The University of Manchester Jodrell Bank Observatory

EUROPEAN VLBI NETWORK

THE UNIVERSITY of MANCHESTER

Minor Flares on Cygnus X-3 –VLBI Prospects

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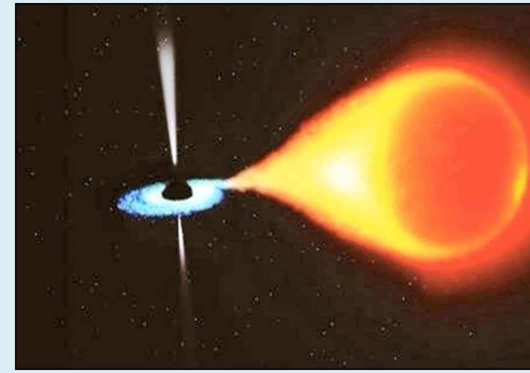
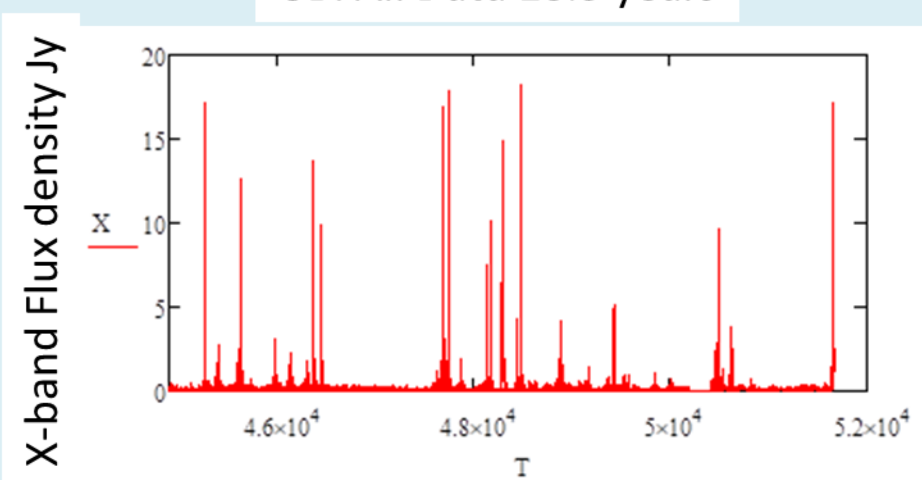
Cygnus X-3



- Intense High Mass X-ray binary star at 7.4 kpc
- 4.8 hr period in IR, X-rays and Gamma rays, obscured in visual
- Compact object BH or N with Wolf-Rayet companion
- Noted for its strong flares in radio: brightest in sky
- What about weaker short duration flares? Spencer+2022
- Physical conditions --compare with major flares

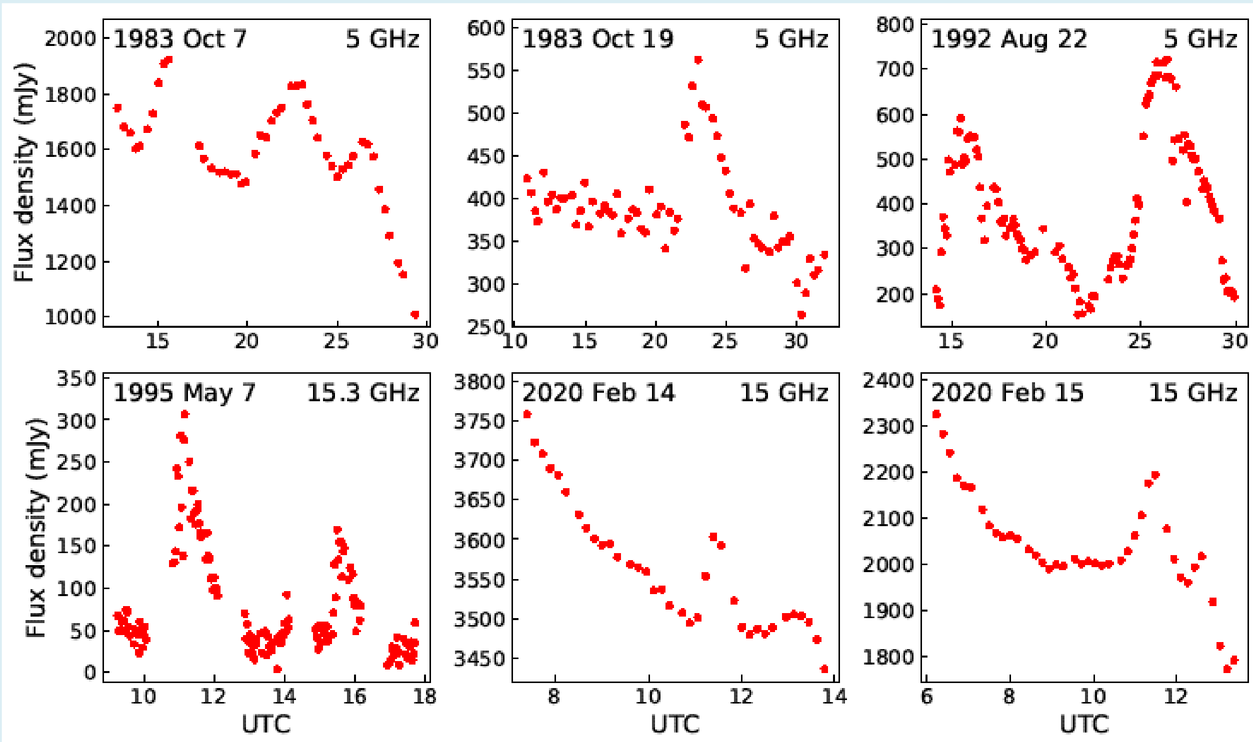
GBI All Data 18.5 years



MJD

GBI 1978-2000

Minor Flares < 1 Jy



Spencer+2022
arXiv2203.05637
MERLIN, VLBA, AMI
DOI/10.1093/mnras/stac666

Fender 2006
Ryle 15 GHz

Ogley+2001
Merlin 5 GHz

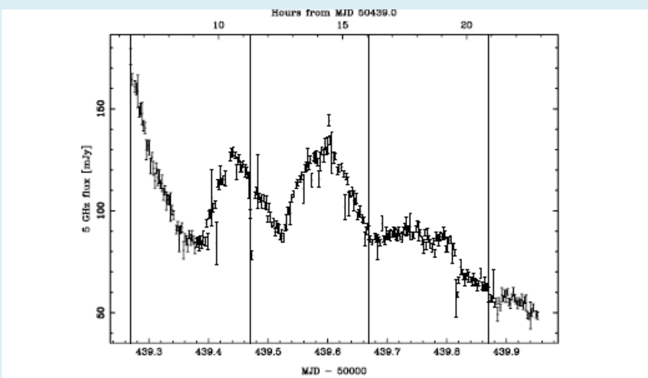


Figure 7. Cyg X-3 photometry on 1996 December 21. Time bins are 4.0 min.

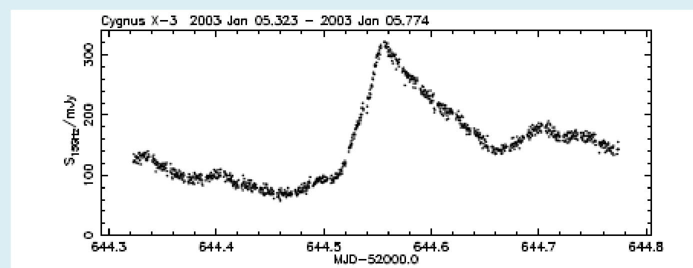
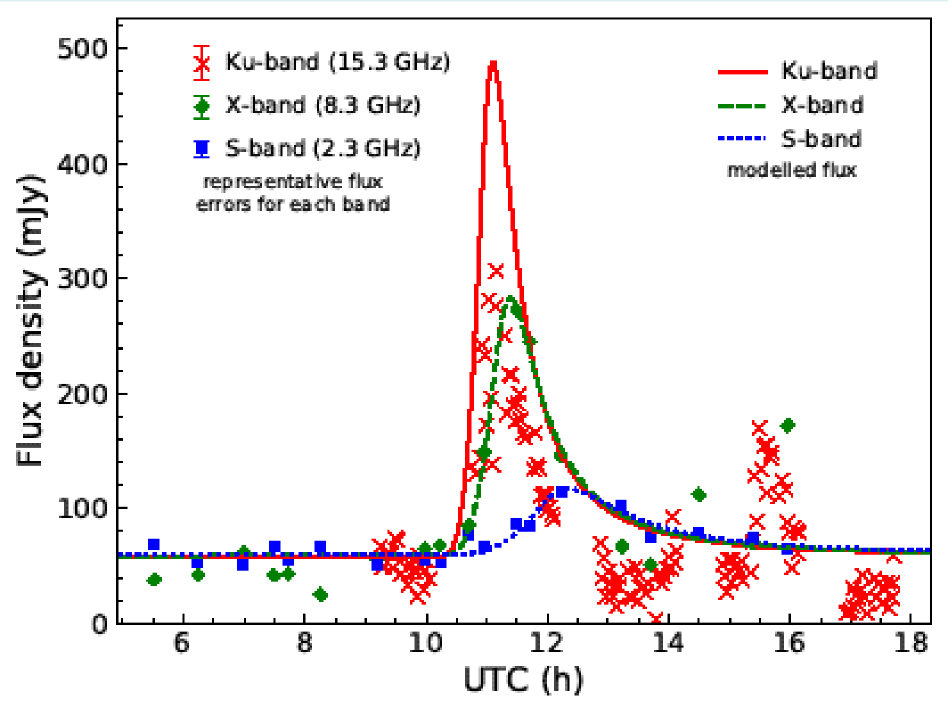


Fig. 9.3. Observation of a 'clean' radio flare event from the jet source Cyg X-3 at 15 GHz. The rise time of the event ~ 0.04 d, allows an estimation of the size of the region associated with the event, and thus the minimum energy. Observations from the Ryle Telescope (Guy Pooley, private communication).



- Some simultaneous data with GBI and VLBA for 1995 May 7 flare.
- Expanding synchrotron source with adiabatic losses (Ball an d Vlassos 1993)
- Least square fit including background flux to first flare.
- Good fit to X and S band
- - doesn’t fit 15 GHz flux – inverse Compton losses needed at freqs > ~10 GHz

Cyg X-3 states (Waltman+1996, Szostek+2008, Koljonen+2010)

- Radio: Quiescent ~100 mJy, Xray: Quiescent/transition,
- Radio: minor flaring ~300 mJy, Xray: flaring hard state
- Radio quenched <30 mJy, Xray: hypersoft, Occurs before major flaring
- Radio major flaring ~10 Jy, Xray: flaring, soft
- Major radio flares rise in ~ 1 day, duration (FWHM) 3 days
- Minor flares rise in ~ 1 hr, duration 2-3 hrs

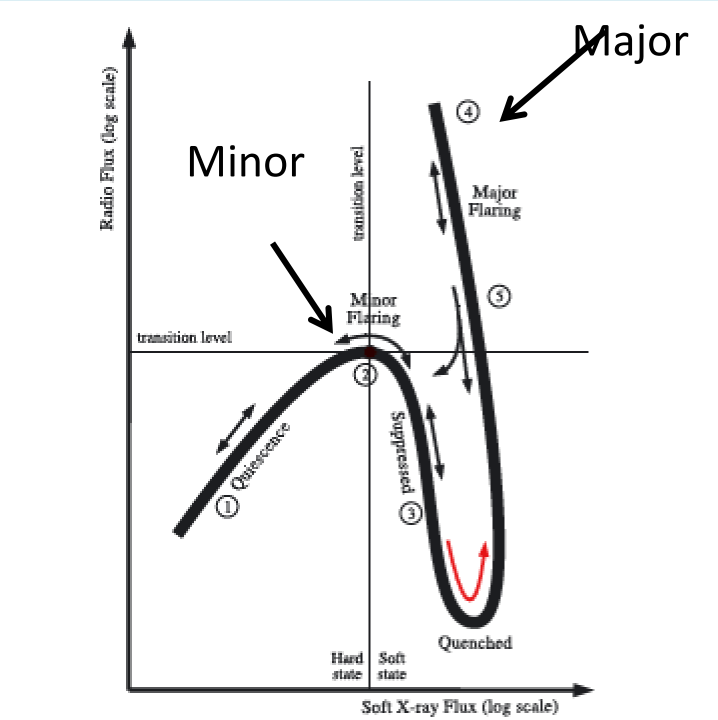


Figure 6. A schematic representation of the evolution of Cyg X-3 through its radio and X-ray states. The dotted lines represent the transition levels, with a dot at their intersection. The arrows show the possible directions of the source evolution. The numbers correspond (approximately) to the X-ray spectral states.

Szostek+2008 radio vs X-ray

We applied Fender and Bright 2019 formulae to the radio observations. Assumes minimum energy and self-absorption, single frequency formulae:

$$\beta_m = 5.6 \times 10^1 D_{\rm kpc}^{16/17} F_{\nu,\rm mJy}^{8/17} \nu_{\rm GHz}^{-33/34} \Delta t_{\rm sec}^{-1} \quad (28)$$

$$E_m = 1.5 \times 10^{35} D_{\rm kpc}^{40/17} F_{\nu,\rm mJy}^{20/17} \nu_{\rm GHz}^{-23/34} \quad (29)$$

$$B_m = 2.5 \times 10^{-1} D_{\rm kpc}^{-4/17} F_{\nu,\rm mJy}^{-2/17} \nu_{\rm GHz}^{19/17} \quad (30)$$

$$T_m = 3.5 \times 10^{10} D_{\rm kpc}^{2/17} F_{\nu,\rm mJy}^{1/17} \nu_{\rm GHz}^{-1/17} \quad (31)$$

Size= $\beta c\, t_w$

$V=(4/3)(\beta c \Delta t)^3$ Volume

$U=E/V$ Energy density

P=E/t_r Power, t_r = rise time in secs

Note weak dependence for T

Assume 7.4 kpc

Major vs Minor flares average values

- Major Flares

  ~10 Jy, twidth~2 d (FWHM)

  ~ 2-3 /yr

  β=0.03

  E=3×10^{41} ergs

  B=0.6 gauss

  U=0.05 ergs cm^{-3}

  P=9×10^{36} ergs sec^{-1}

  Size ~100 au

  (Pedd=1.4×10^{38} M/Msun)

- Minor flares

  ~0.3 Jy, twidth~2 hr (FWHM)

  ~ 2-3 /month?

  β=0.17

  E=5×10^{39} ergs

  B=0.7 gauss

  U=0.1 ergs cm^{-3}

  P=1×10^{36} ergs sec^{-1}

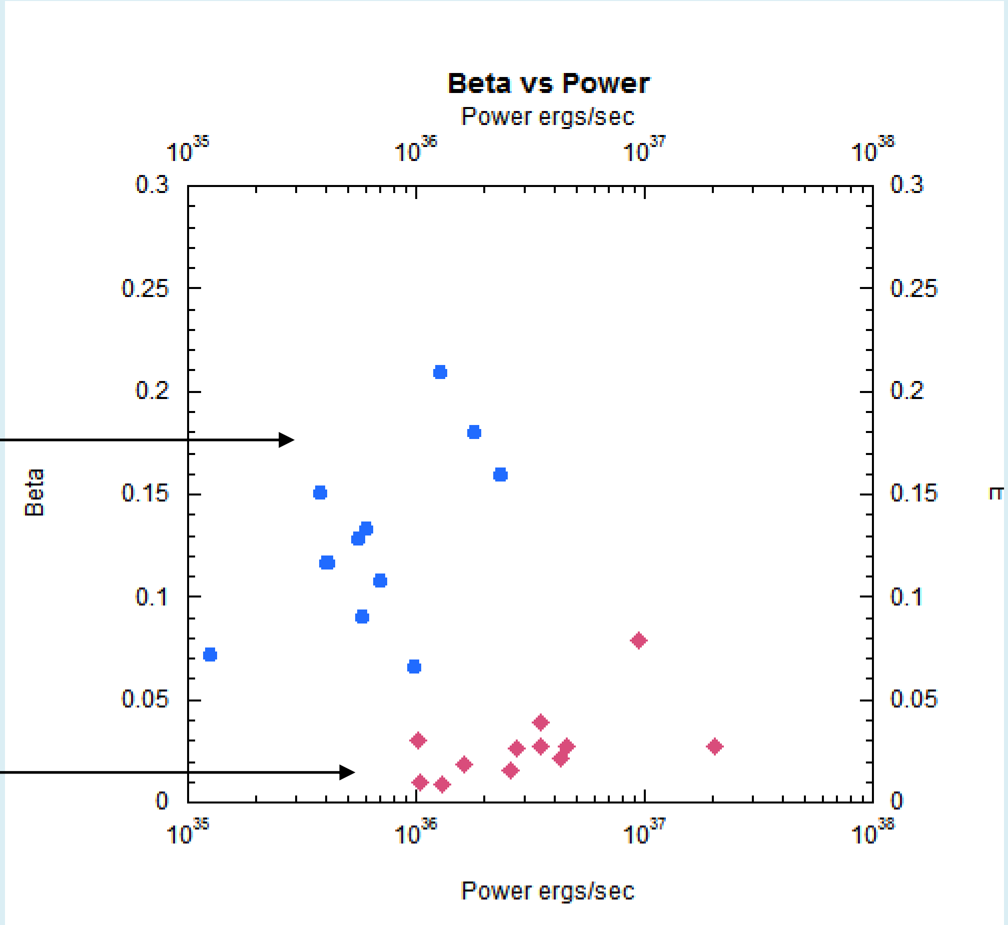
  Size ~3 au

  NB minimum energy and power

Expansion velocity vs power

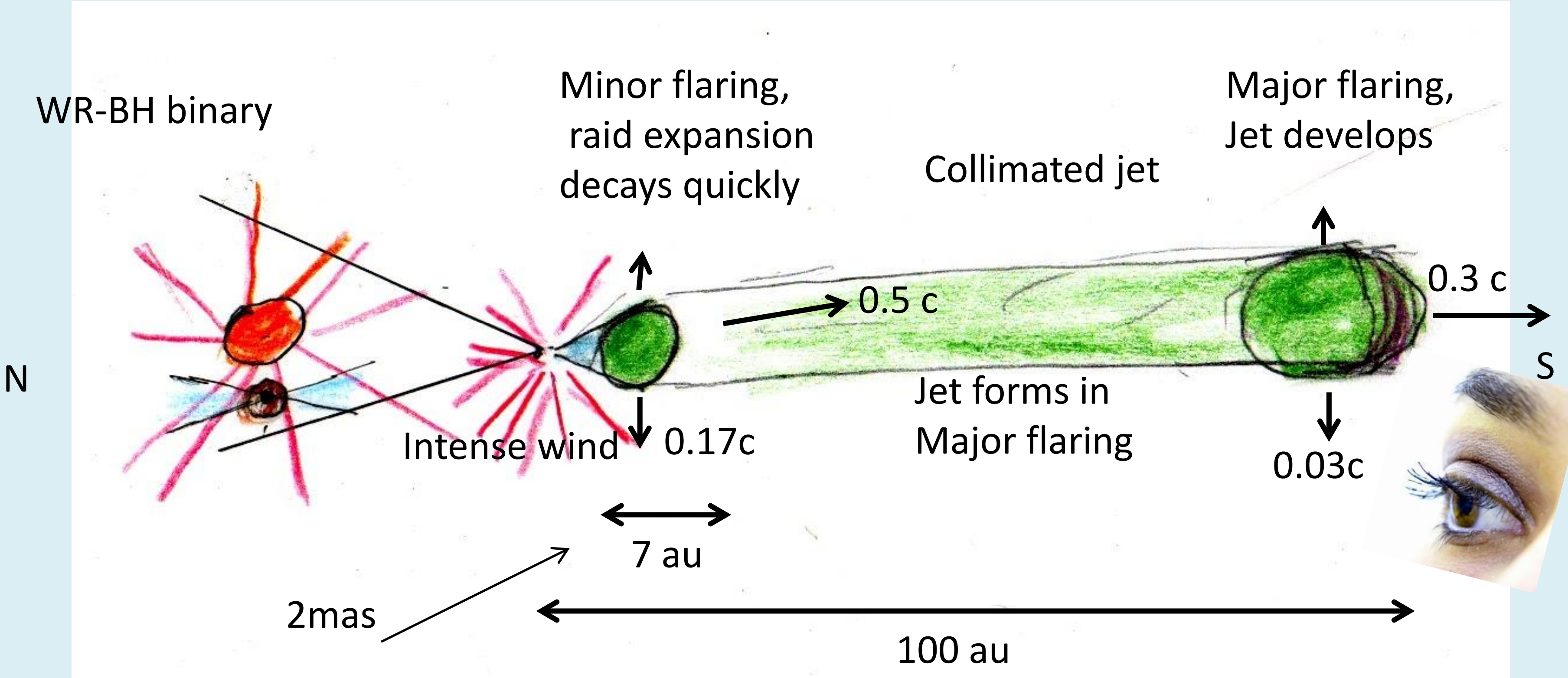
Minor flares

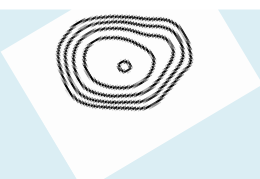
Major flares



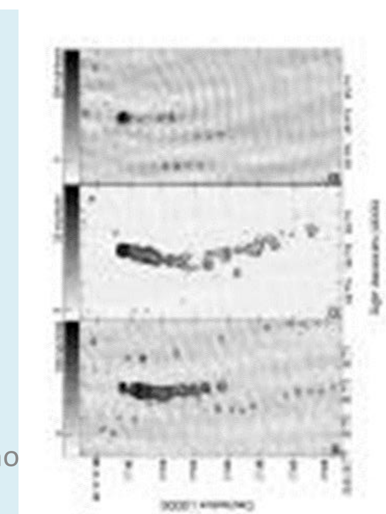
Bulk / jet velocity expected to be higher

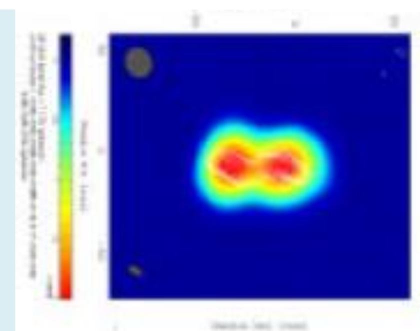
Shock-in-jet model -- a composite picture





VLBA Newell+1998





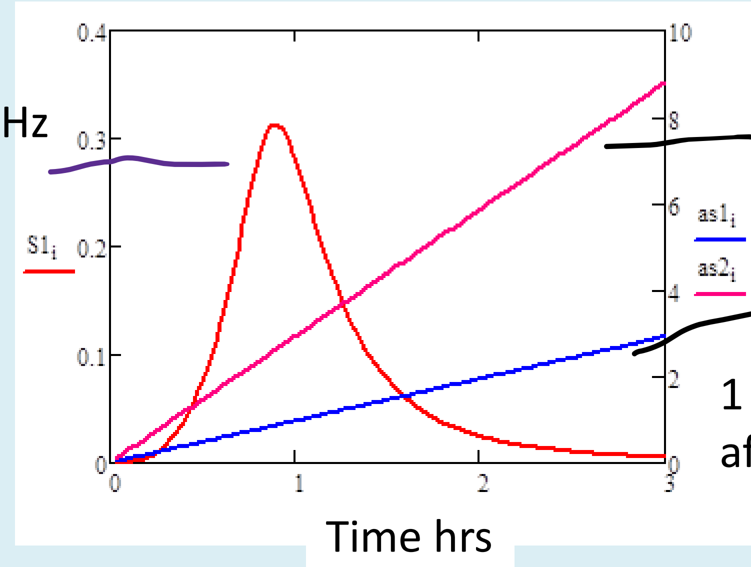
VLA AM

VLBA AM+2001

VLBI Issues:

- To investigate minor flares need high resolution VLBI, BUT…..
- Rapid variability, difficult to image – snapshots? Many antennas needed
- Interstellar scattering is strong:
  - size = $\frac{448}{(f)^{\wedge}2.09}$ mas (Mioduszewski+ 2001)
- Higher frequencies better but less antennas

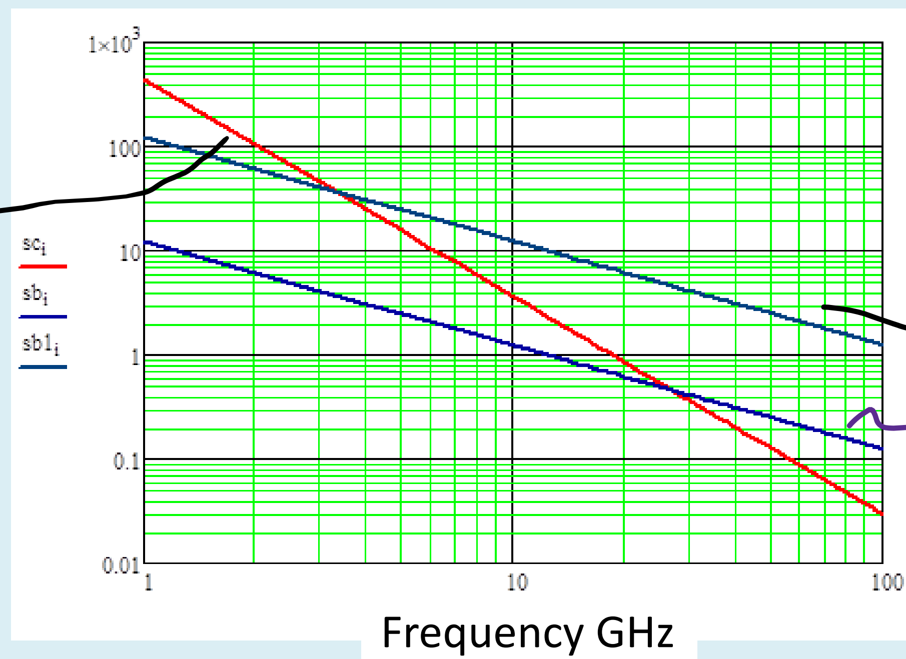
Flux density of expanding synchrotron source at15 GHz (Ball+Vlassis 1993) model.



Size vs time for
0.3 c
0.1 c
(7.4 kpc)

1 – 3 mas size expected after 1 hr for constant velocity

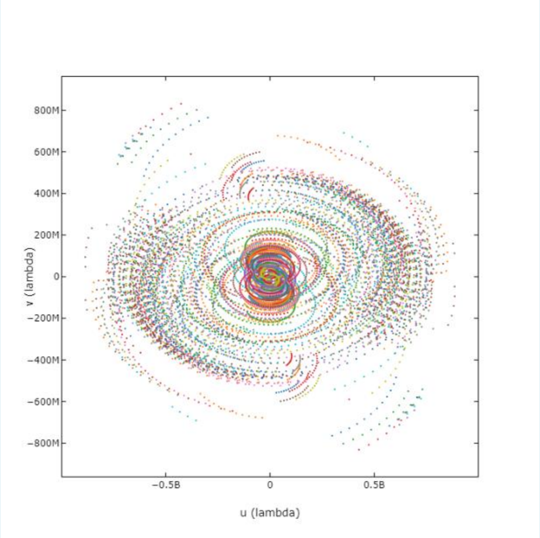
IS scattering size vs freq. mas



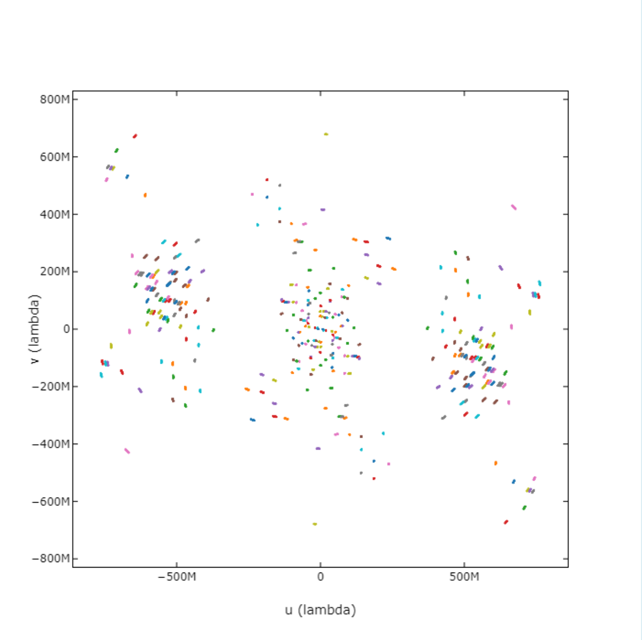
Resolution in mas for Baselines
500 km
5000 km

Using EVN planner

EVN+VLBA at 23 GHz, 11 hr run



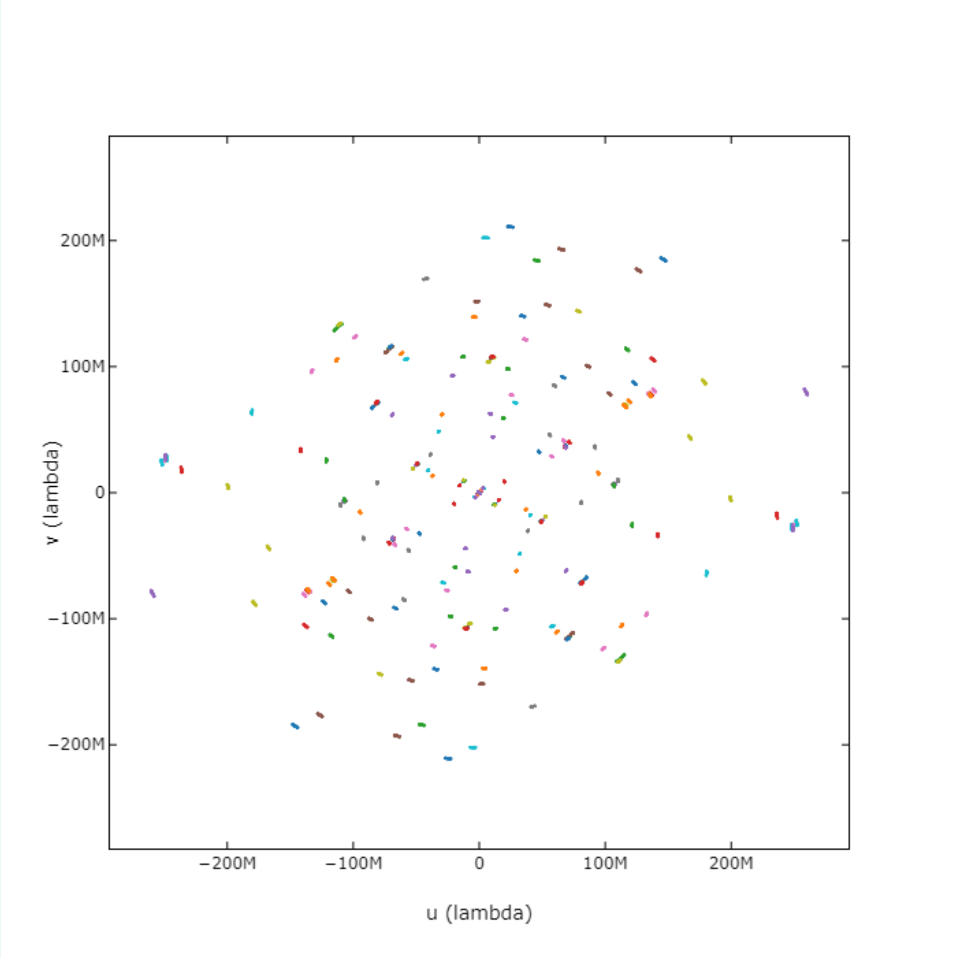
6 min. Snapshot observation at 2147 GST Large gaps in uv coverage.



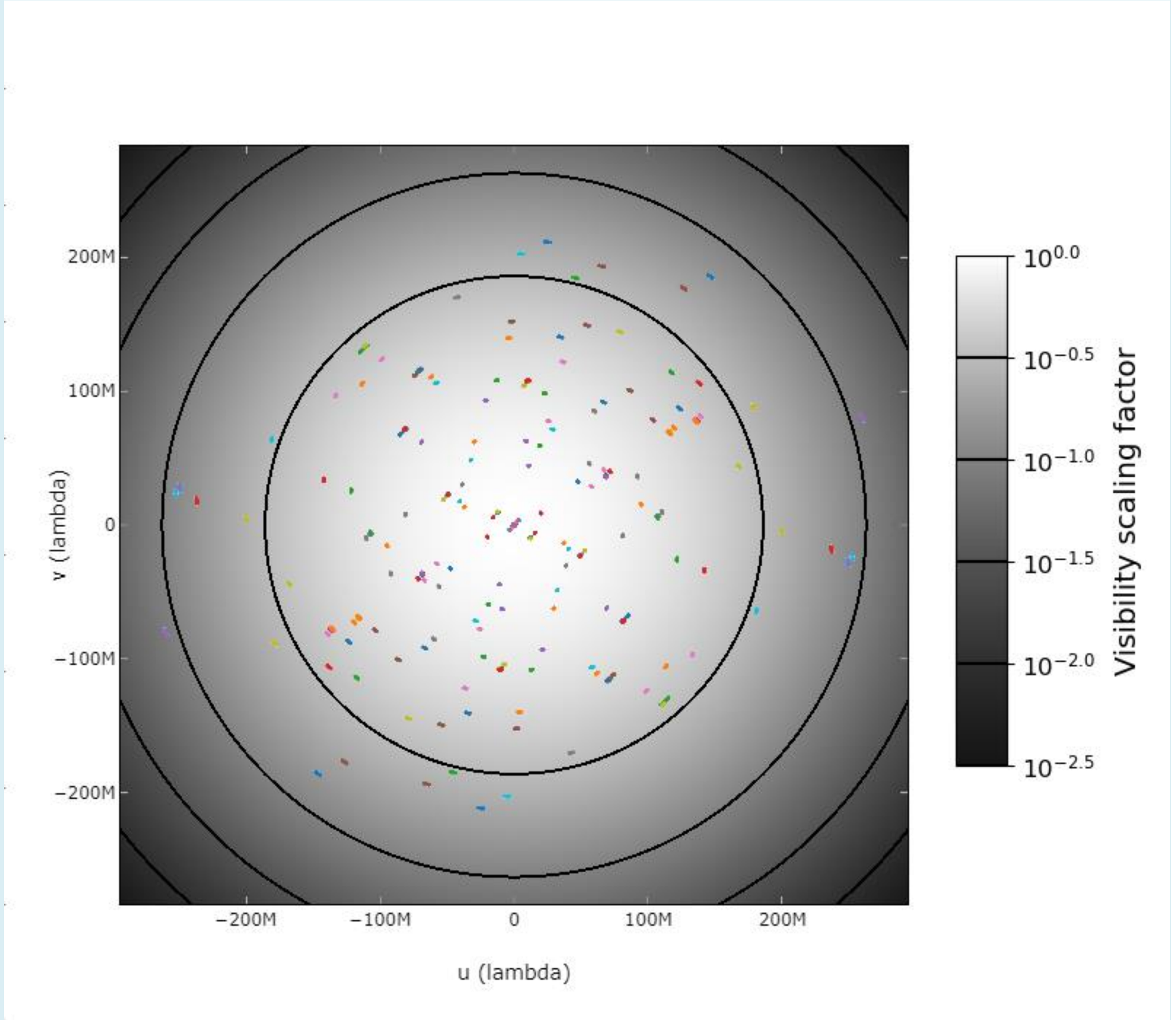
EVN only

2021 GST
1 mas beam 23 GHz EVN only
15 telescopes inc. Russian ones

1x0.8 mas beam rms. 0.1 mJy/b



Effect of scattering – will reduce visibility on the longer baselines



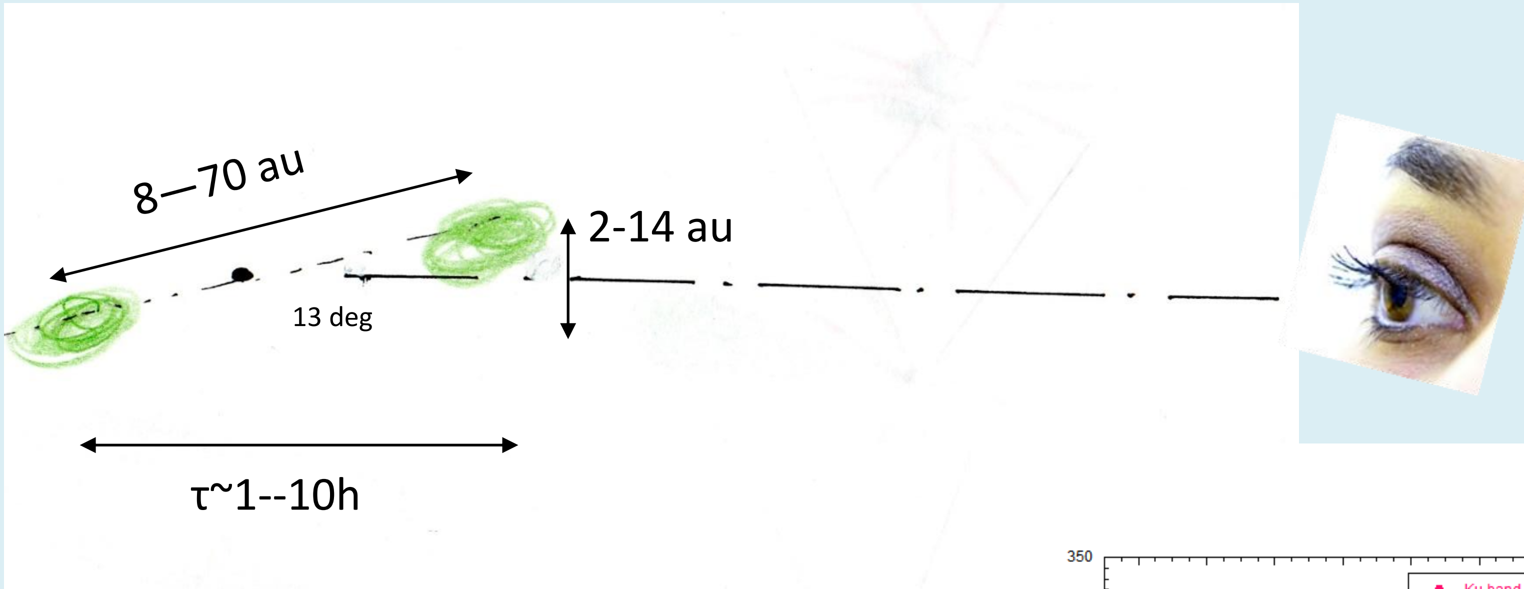
Compromise between observing frequency, scattering, resolution and number of telescopes available

Conclusion

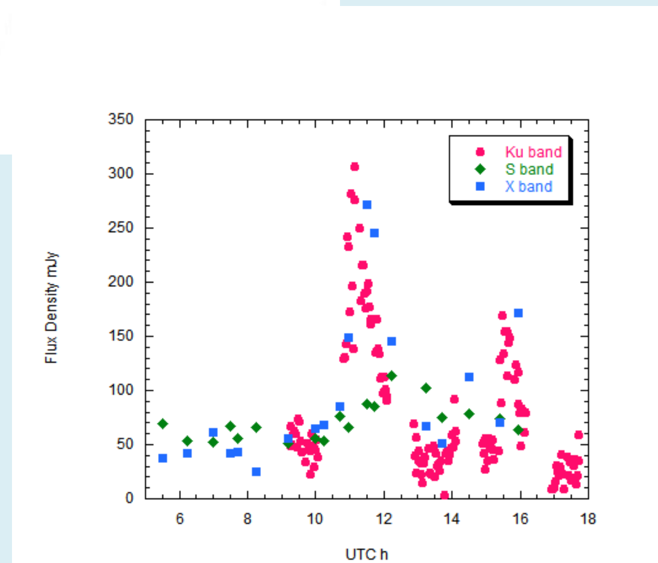
- Minor flares are short lived, have higher expansion velocities, contain less minimum energy and need less power to form
- Longer injection of energy (particles and field) gives rise to strong flares
- Slower expansion even though internal pressure similar implies confinement in strong flares – external medium/ magnetic field?
- Rapid variability means short snap-shot imaging on 1 mas scale , needs rapid sampling and many telescopes (IS scattering an issue)
- OR Bayesian imaging approach: Broderick+2022
- Cyg X-3 is a very complicated beast and awkward to image!

Extra Slides

Double flares = a brightening zone cf. SS433???



7 May 1995 data



τ=5h

Science to be addressed !

- Rapid decay of flares: adiabatic expansion losses can explain
- But inverse Compton losses in the radiation field from the WR star important at frequencies >= 15 GHz
- Free-free absorption in a wind could also affect minor flare development, Need good frequency coverage in radio
- Jet images sometimes one sided, sometime 2 sided (Mioduszewski+2005) – why?
- Core emission difficult to disentangle from the jet (Tudose+2010)
- Need more high resolution images!
- 4.8 hr period has been claimed in radio minor flaring (e.g. Egron+2020), in reality variety of intervals between minor flares
- What causes the ejections, major and minor, in the first place?!!!

Schedule

10 February 2023 11:00-11:06 UTC

GST range: 20:21-20:21.

4.2 min are on target.

Target source: 20h32m25.78008s +40d57m27.9s (Cygnus X-3).

Output FITS file size: 154 Mbyte.

Frequency Setup

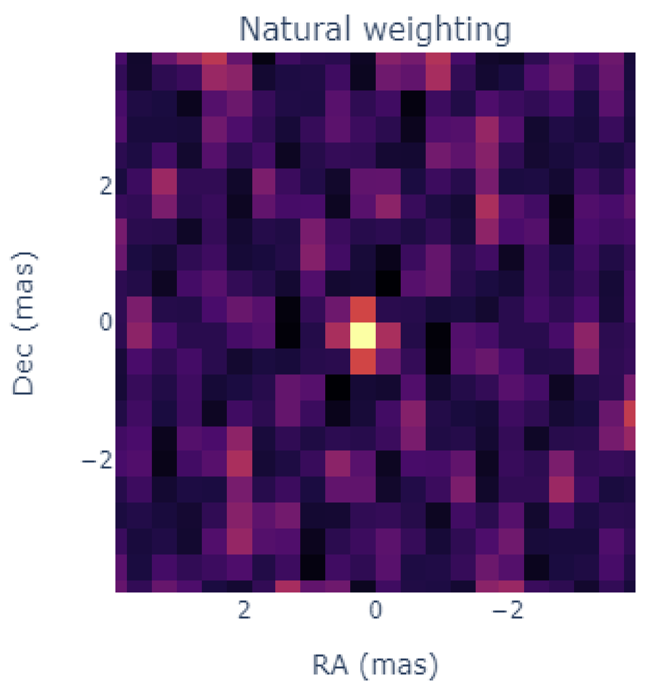
Central frequency: 23.1 GHz (1.3 cm).

8 subbands of 32 MHz each.

Channels per subband: 32.

Polarization: full.

time integration: 2 s.



VLBI Network

Participating antennas: Cm, Da, Ef, Jb2, Kn, Mc, Mh, Nt, On, Pi, Sr, Sv, Tr, Ys, Zc.

The expected synthesized beam will be approx. 1.05 x 0.759 mas, PA = -163 deg.

Expected rms thermal noise level: 111 uJy/beam.

Per spectral channel: 1.78 mJy/beam.

Time smearing (10% loss): 3.41 arcsec.

Frequency smearing (10% loss): 14 arcsec.