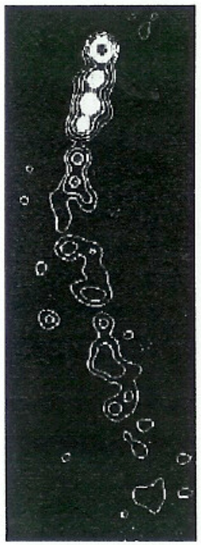
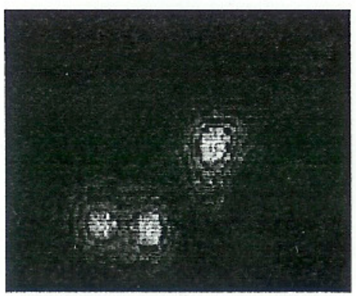
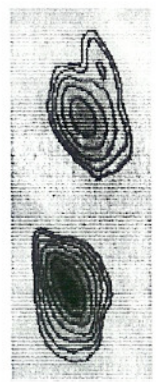
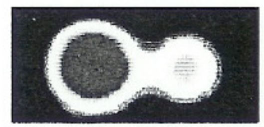
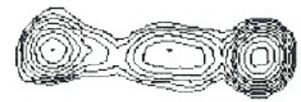
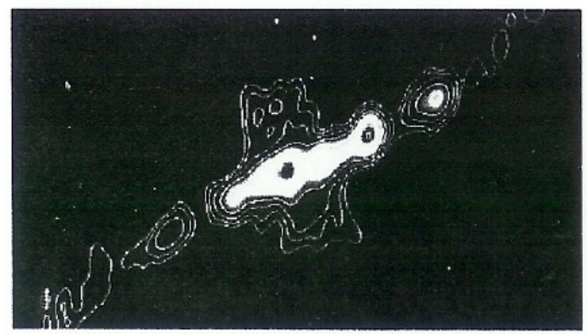
The Radio/X-ray Connection in the Chandra/XMM Era



Michael P. Rupen

Boston 14nov02

I - Radio/X-ray correlations & complexities

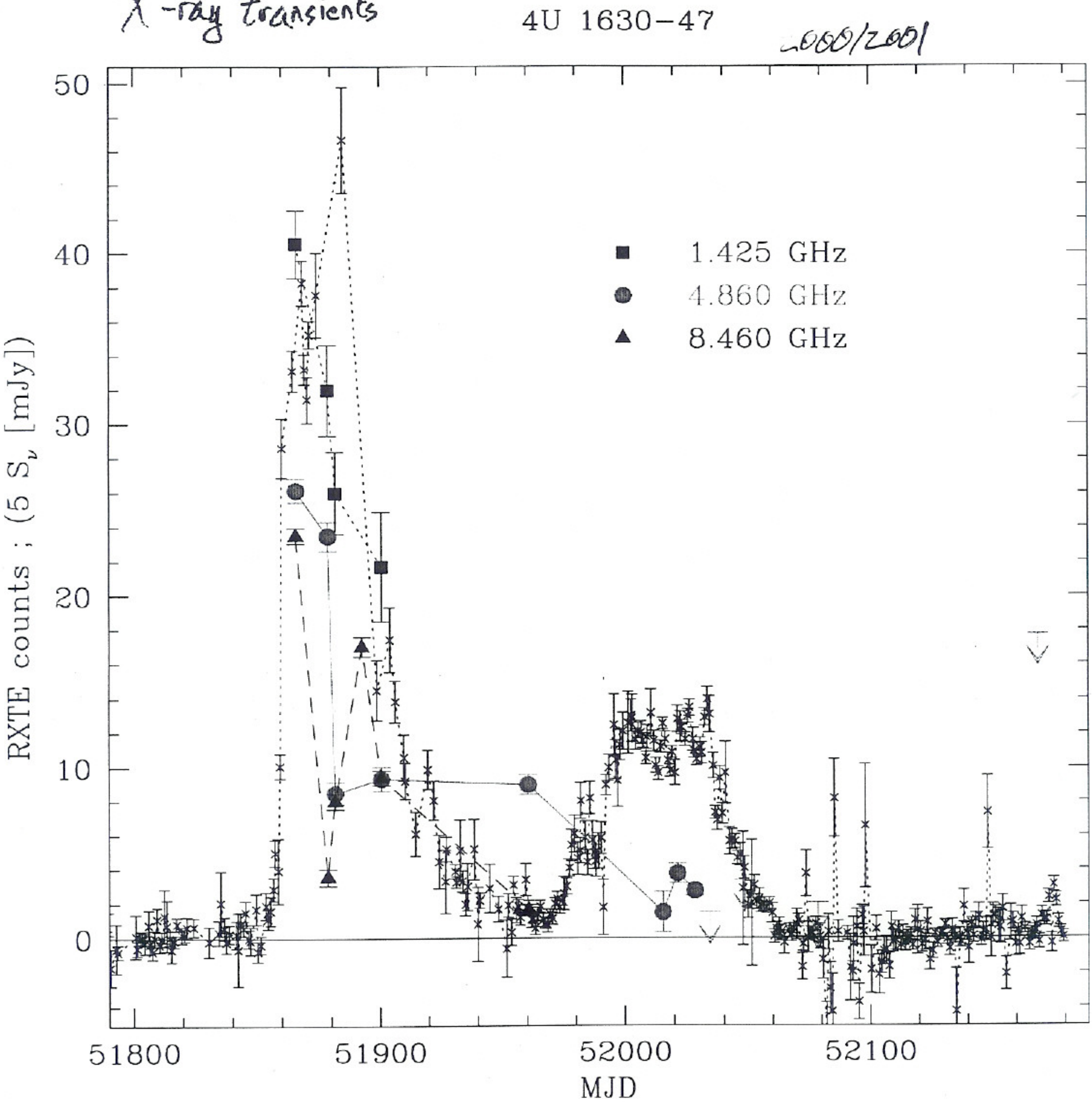
II - Radio vs. X-rays: finding, monitoring, triggering

III - The next steps: possibilities and opportunities

- Chandra/XMM
- Radio
- The future

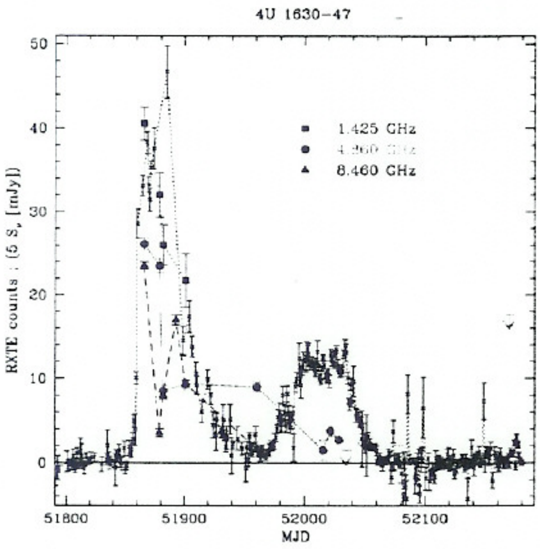
X-ray transients

2000/2001

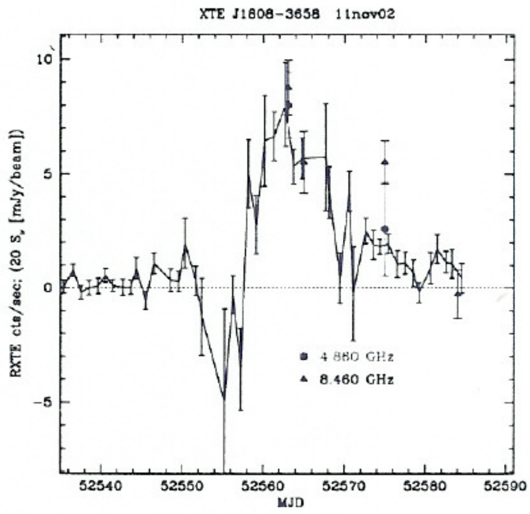


simultaneous X-ray/radio flare,
1998 similar – BATSE turned on ~ same time

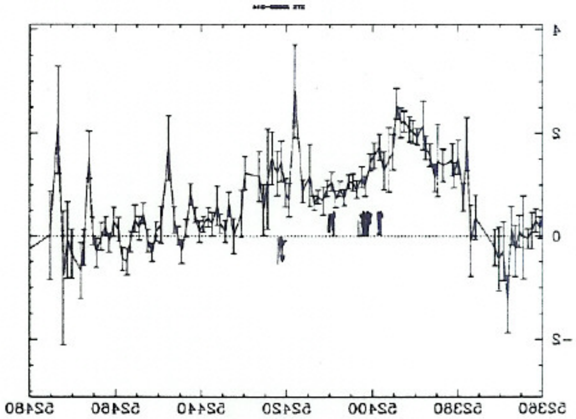
Some Recent X–ray Transients



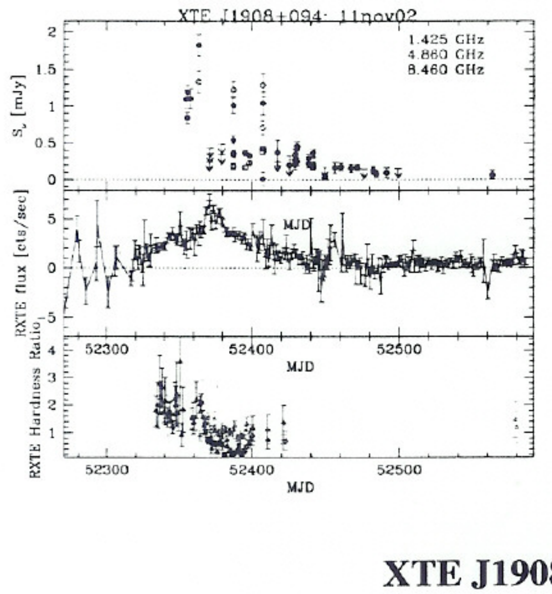
4U 1630–47 (2000/2001)

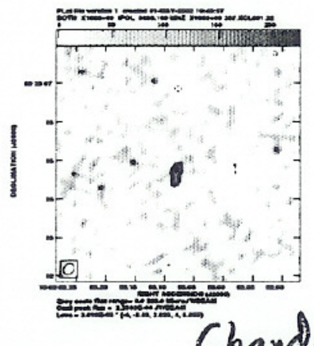


Two msec X–ray Pulsars



X0929-314

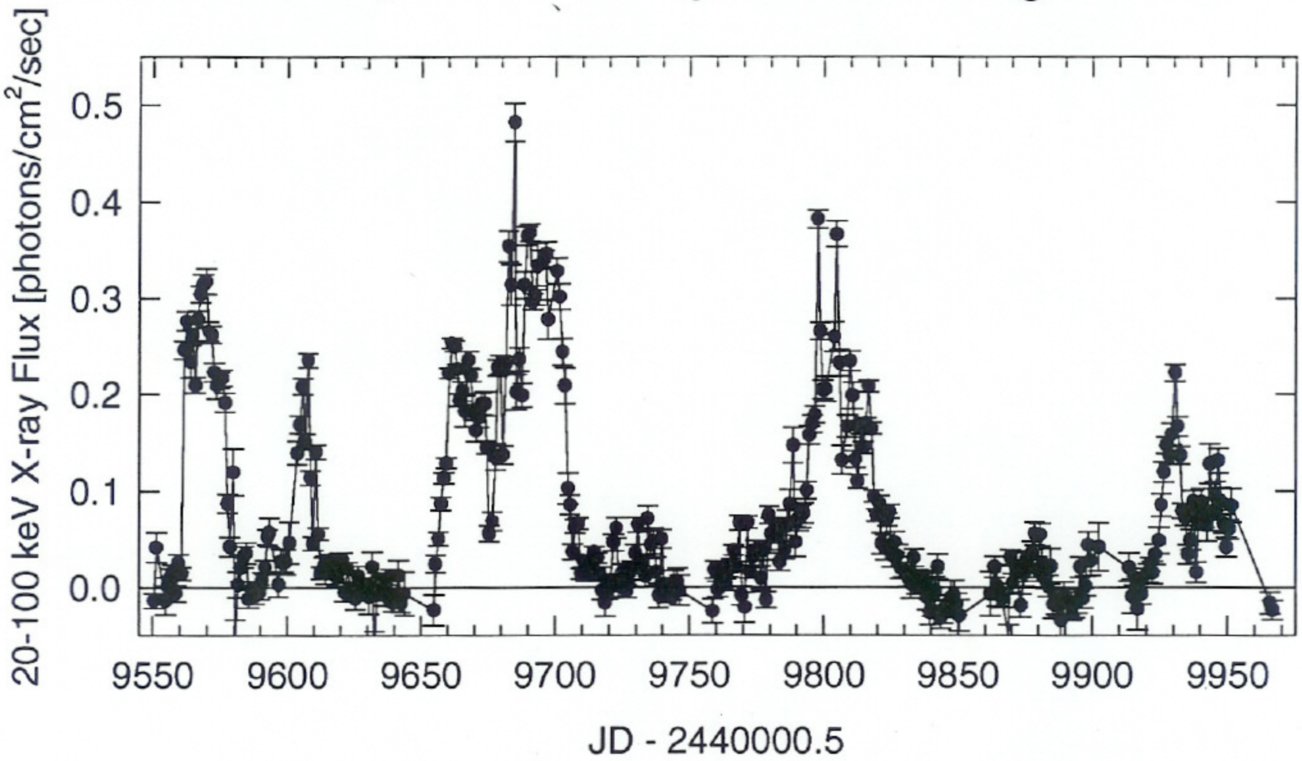


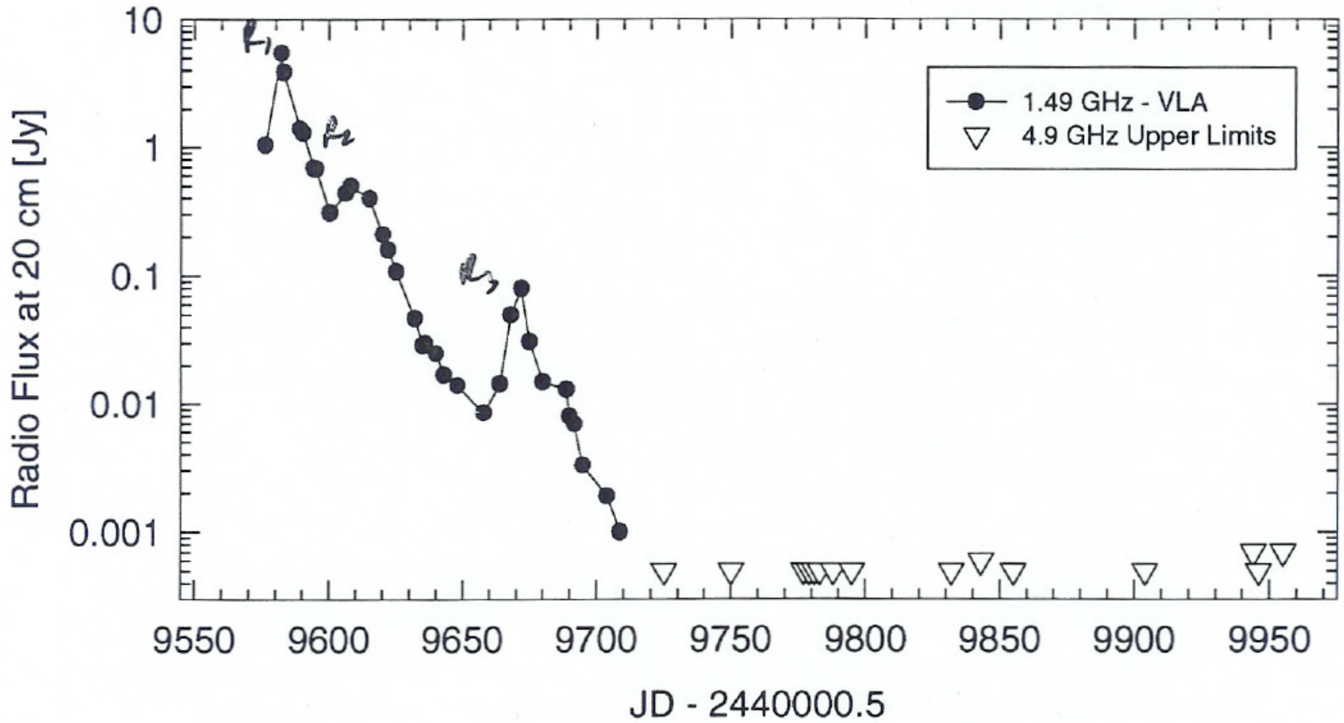


Chandra ToO → position

XTE J1908+094

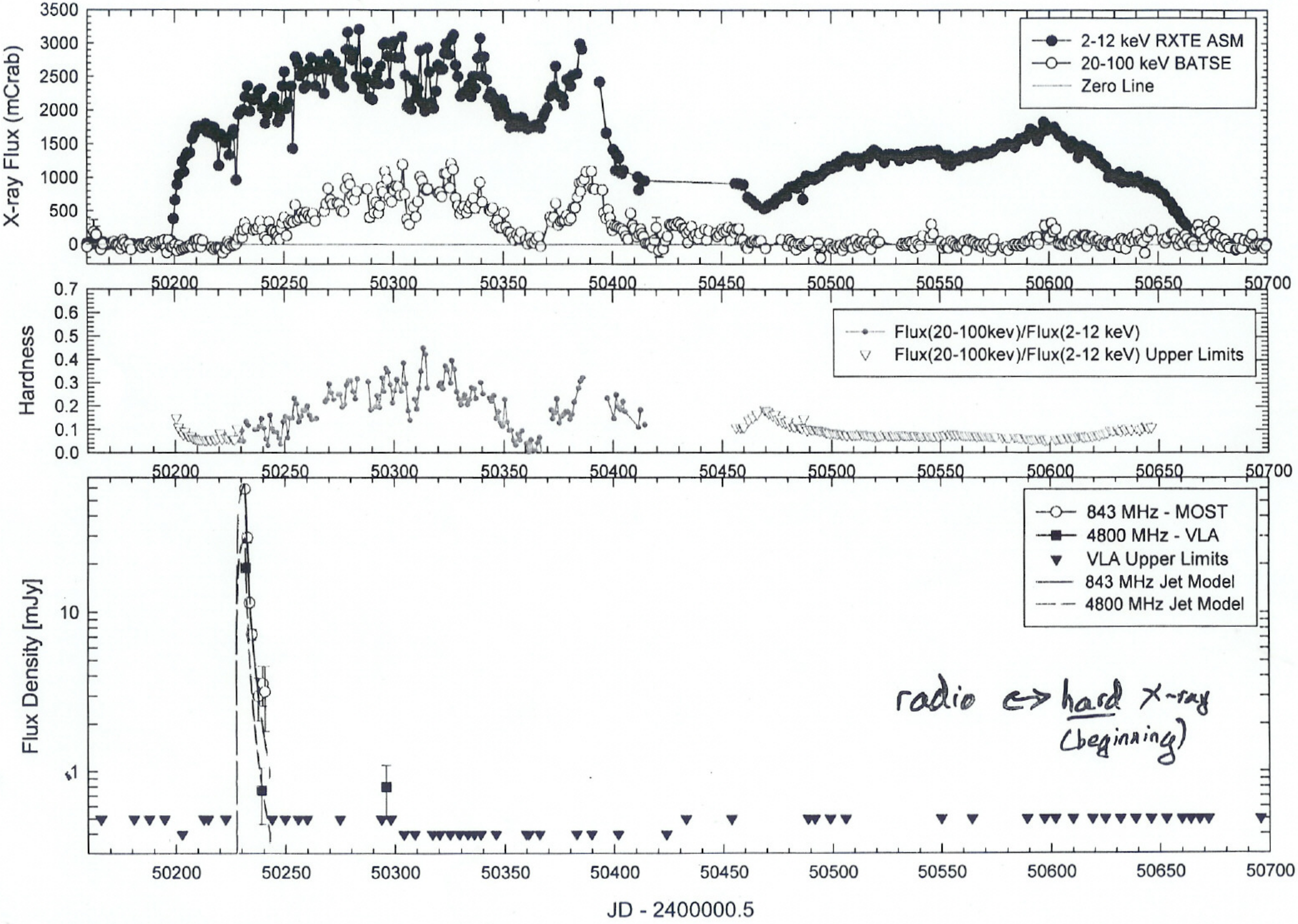
GRO J1655-40, 1994-95 X-ray and Radio Light Curves



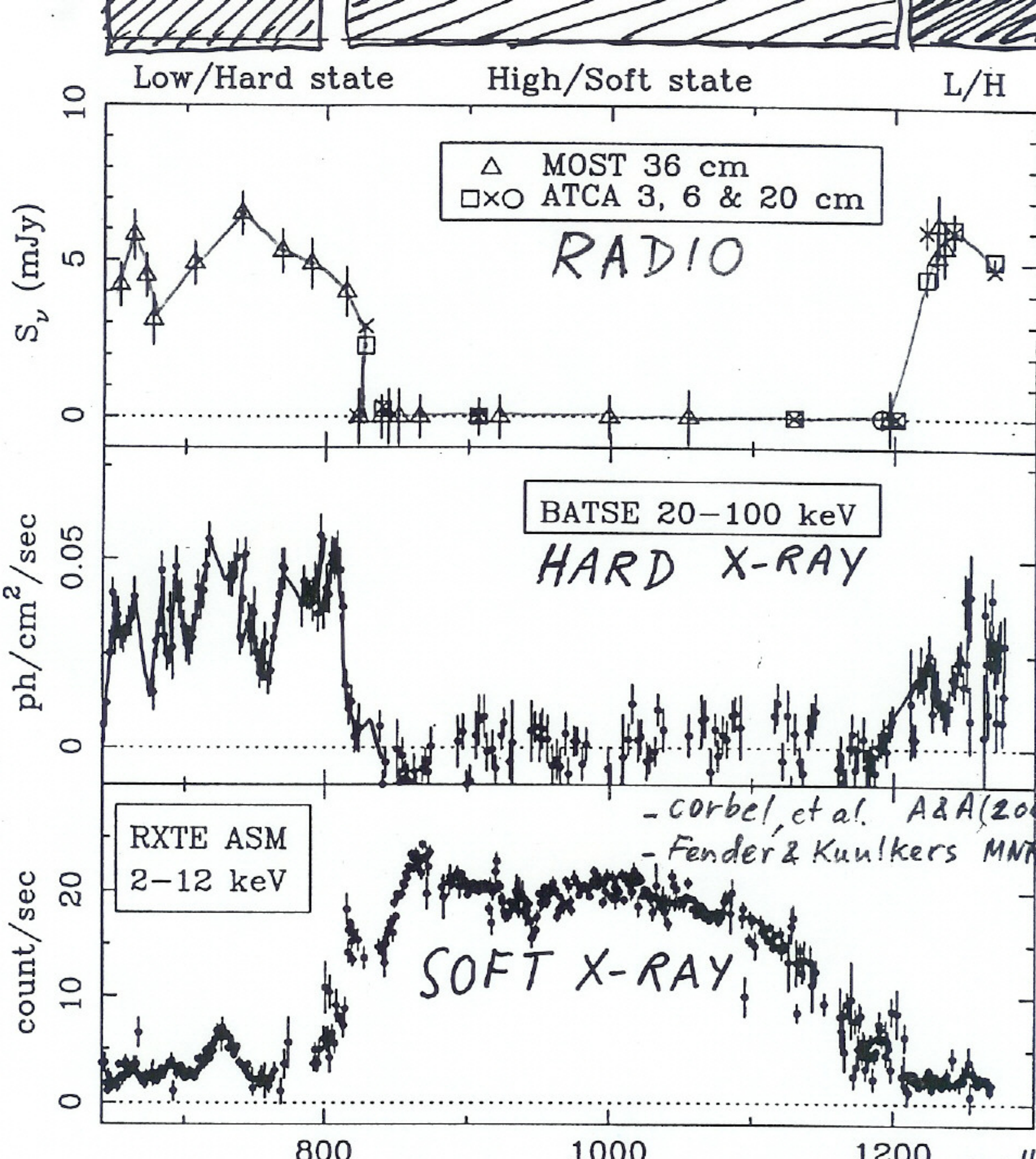


· linked to hard X-rays and state changes
· not all HXR flares produce (big) jets!

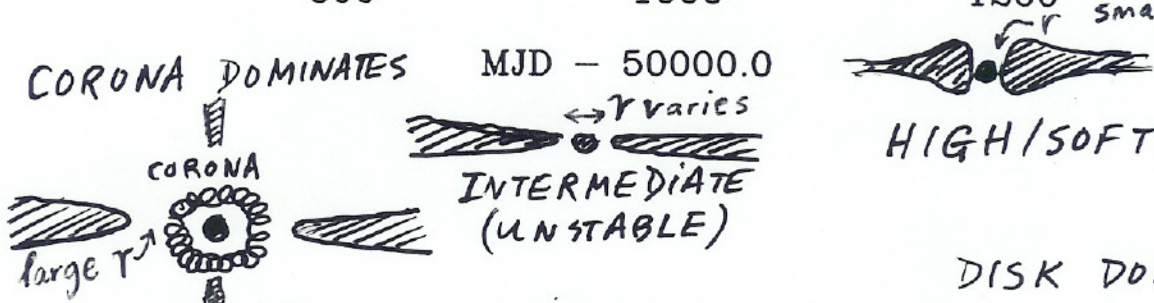
1996-1997 XR and Radio Light Curves of GRO J1655-40



STATE TRANSITIONS in GX 339-4



- Corbel, et al. A&A (2000) 359, 2
- Fender & Kuulkers MNRAS 324, 9 (2001)



DAF
ADAF
ADAF
ADAF
VERY LOW $\dot{M}$

LOW/HARD
RADIO ON
LOW $\dot{M}$

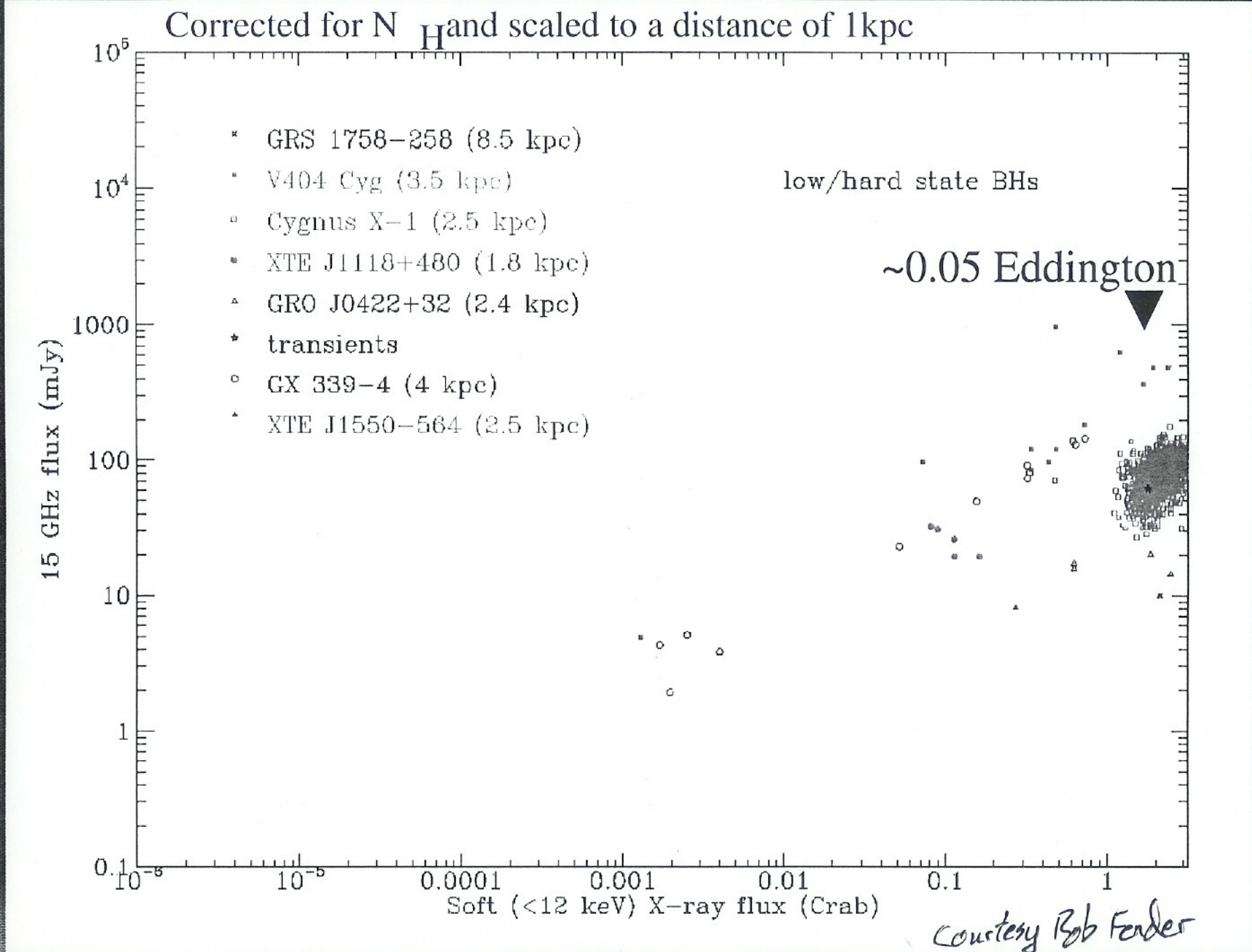
TRANSIENT FLARES
HIGH? $\dot{M}$

DISK DOMINATES
RADIO OFF
HIGH $\dot{M}$

X-RAY STATES

KIK@65

Correlated X-ray and radio fluxes in all low/hard state black hole binaries



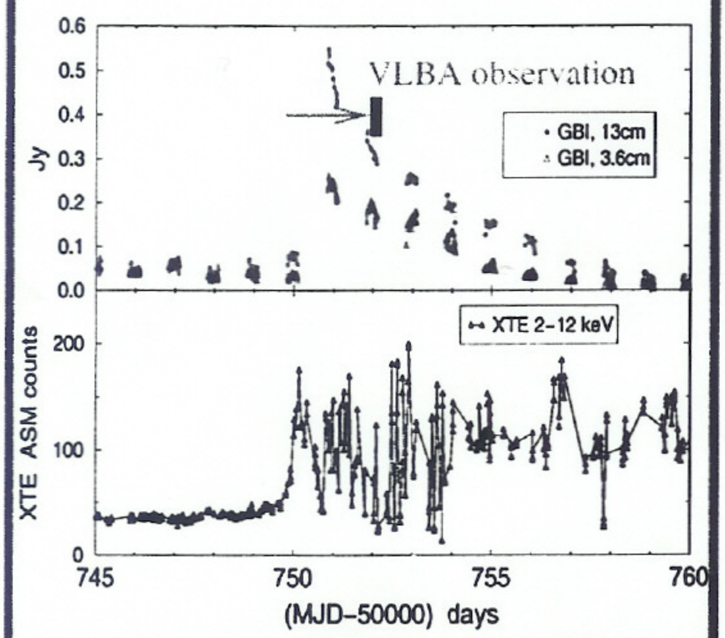
Gallo et al. (2002) and Corbel et al. (2002)

Microquasar GRS 1915+105 : VLBA Images of the AU–Scale Jet.

V. Dhawan, I.F. Mirabel, L.F. Rodriguez ApJ 543, 1 Nov 2000

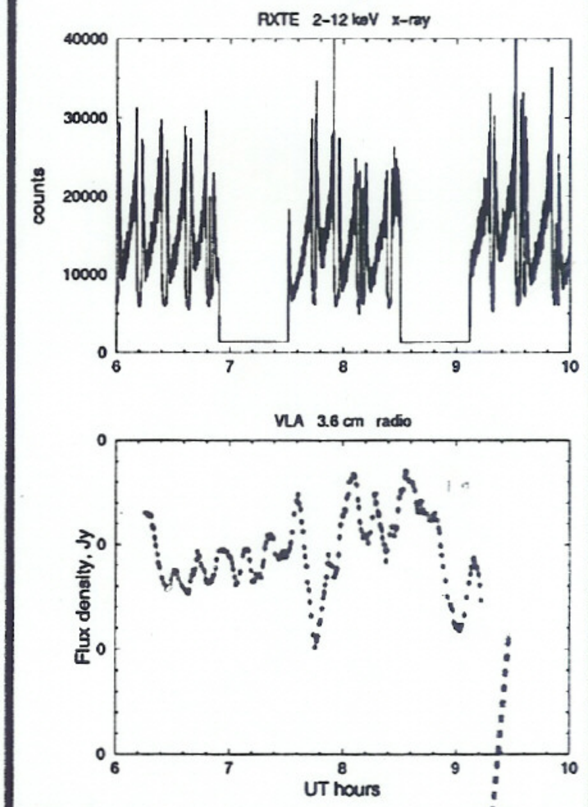
A: Radio / X–ray Flares

1997 Oct 24 – Nov 08

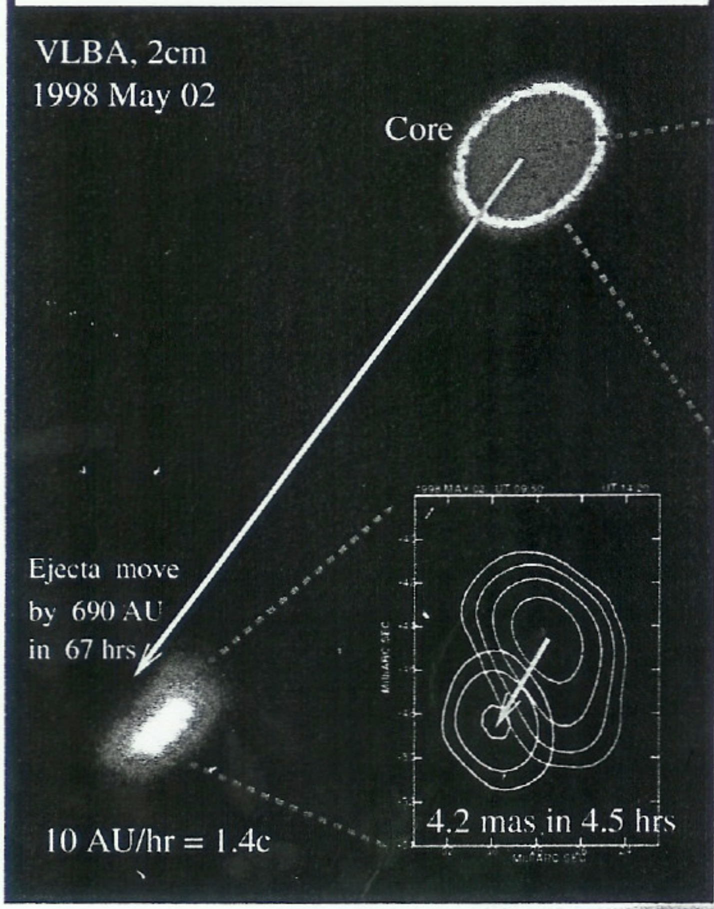


D: Disk & Jet co–evolution

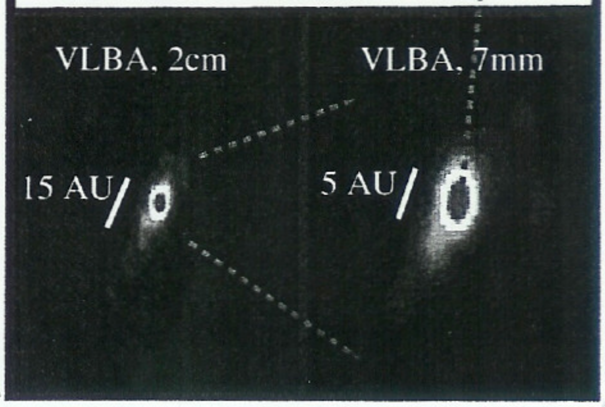
1997 Sept 05



B: Superluminal ejecta.

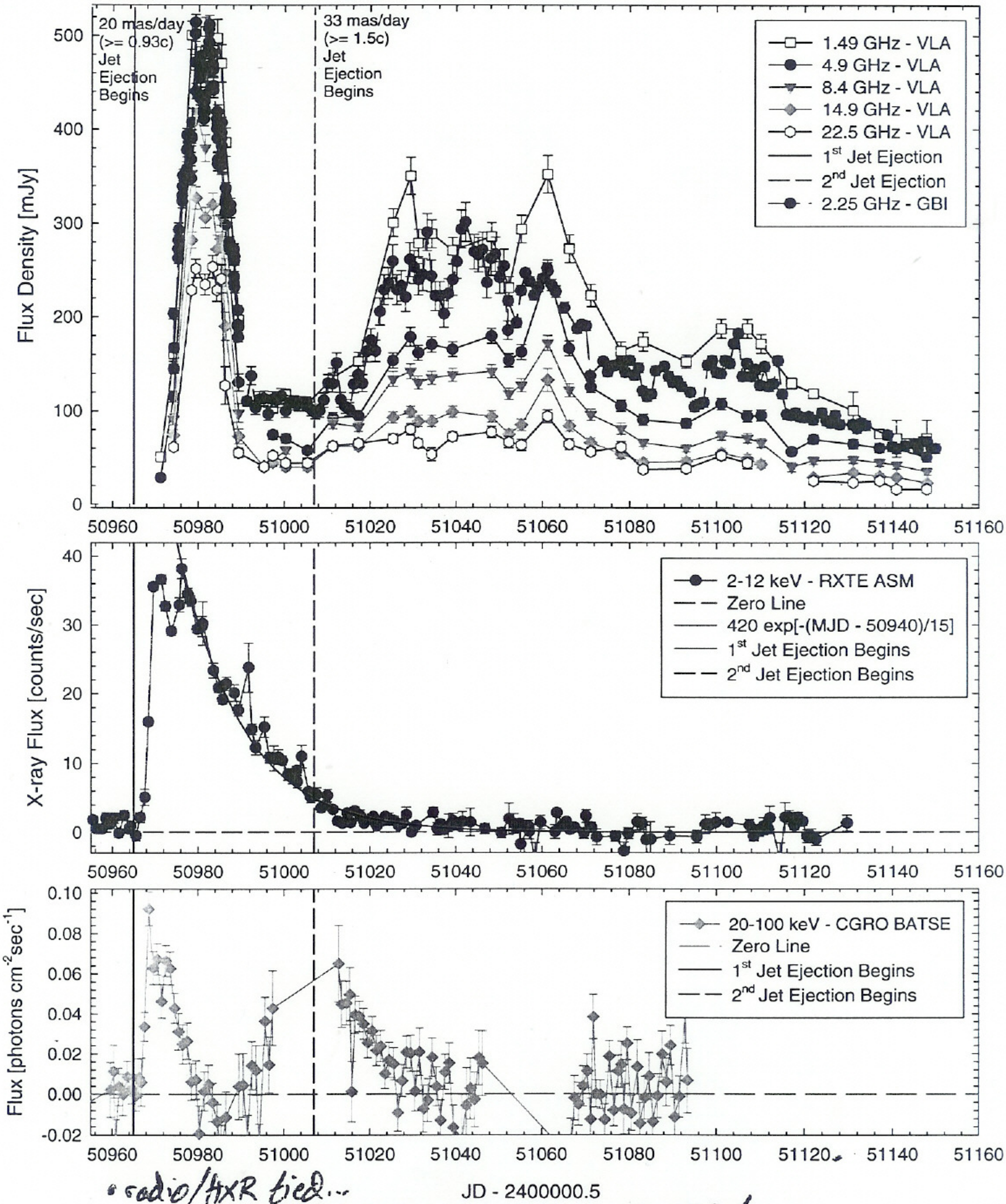


C: AU–sized nuclear jet



Tight soft X-ray ⟷ radio
connection
(c.f. QPOs too)

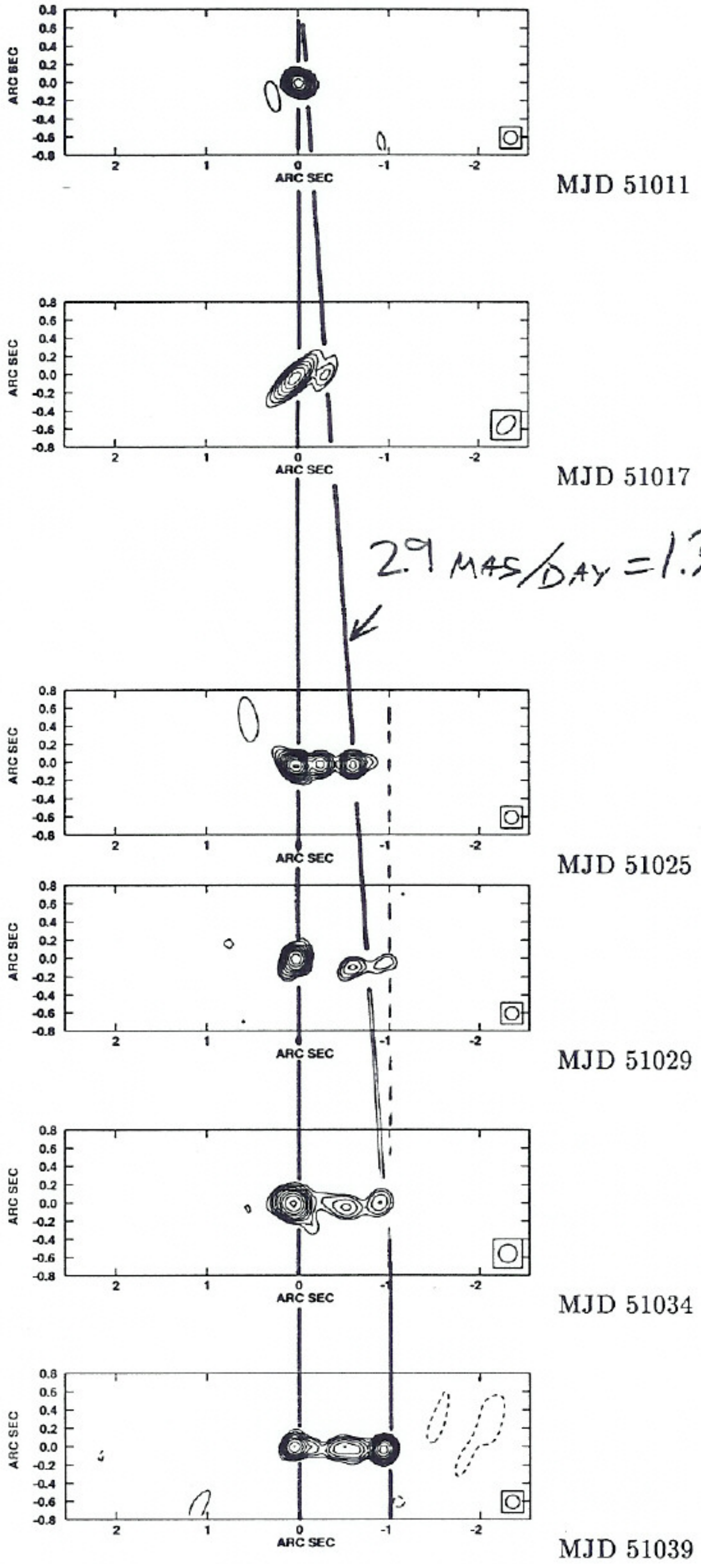
XTE J1748-288 VLA Radio & X-ray Light Curves



• radio/HXR tied...
but radio story is more complicated!

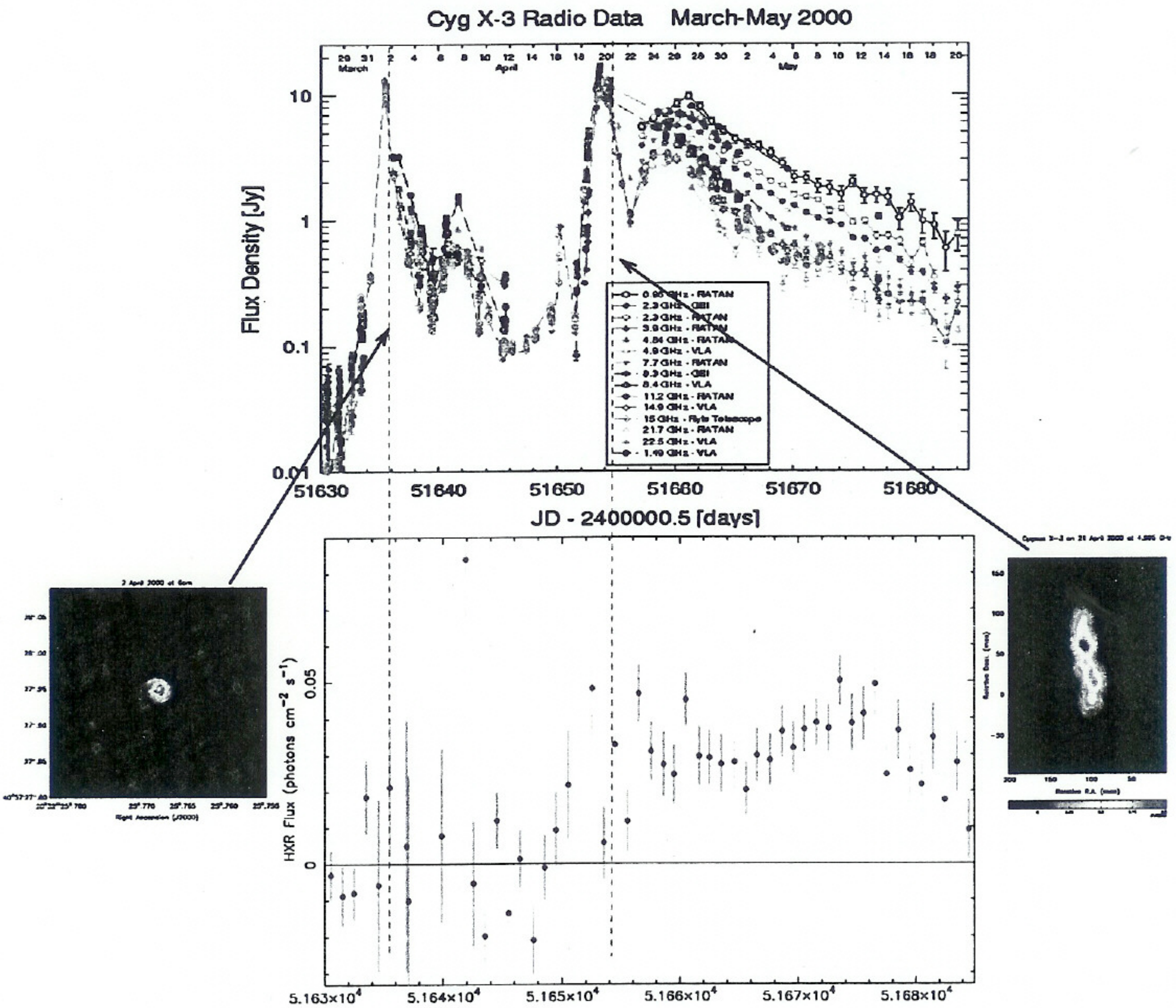
XTE J1748-288

July 17 – Aug 19, 1998



2.9 MAS/DAY $= 1.3\,c \left(\frac{d_{kpc}}{8}\right)$

DECELERATION AND BRIGHTENING



radio flares may or may not produce jets!

early jets
later NOT → need
fast
response

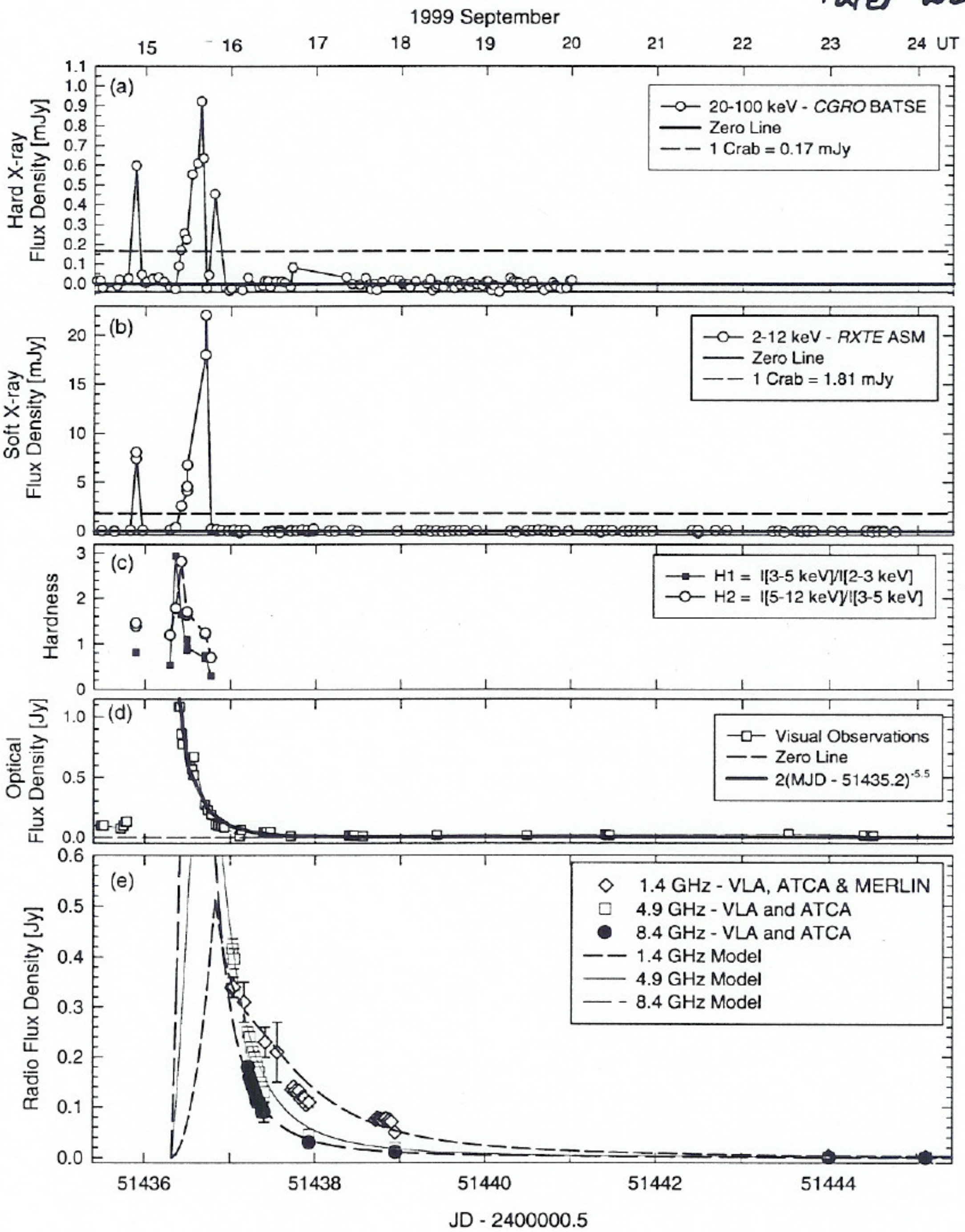
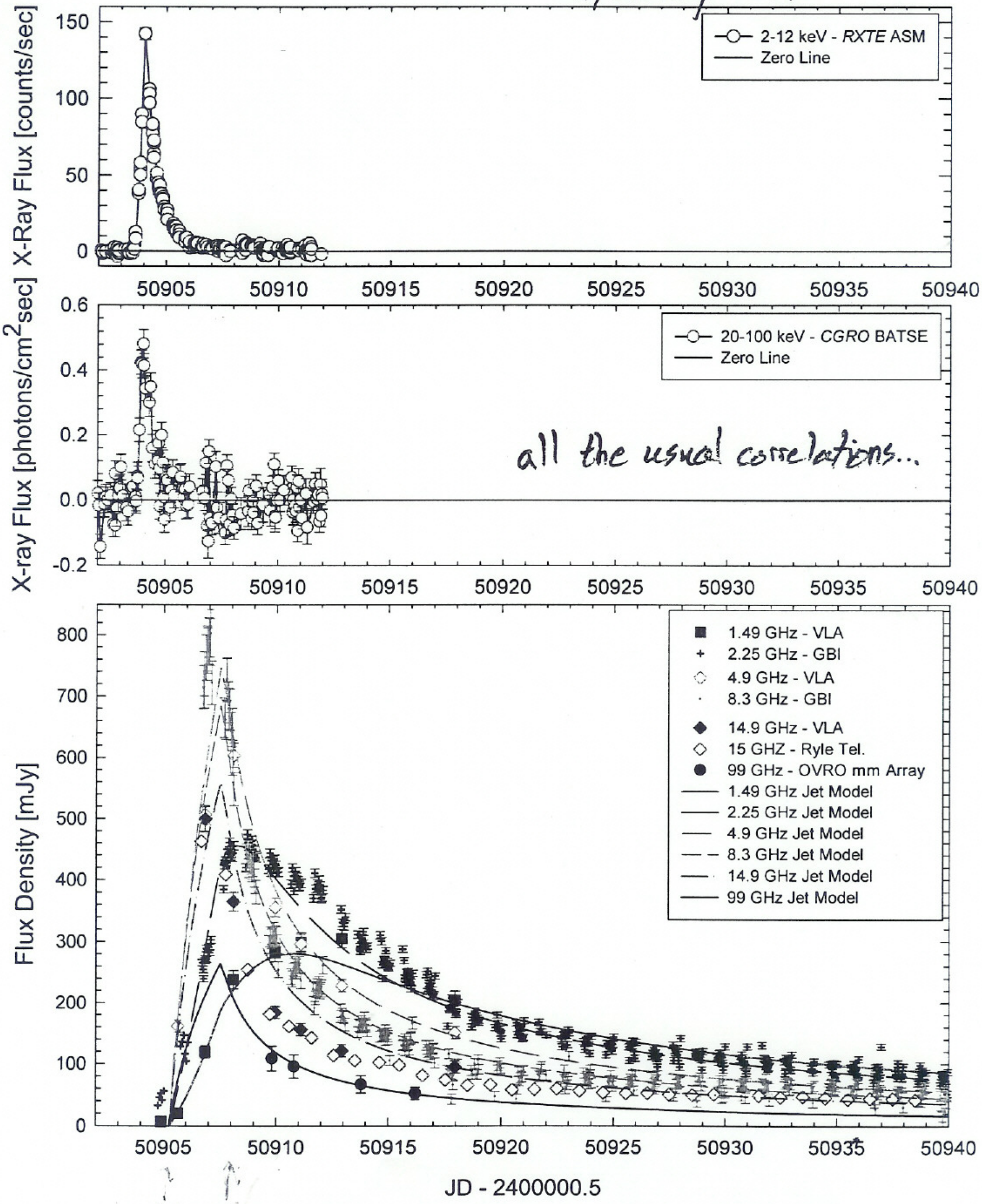


Fig. 1.— V4641 Sgr light curves for: (a) hard X-ray (*CGRO* BATSE, 20-100 keV); (b) soft X-ray (*RXTE* ASM, 2-12 keV); (c) *RXTE* ASM hardness (H1 = I[3-5 keV]/I[2-3 keV], H2 = I[5-12 keV]/I[3-5 keV]); (d) visual flux density; and (e) radio flux density for three of the observed frequencies — all plotted in units of Jy or mJy as a function of UT time (top axis) and MJD = JD −2400000.5 (bottom axis). The solid curves in (e) show the models for the plotted frequencies that fit both the radio light curve data and the observed images structures (cf. Section 6.2.2).

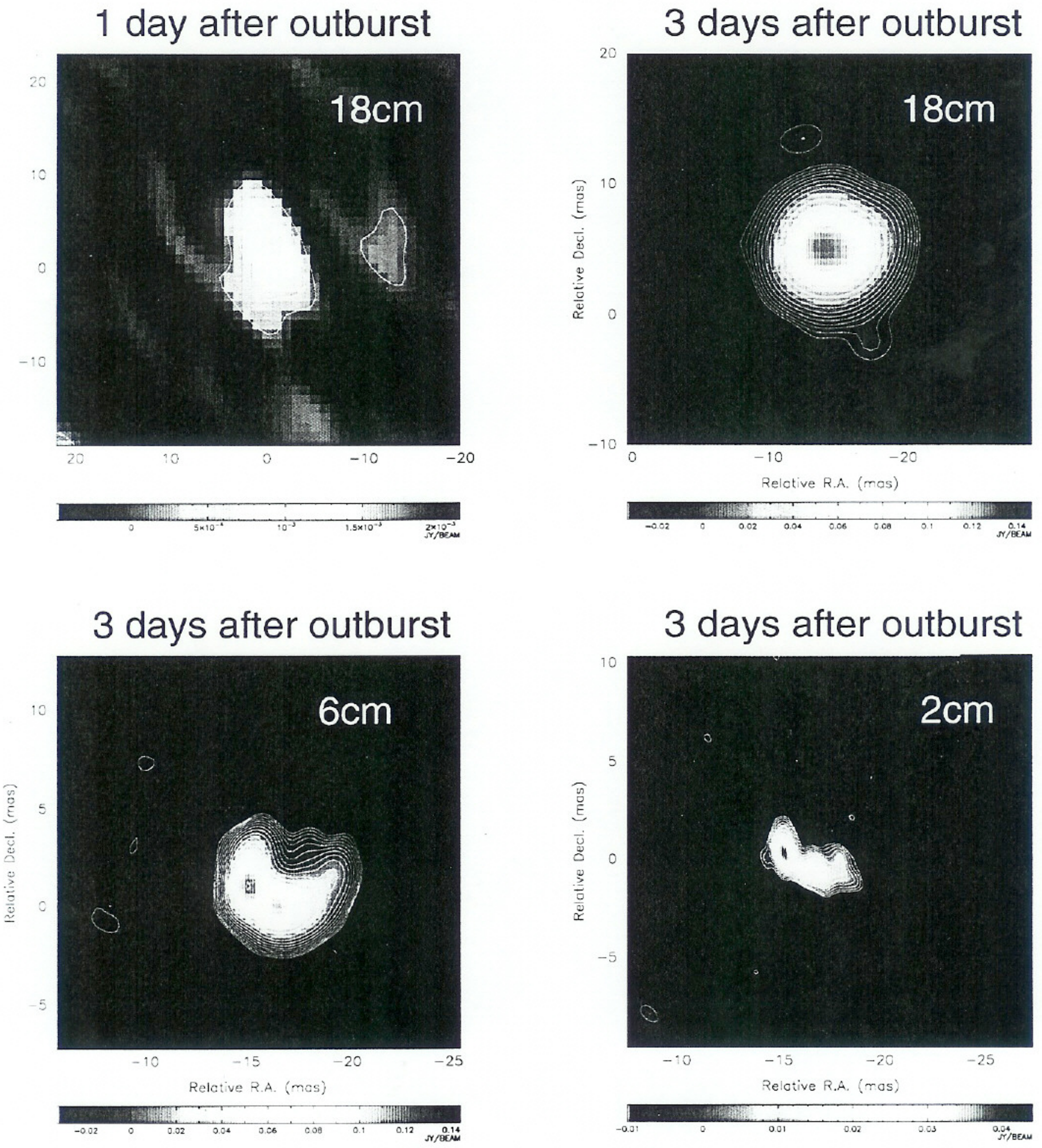
CI Cam (=XTE J0421+560)

Hjellming 1998



VLBA Obs.

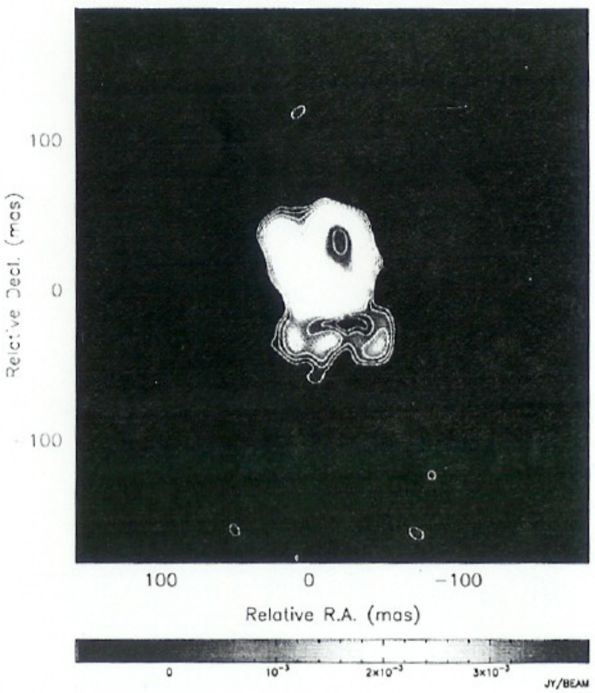
VLBA Images of CI Cam soon after X–ray/radio/optical flare



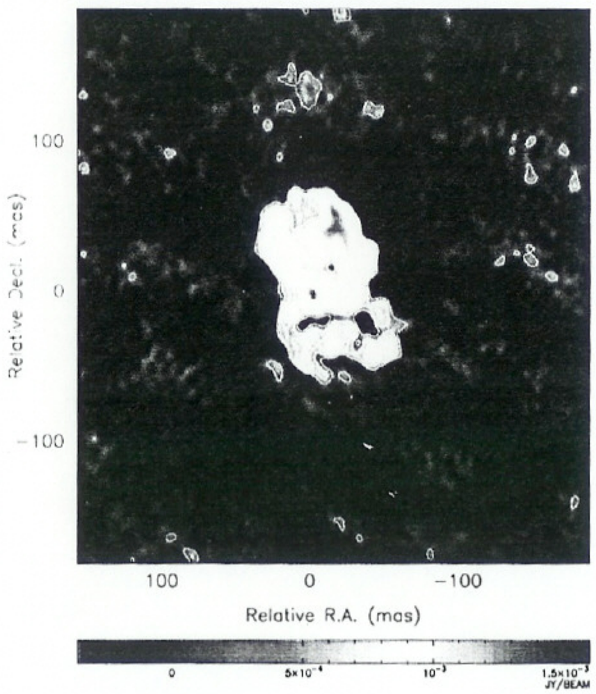
but no jet!

VLBA Images of Remnant in CI Cam Months after X–ray/radio/optical flare

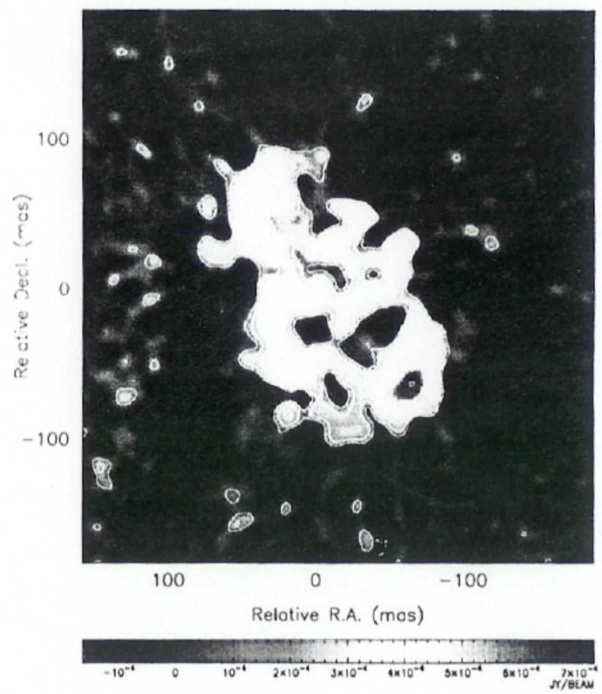
75 days after outburst



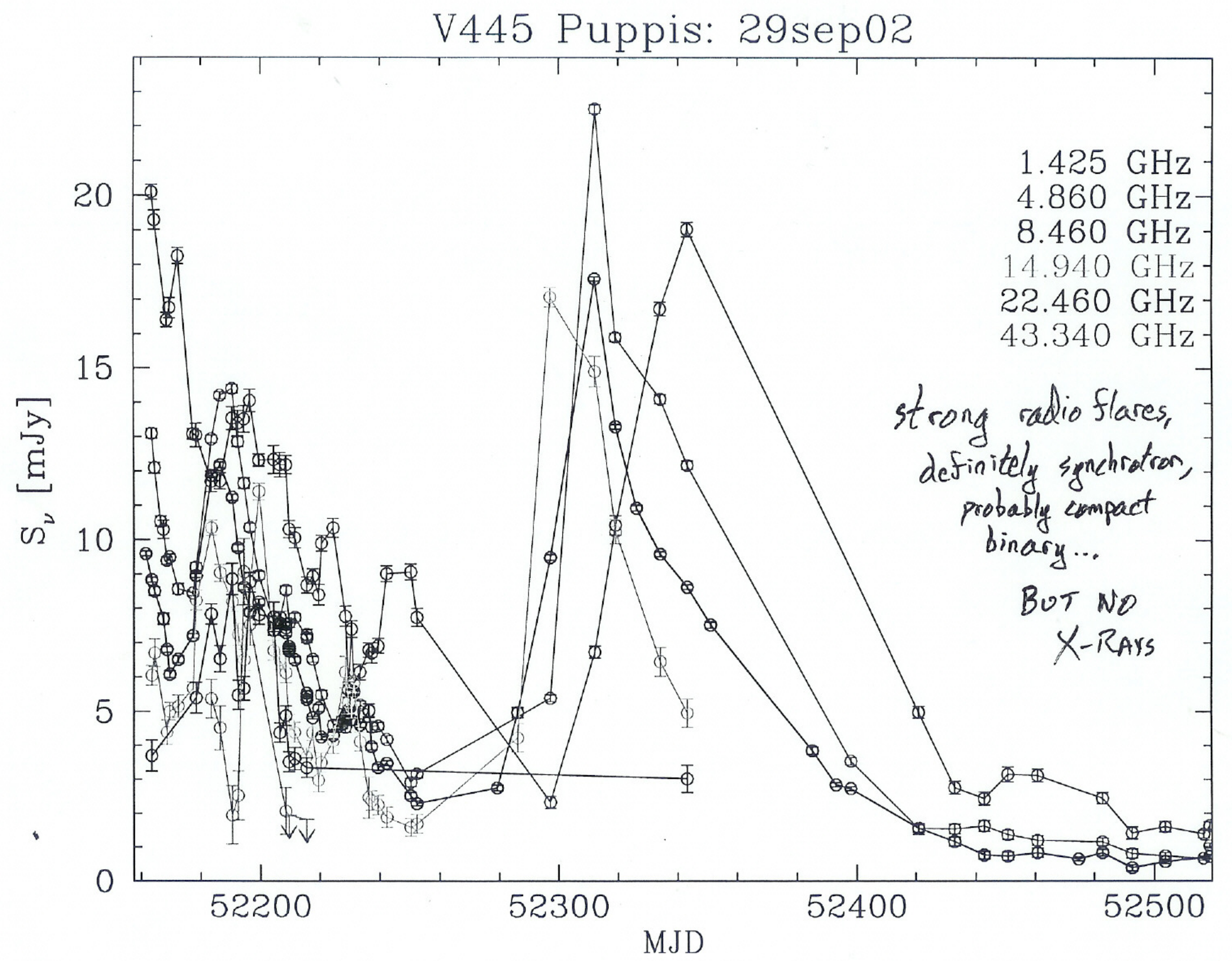
93 days after outburst



163 days after outburst



Mioduszewski, Hjellming & Rupen


V445 Puppis: 29sep02
1.425 GHz
4.860 GHz
8.460 GHz
14.940 GHz
22.460 GHz
43.340 GHz
strong radio flares, definitely synchrotron, probably compact binary...
BUT NO X-RAYS
S_ν [mJy]
0
5
10
15
20
52200
52300
52400
52500
MJD

X-ray LINES in SS 433 JETS.

Marshall, et al. 2002, ApJ, 564, 941

0·01 AU

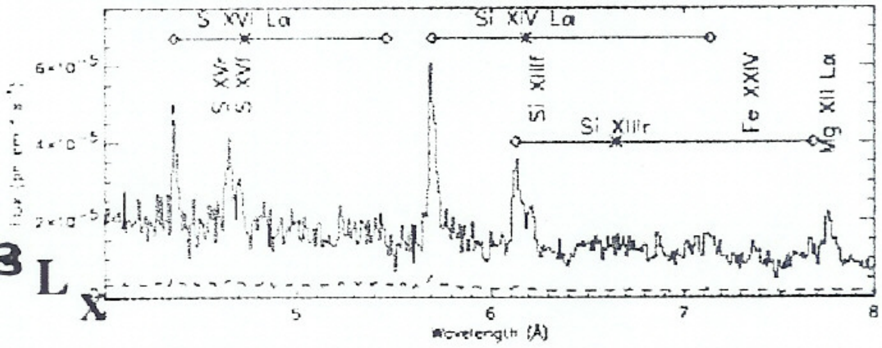
$r \sim 10^{11}$ cm

$T \sim 10^{7-8}$ K

$N_e = 10^{14}$/cc

$L_{jet} \sim 3.10^{38}$ erg/s $= 10^3\ L_X$

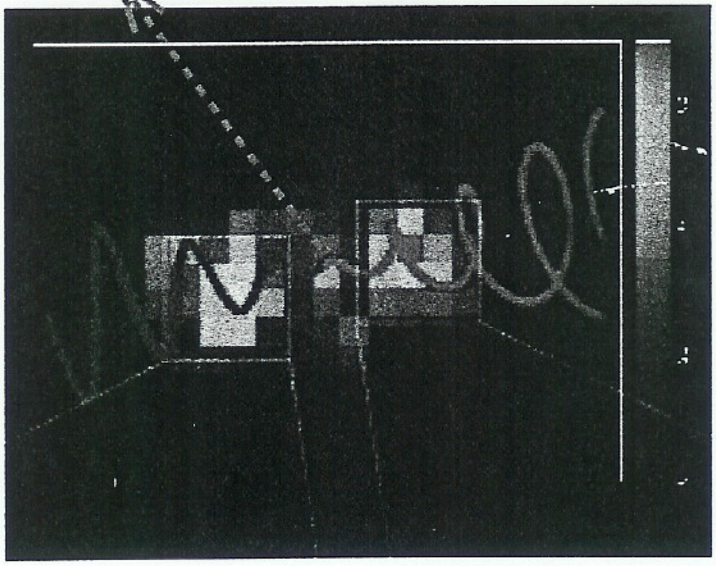
$v = +\_\ 0.26$ c



100 AU
OPTICAL LINES:

$r \sim 10^{15}$ cm

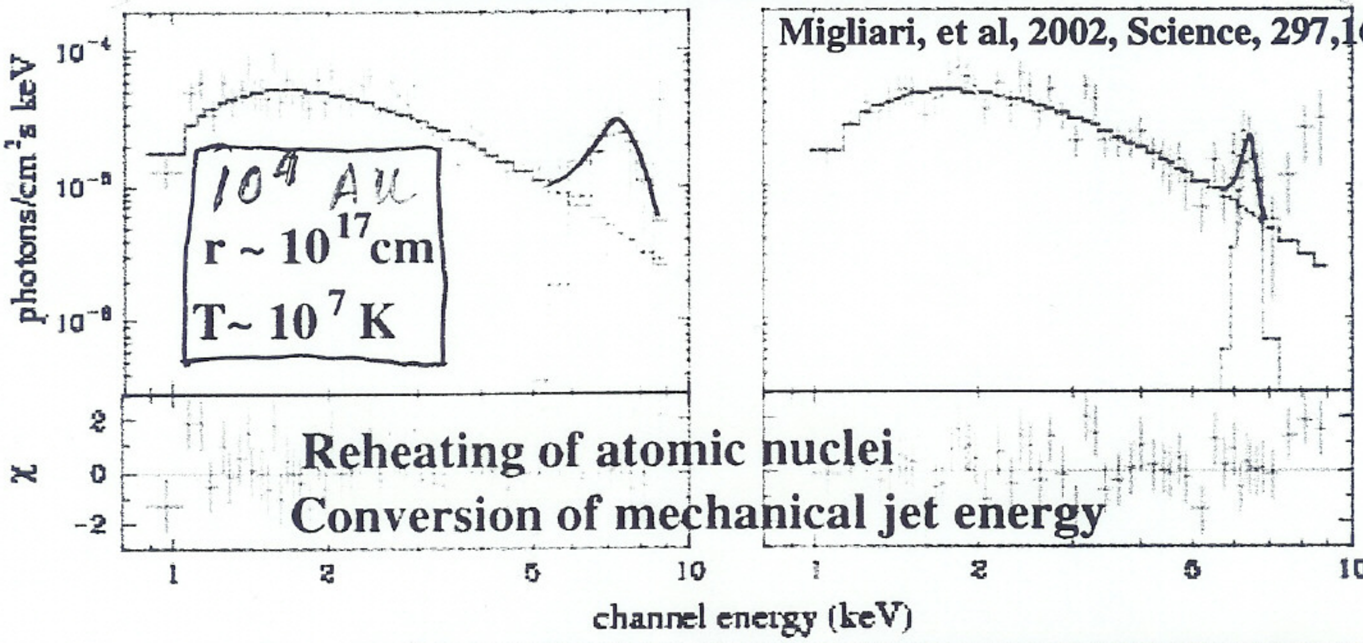
$T \sim 10^4$ K



X-ray and radio may see the same thing!

cf. 1E1740 etc.

Migliari, et al, 2002, Science, 297, 1674



10^4 AU

$r \sim 10^{17}$ cm

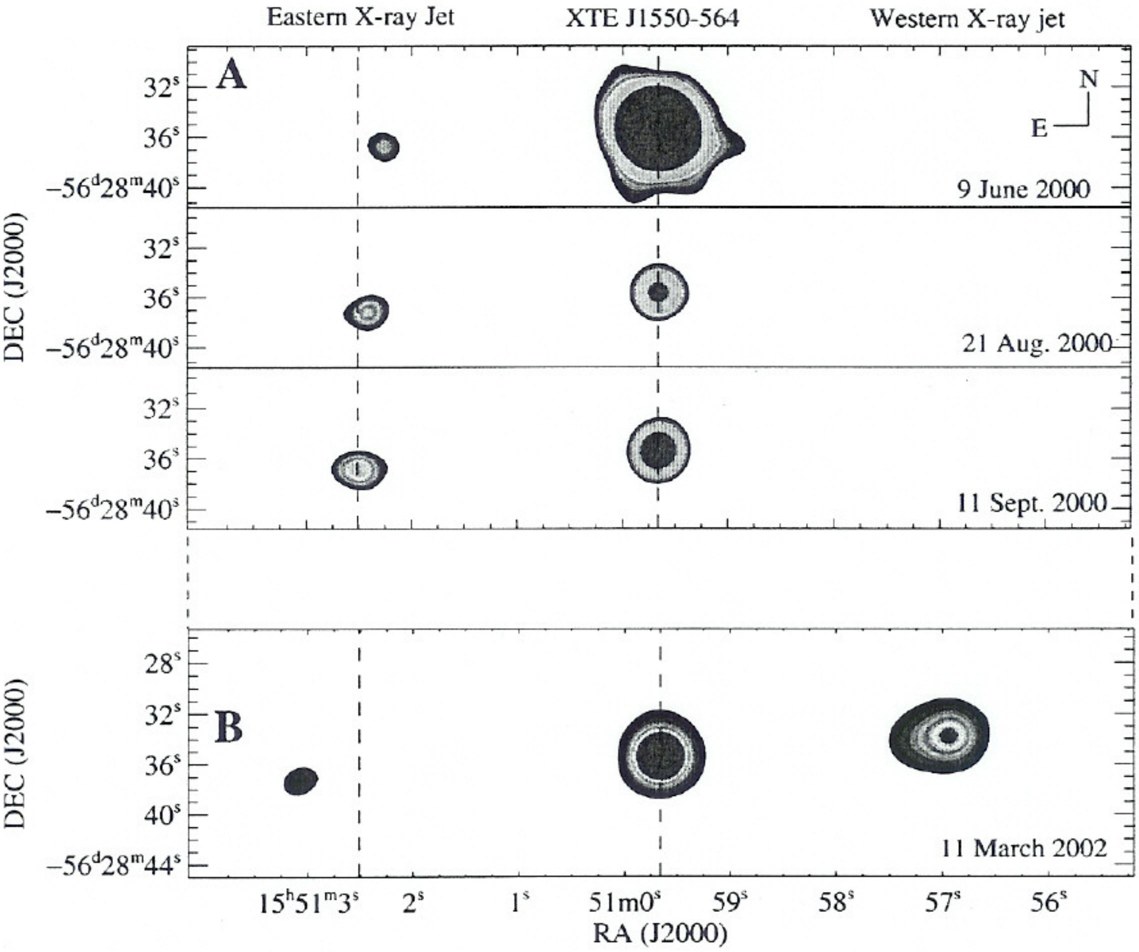
$T \sim 10^7$ K

Reheating of atomic nuclei

Conversion of mechanical jet energy

HAS CIRCULAR POL.: Fender, et al. 2000, ApJ, 530, L29

Figure 2: (Top) Raw (i.e.. not regridded) Chandra ACIS-S image of SS 433 with the



Corbel et al. '02

Summary

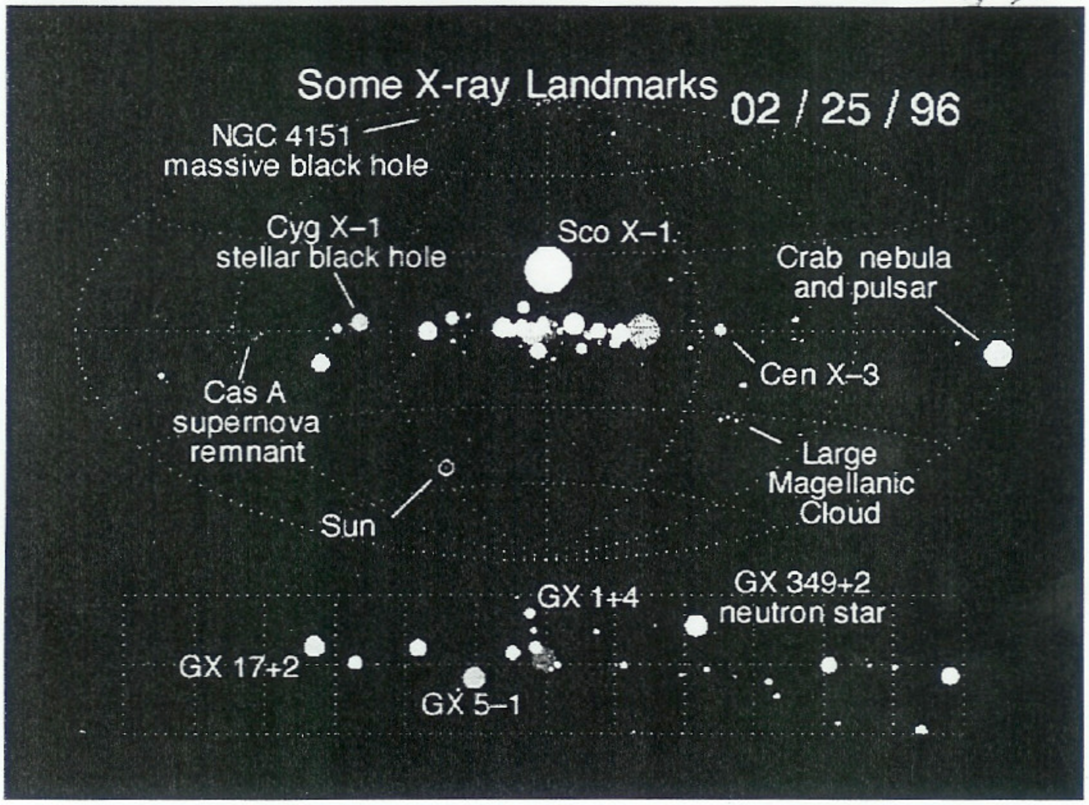
- radio emission most closely connected with changes in hard X-rays, either quenching or appearing, in X-ray transients) (note also low/hard state and radio in XRBs)
- there are many examples of strong, hard X-ray flares without radio emission, and a few cases of the reverse (radio w/o X-rays)
- many soft X-ray events give no detectable radio emission

- most (not all) radio sources are fast jets (note lingering remnants too)

  ... which are now (sometimes) being seen directly in X-rays

Why is there no radio ASM?

(yet)



$\Theta \sim \frac{\lambda}{D}$ $\Rightarrow$ large ~~small~~ telescopes with small FoV (VLA: 30' @ 20cm) ~~[illegible]~~

or ~~[illegible]~~

long wavelengths with lots of confusion & absorption & relatively low sensitivity

There have been a few attempts at finding radio transients:

single dish (NRAO 140ft) e.g. Gregory & Taylor, 32 variables, incl.

Cas γ-1

4U 2316+61

interferometric just starting: Hyman et al. 2000

2°.5 on Gal Ctr @ 90cm

$\Rightarrow$ XTE J1748-288

GCRT 1746-2757 (no X-rays!)

globular clusters?

Still mostly serendipitous: e.g. Gal Ctr. transient Zhao et al. 92 no X-rays!

⇒ most radio work requires rough positions

Radio follow-up of other λ has been most productive

① Direct triggering by X-ray transient or flares

e.g. VLA:

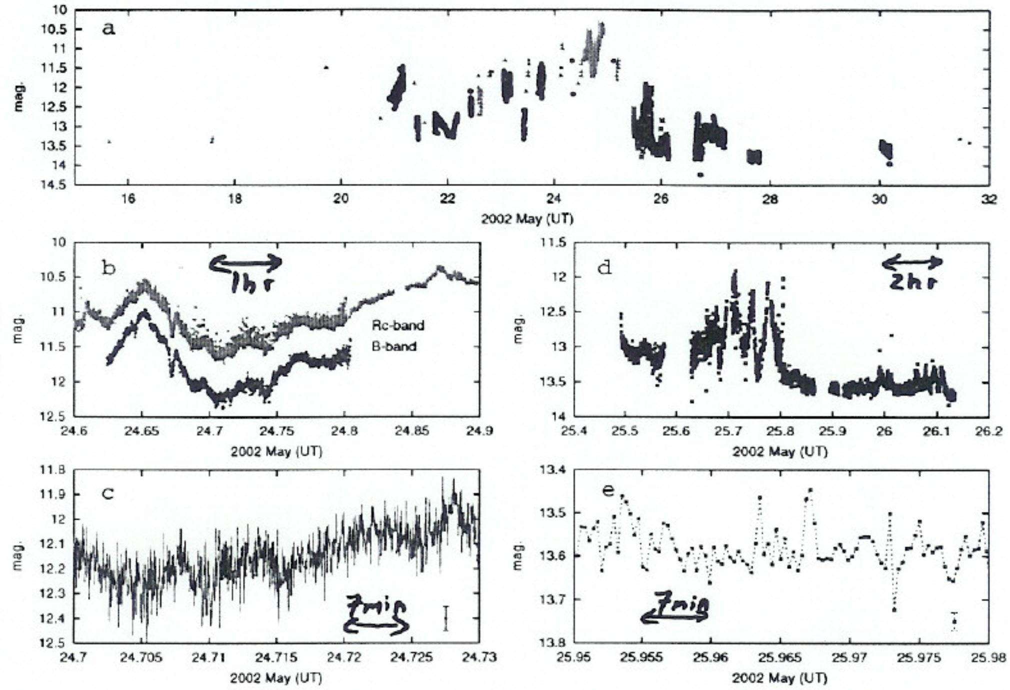
- flare is announced (e-mail, ATEL, IAUC)
  ... occasionally much delayed, esp. in known sources
- request to TAC: may we look?

→ permission to observe (monitoring program, each 7-14 days)
& to beg (NO BUMPING, esp. of non-NRAO)

⇒ response time < 1 day to a week

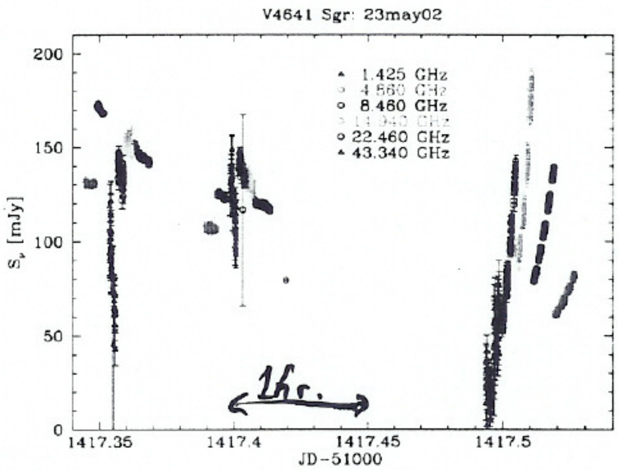
⇒ requires energy & persistence (& luck ☺)

n.b. no automated data reduction or scheduling



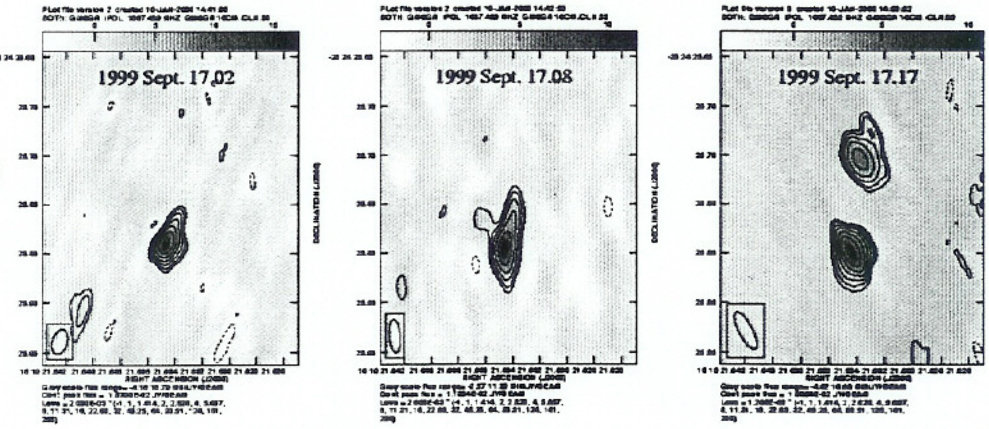
1^{M}

VSNet May02



VLA 23may02

0".1 (700 au)



VLBA Sep99

1.4 hrs

3.6 hrs

~0".4/day →

$\boxed{\gtrsim 17c \text{ @ } 7\text{kpc}}$

V4641 Sgr

3) Radio follow-up & monitoring of known X-ray sources selected by...

ⓐ previous transients: radio events NOT triggered by X-rays

- 1118+480 (#2)
- V4641 Sgr 2002 ← Chandra ToO
- GRS 1758-258 recently

ⓑ Check sources chosen by X-ray "colors"

Mirabel et al., e.g. GRS 1915+105

Tsarevsky et al., e.g. J1628-41

ⓒ General location

Hyman, Lazio et al.: Gal. Ctr.

Nearby galaxies for IXOs (e.g. Sjouwerman M31)

These can lead to X-ray triggers, based either on radio flares or on resolved images

We are not yet aggressive enough

n. b. Trushkin: daily snapshots of Cyg X-3 RATAN on few-10 mJy

Pooley: detailed 15GHz lightcurves of bright-ish N sources Ryle

Cyg X-1 Cyg X-3 GRS 1915+105

3) Multiλ Campaigns on known, persistent sources

- scheduled in advance $\Rightarrow$ easier for operations
- LOTS of effort
- generally random states $\Rightarrow$ LUCK OF THE DRAW

e.g. GX17+1, GX13+2, etc.

- if dull, UNPUBLISHED ☹

Some sources allow PREDICTIONS...

example: Cyg X-3 quenches before big flares

"before" $\Rightarrow$ weeks, months... and then it's

very fast

The Next Steps

Chandra/XMM Opportunities

- sensitivity
- imaging
- spectroscopy

- check X-ray vs. radio positions, confirm counterparts
  - occasionally useful: X1908+094
  - response time req'd ~ τ_{source}, hours → months

- imaging X-ray jets (1550-564) *
  - few extended enough
  - some too obscured (1748-288)
  - some seldom big enough (Cyg X-3)
  - ~~some~~ few are VERY fast (V4641 Sgr)

$0.''5$ @ 10 kpc = $30/\beta_{app}$ days response time

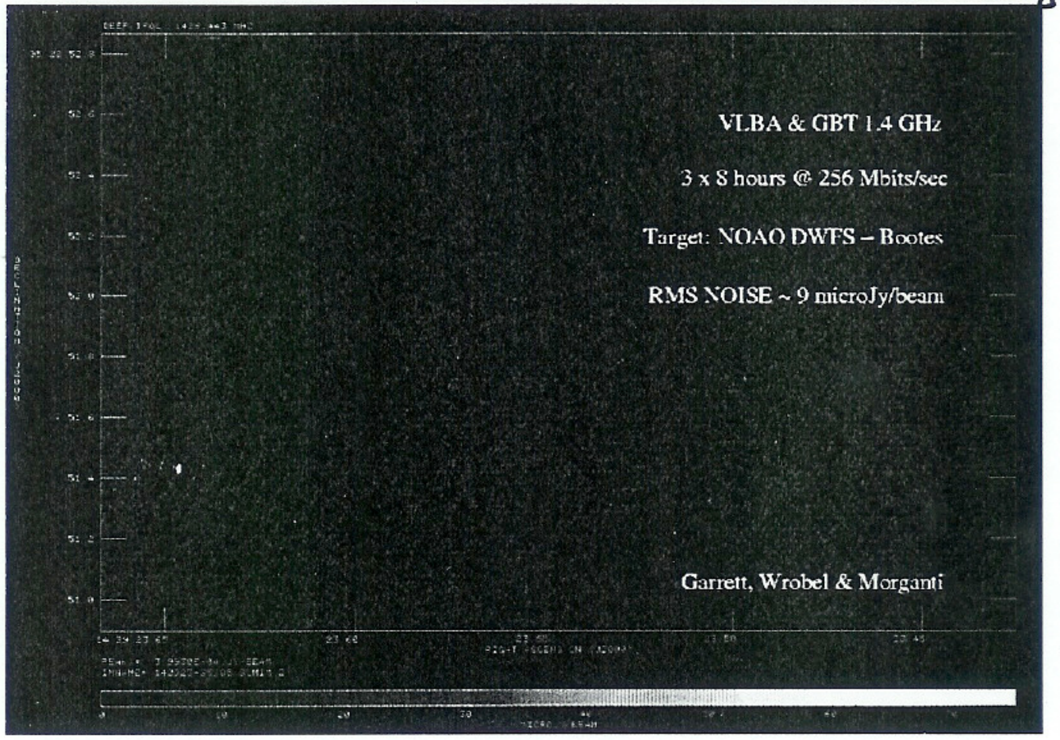
→ DAYS	V4641 Sgr
weeks to months	Cyg X-3 ** (also 1655-40, 1915+105)
years	1550

- SPECTROSCOPY during jet ejections
  - tie inner orbit (Fe lines) to ejection events
  - look for Doppler shifts: BARYONS! SS433, N Mus (?), etc.

  requires RAPID RESPONSE (by both instruments): days, usually

Radio Observations

- in principle: can image sub-mJy sources
  - quiescence
  - faint transients
  - follow longer



- ASTROMETRY should become routine
  GRS 1915+105 XTE J1118+480

- Simultaneous radio/X-ray of persistent sources & more regular imaging!!

- More rapid reduction & dissemination

- Pol'n anomalous emission persistent remnants
  precession jet inclinations

⇒ Manpower limited!
There are NO students/postdocs!!

The Future

Short-term: Gal Ctr monitoring (see also LOFAR!)
GMRT
X-ray transient surveys at KNOWN PLACES & TIMES
(HETE-II; INTEGRAL)
working on ~~automated~~ faster radio response
- dynamic scheduling
- unified transients
- automated reduction

more aggressive radio work & triggers
(starting to think about Chandra/XMM ...)
need rapid response on both ends

What's needed:
continuous monitoring of ALL X-ray sources (>500!)
in radio & X-ray
→ trigger go both ways → also needs good sensitivity
→ GBI++

good, easy imaging of ALL sources
- sensitivity
- not just one VLA configuration

Funnily enough, we're working on it...

The VLA Expansion Project

EVLA - Phase I

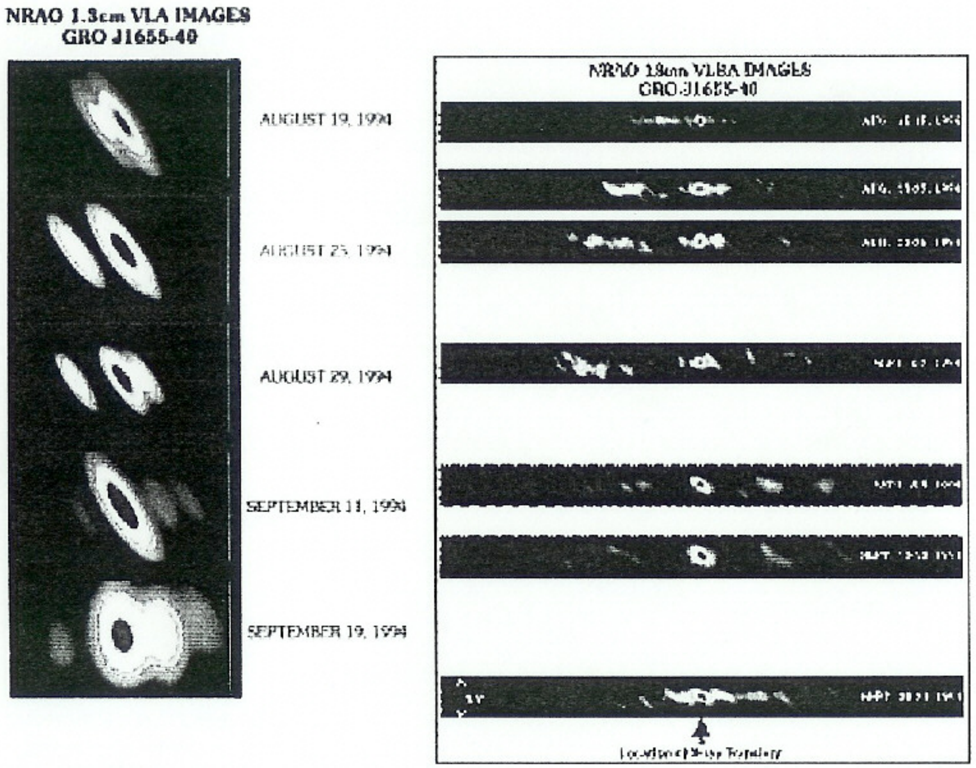
- continuous frequency coverage 1 - 50 GHz
- 16 GHz (vs. 200 MHz) BW

  > 10x sensitivity!
- transients are a MAJOR part of the science case
  - dynamic scheduling
  - automate processing
  - → many more sources   IXOs?   SS433 in nearby gals.
  - → ridiculous light curves (w/ mult. ν)
  - → instantaneous sp. indices (SED)
  - → higher ν ⇒ higher res'n: 50mas @ 50GHz

- FUNDED AND UNDER CONSTRUCTION
  - shared-risk science 2007
  - finished 2012

    sooner & cheaper with faster $

The Next Generation



- Limited freq/time coverage
- Missing spatial scales
- Rely on external triggers
- Poor sensitivity

➔ ***This is only the tip of the iceberg!***

Hjellming & Rupen 1995

EVLA - Phase II: The New Mexico Array

8 new antennas over ~350 km → 10x res'n: $\boxed{4\text{ mas @ 45 GHz}}$

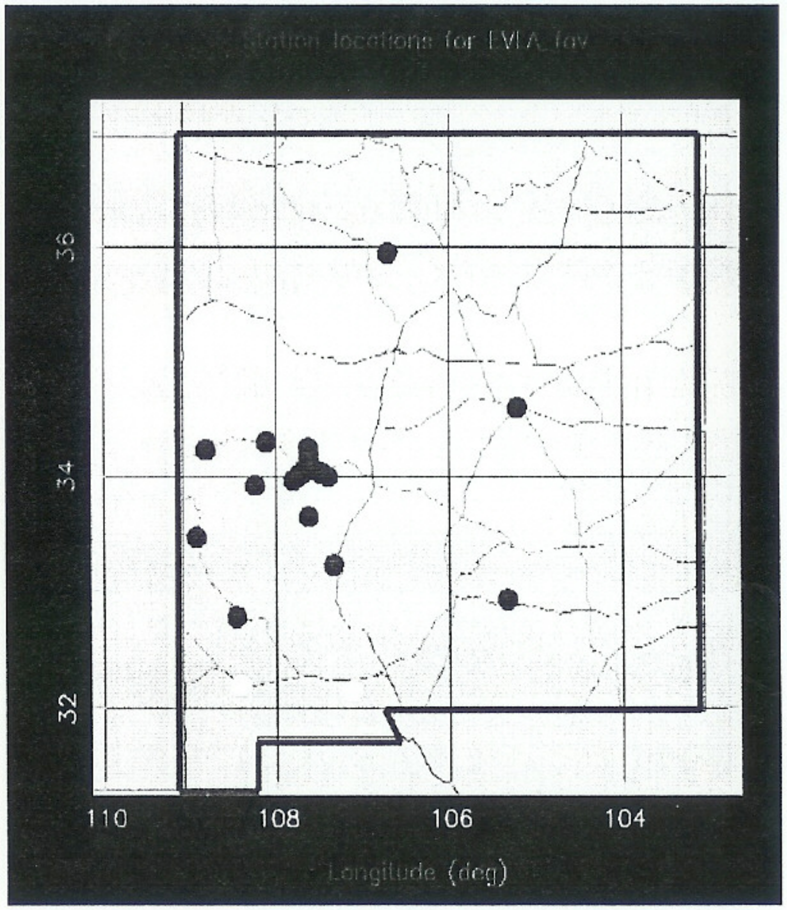
NMA alone: PERFECT MONITORING ARRAY
- 5-50 mas ν - 100% of the time
- $\sigma \sim$ current VLA
- very good imaging

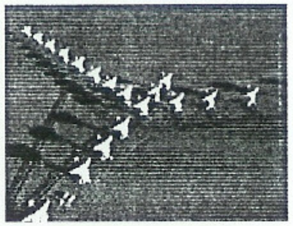
NMA+VLA-I: mas imaging of thermal sources
($\sigma \sim 30$ K @ 4 mas)

Proposal goes in early next year ($90M)
approved & highly ranked by decadal review
could use some NASA help!

The NM Array
An Example

- Red lines: State boundaries
- Orange lines: US Highways
- White lines: State and Country roads
- Blue dots: NM Array stations.
- We are confident that we can acquire good sites.



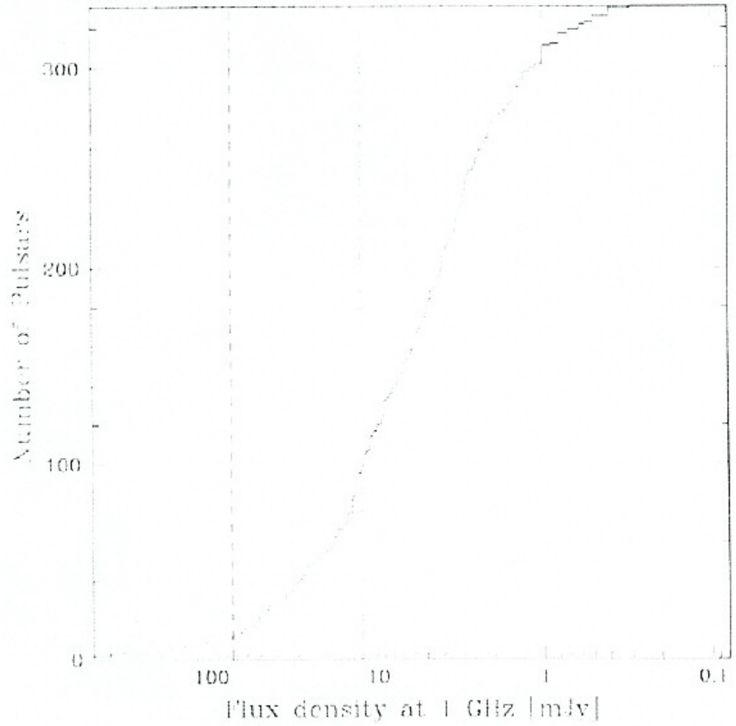


EVLA Project Goals

Expanded
Very Large Array

Parameter	**VLA**	**EVLA Phase I**	**EVLA Phase II**
Point Source Sensitivity [1-σ, 12 hours]	10 μJy	**0.8 μJy**	0.6 μJy
Maximum Bandwidth per Polarization	0.1 GHz	8 GHz	8 GHz
Number of Channels at Max. Bandwidth	16	**16384**	16384
Maximum Number of Channels	512	**262144**	262144
Best Frequency Resolution (Hz)	381 Hz	**~ 1 Hz**	~ 1 Hz
(Log) Freq. Coverage [0.3 – 50 GHz]	25%	**75%**	100%
Number of Baselines	351	351	666
Spatial Resolution: 5 GHz 45 GHz	400 mas 40 mas	400 mas 40 mas	40 mas 4 mas

Phase II: Astrometry



Pulsars with distances measurable to 3 kpc and 8 kpc

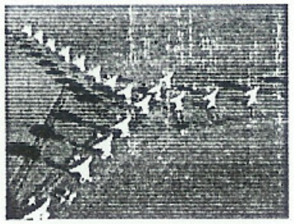
- 10-100 μarcsec positions for 1 mJy sources (in 2 hours, from 2 to 50 GHz)

⇒ parallaxes of active stars to several kpc

⇒ angular expansion rates (10s of km/s) of planetary nebulae & stellar winds

⇒ pulsar parallaxes: 150 out to 3 kpc, 50 out to 8 kpc

⇒ accelerations of ionized gas & masers near the Galactic center



A New Era for Radio Astronomy

Expanded Very Large Array

After a long dry spell, telescopes galore:

- Already constructed: GMRT
- Funded & under way: EVLA, ALMA, ATA, eMERLIN
- Actively moving forward: LOFAR (x2?), DSN-A
- Looming on the horizon: the Square Kilometer Array

A great time to start observing low-energy photons!!