Cygnus X-1 in the hard state: the low radio frequency follow-up

Benito Marcote

S. Markoff, J. Miller-Jones, J. Broderick, R. Fender

Joint Institute for VLBI ERIC (JIVE)

August 17, 2016

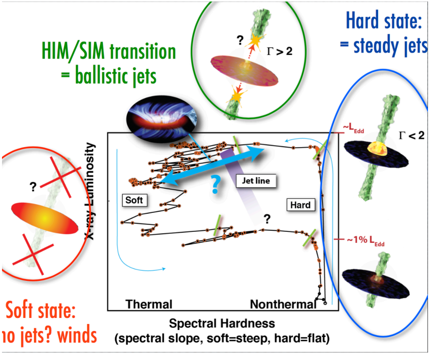
LOFAR Status Meeting

High-Mass X-ray Binaries

Introduction

High-mass X-ray Binaries are systems composed of a compact object orbiting a massive star. They exhibit the peak of their Spectral Energy Distribution at the X-rays, as a consequence of accretion/ejection mechanisms around the compact object.

- Hard/soft states (Fender et al. 2004)
- The hard state of black hole X-ray binaries (XRBs) provides an excellent laboratory for the study of accretion and relativistic jet ejection.
- Strong jet at mas scales in hard state
- Signatures of a weak jet in soft state (Rushton et al. 2011)

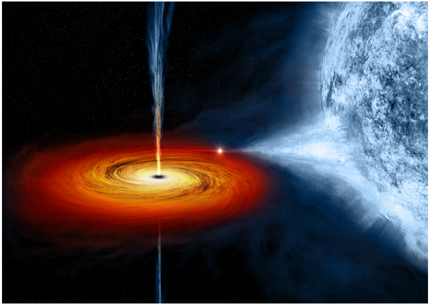


Cygnus X-1

Introduction

The HMXRB Cygnus X-1 is one of the strongest X-ray sources visible from Earth

- O9.7 Iab star + BH with $14.8 \pm 0.1\ \mathrm{M}_{\odot}$
- Orbital period: 5.6 d (Pooley et al. 1999)
- Distance: $1.86 \pm 0.12\ \mathrm{kpc}$ (Reid et al. 2011)
- Emission from radio to γ-rays
- Maybe up to TeV energies during some flares



It is the only microquasar, together with Cygnus X-3, emitting at γ-rays

Cygnus X-1

Previous (low-frequency) observations

- Flat spectrum in the 1–220 GHz range:
  Superposition of individual self-absorbed sync. components
- Jet velocity of $\gtrsim 0.3c$. Lorentz factor? (Fender et al. 2006)
- Previous studies at 150–610 MHz (Pandey et al. 2006,2008)
  1–10 mJy with variability on day timescales. $\alpha \lesssim |0.3|$
- Correlation between $\sim$150 MHz and 15 GHz
- Probably scintillation affects the low frequencies
- Cygnus X-1 has been in a hard X-ray state from 1995 to 2010 with $\sim 10\ \mathrm{mJy}$ (Fender et al. 2000)

Determining the cut-off would constrain the electron density of the jet and the magnetic field (e.g. Zdziarski et al. 2014)

Multiwavelength ToO campaign

An on-going ToO multiwavelength campaign has been approved for the last years waiting for the hard state:

- Radio: VLBA, e-EVN, JVLA, KVN, SRT, AMI, eMERLIN, NOEMA,
- X-rays: *XMM-Newton*, *Chandra*, *NuSTAR*, *ASTROSAT*
- γ-rays: *INTEGRAL*, MAGIC
- Plus some optical observatories

At the end of May there was a putative flare (with the source already reported to be in the hard state):

- *MAXI* light-curve showed a increase emission at X-rays during few days, resembling the starting of a bright hard state flare.
- Sardinia Radio Telescope detected for first time Cygnus X-1 with a flux of 13 ± 2 mJy at 7.2 GHz.
- The AMI light-curve also showed an emission increasing during three days.

DDTs: LOFAR and GMRT

We requested a LOFAR DDT observation contemporaneous with the ToO campaign to extend the observations to low radio frequencies (150 MHz) during the “flare” with the following goals:

- Determine the time delay between frequencies as a disturbance propagates downstream (constraining the jet speed and its Lorentz factor for the first time)
- Improve our knowledge about the connection between the accretion flow and the persistent radio jet (jet formation, engine powering it
- Determine the existence of a turnover in the frequency range 0.1–1 GHz
- If present, determine the properties of the emitting region (electron density, magnetic field).

No GMRT observations were performed (no reply).

LOFAR observation

- Cygnus X-1 was observed on 6 June 2016 03:00–07:30 (4-h on-source)
- 24 CS + 14 RS
- 244 subbands, 16 channels each, 2-s int. time
- Several stations off (high-temp)
- Three scans:
  3C48+Cyg X-1+3C48
  First one unusable (strong ionosphere)
  Other two great data (small RFI)

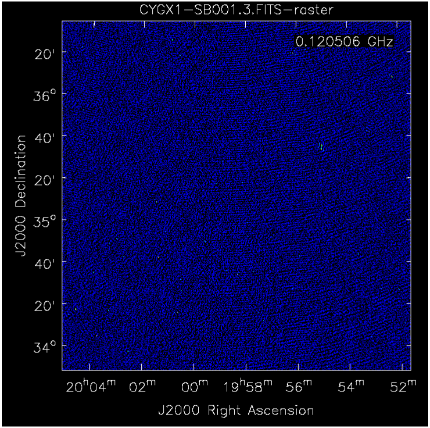


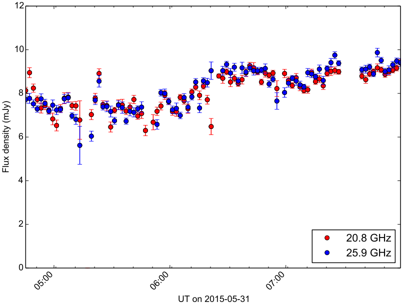
Image from SB001 after 6 phase self-cal with CASA clean.
rms noise level: 9 mJy beam^{-1}

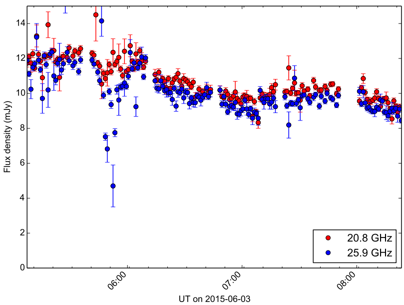
LOFAR observation

- Cygnus A was demixed (only 5 degrees away)
- Pre-processed in CEP3
- Flux calibration: 3C 48 data calibrated using a model from GMRT data (Marcote et al. 2015,2016)
- Standard calibration with NDPPP and BBS. Manual flagging
- Imaging and phase self-calibration rounds done in CASA at the moment (AWImager or WSClean)
- Calibrating single SBs, combining them, imaging+self-cal combined
- Already processed $\sim$20–40 subbands
- Image combining 20 subbands (001–020) produced a rms of 1–2 mJy
- No signal above the noise at Cygnus X-1 position
- We expect to obtain a final noise level of $\sim$0.1–0.3 mJy (theoretical rms 32 $\mu\mathrm{Jy\ beam}^{-1}$ but values close to 1 mJy were expected due to the contribution of Cyg A)

Contemporaneous observations

- AMI is daily observing Cygnus X-1. It observed several times per day from June 5 to 7, including during the LOFAR observation.
- The JVLA also observed Cygnus X-1 on May 31 and June 3 (bad weather during the LOFAR observation avoid a simultaneous observation). Also observed 48 h after LOFAR. Data from previous days at K band already analyzed (preliminary):





Discussion and conclusions

- Measurements:
  20 GHz: $S_\nu \sim 9$ mJy, $\alpha \sim 0$
  150 MHz: $S_\nu < 3 \times \mathrm{rms}$ of ~ 2 mJy (deeper images coming)
- There will be data at 15 (simultaneous) and 5 GHz (48 h later)
- We have already reveal the presence of the turnover frequency to be between 150 MHz and 20 GHz (1 GHz)
- With the flux density at 15 GHz we will be able to fit the expected synchrotron self-absorption model and obtain the physical parameters of the region.
- This model must also fit the multiwavelength data (IR, optical, X-ray)
- Also, LOFAR observations as close as this one to Cyg A are feasible with the current demixing implementation