } p\gamma \rightarrow \pi^0 \rightarrow 2\gamma \ (\sim 70 \text{ MeV CM frame}) \]

\[ \rightarrow \pi^{+/−} \rightarrow \mu^{+/−} + \nu_\mu \]

\[ \rightarrow e^{+/−} + \nu_e + \nu_\mu \]

☛ Submitted proposals to trigger MAGIC and IceCube with first bright LOFAR transients, as well as mutual monitoring of known sources

☛ Will directly address questions about particle acceleration and internal energetics/matter content
If protons accelerated in the jets, additional contribution from hadronic interactions \( pp \) or \( p\gamma \) could be observed. This process could lead to the production of \( \pi^0 \) mesons, which subsequently decay into two \( \gamma \) rays: \( \pi^0 \rightarrow \gamma \rightarrow 2\pi \). The \( (\gamma, \gamma') \) signature provides insights into the nature of the acceleration process and the internal energy content of the system.

"Multimessenger" = multiwavelength approach

- Submitted proposals to trigger MAGIC and IceCube with first bright LOFAR transients, as well as mutual monitoring of known sources.
- Will directly address questions about particle acceleration and internal energetics/matter content.
**Summary**

- **LOFAR promises significant progress in understanding jet physics in accreting black holes** exploiting multi-\( \lambda \) and 8 orders of magnitude in mass/power scales!
  - **RSM**: helping understand radio-dominated states
  - **Low-\( \nu \) alone**: jet energetics, e\(^-\) distribution, prompt synchrotron
  - **LOFAR in combination with multiwavelength**: new constraints on bulk velocity, geometry, emission mechanisms
  - **LOFAR/\( \gamma \)-ray**: expanding spectrum on both ends, determination of hadronic component? Eventually in combination with direct neutrino detections?
  - **Spectral fitting**: constraints on geometry and plasma conditions very close to BH clues about jet formation
A few extra slides
Predictions for radio/X-ray correlations

For objects with the same mass:

\[ L_R \propto L_X^m \]

\[ m = \frac{17/12 - 2/3 \alpha_R}{q} \approx \frac{1.4}{q} \]

Synchrotron: \( q=2 \), ADAF/RIAF: \( q=2-2.3 \),
Radiatively efficient disk/corona: \( q=1 \) → problematic

Jet energetics: radiating particles

\[ F_{\nu} \sim \nu^{-\frac{5}{2}} \]

\[ \nu_{SSA}(B,\nu,n,r) \]

\[ \sim \nu^{-(p-1)/2} \]
Jet energetics: radiating particles