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

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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

4U 1630-47

simultaneous X-ray/radio flare,

1998 similar - BATSE turned on at same time
Some Recent X–ray Transients


Two msec X–ray Pulsars

XTE J1908+094

Chandra TOO position
linked to hard X-rays and state changes
not all HXR flares produce (big) jets

X-ray Flux (mCrab)

Hardness

Flux Density [mJy]

radio $\leftrightarrow$ hard X-ray (beginning)
STATE TRANSITIONS in GX 339-4

X-RAY STATES

- Corbel et al. (2000)
- Fender & Knigge (2003)

Low/Hard
- RXTE ASM
- BATSE 20-100 keV
- MOST 36 cm
- ATCA 3, 6 & 20 cm

Hard X-Ray

Soft X-Ray

High/Soft

- Disk Dominates
- Corona
- INTERMEDIATE

Low/Hard
- Radio
- Transient
- Flares
- Very Low

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

Corrected for $N_H$ and scaled to a distance of 1 kpc

- GRS 1758–258 (8.5 kpc)
- V404 Cyg (3.5 kpc)
- Cygnus X–1 (2.5 kpc)
- XTE J1118+480 (1.8 kpc)
- GRO J0422+32 (2.4 kpc)
- transients
- GX 339–4 (4 kpc)
- XTE J1550–564 (2.5 kpc)

low/hard state BHs

~0.05 Eddington

15 GHz flux (mJy)

Soft (<12 keV) X-ray flux (Crab)

Gallo et al. (2002) and Corbel et al. (2002)
Microquasar GRS 1915+105: VLBA Images of the AU-Scale Jet.

A: Radio/X-ray Flares
1997 Oct 24 – Nov 08

VLBA observation
- GBI, 13cm
- GBI, 3.6cm

XTE ASM counts
0
100
200
300
400
500
600
700
745 750 755 760 (MJD-50000) days

D: Disk & Jet co-evolution
1997 Sept 05
RXTE 2-12 keV X-ray

VLA 2.8 cm radio

B: Superluminal ejecta.
VLBA, 2cm
1998 May 02

Core
Ejecta move by 690 AU in 67 hrs
10 AU/hr = 1.4c
4.2 mas in 4.5 hrs

C: AU-sized nuclear jet
VLBA, 2cm
VLBA, 7mm
15 AU
5 AU

Tight x-ray <=> radio connection
(CFs. QPOs too)
XTE J1748-288 VLA Radio & X-ray Light Curves

20 mas/day
[>= 0.93c]
Jet
Ejection
Begins

33 mas/day
[>= 1.5c]
Jet
Ejection
Begins

- 1.49 GHz - VLA
- 4.9 GHz - VLA
- 8.4 GHz - VLA
- 14.9 GHz - VLA
- 22.5 GHz - VLA
- 1st Jet Ejection
- 2nd Jet Ejection
- 2.25 GHz - GBI

Flux Density [mJy]

50960 50980 51000 51020 51040 51060 51080 51100 51120 51140 51160

X-ray Flux [counts/sec]

50960 50980 51000 51020 51040 51060 51080 51100 51120 51140 51160

Flux [photons cm^-2 sec^-1]

50960 50980 51000 51020 51040 51060 51080 51100 51120 51140 51160

"radio/XRB dead..." JD - 2400000.5

but radio story is more complicated..."
XTE J1748-288
July 17 - Aug. 19, 1998

MJD 51011

291 mas/day = 1.3 c ($\frac{c}{8}$)

MJD 51017

MJD 51025

MJD 51029

MJD 51034

MJD 51039

DECELERATION AND BRIGHTENING
radio flares may or may not produce jets.
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

X-ray Flux [counts/sec]

- ○ 2-12 keV - RXTE ASM
- --- Zero Line

X-ray Flux [photons/cm²/second] X-Ray Flux [counts/sec]

- ○ 20-100 keV - CGRO BATSE
- --- Zero Line

all the usual correlations...

Flux Density [mJy]

- ■ 1.49 GHz - VLA
- + 2.25 GHz - GBI
- ◇ 4.9 GHz - VLA
- ● 8.3 GHz - GBI
- ▲ 14.9 GHz - VLA
- ○ 15 GHz - Ryle Tel.
- ● 99 GHz - OVRO mm Array
- ■ 1.49 GHz Jet Model
- + 2.25 GHz Jet Model
- ◇ 4.9 GHz Jet Model
- ● 8.3 GHz Jet Model
- ▲ 14.9 GHz Jet Model
- ○ 99 GHz Jet Model

JD - 2400000.5
VLBA Images of CI Cam soon after X-ray/radio/optical flare

1 day after outburst

3 days after outburst

3 days after outburst

3 days after outburst

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
X-ray LINES in SS 433 JETS.

$0.01 \text{ AU}$

$r \sim 10^{11} \text{ cm}$

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

$N_e = 10^{14} / \text{cc}$

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

$v = +_- 0.26 c$

---

100 AU

OPTICAL LINES:

$r \sim 10^{15} \text{ cm}$

$T \sim 10^4 \text{ K}$

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

Some X-ray Landmarks

NGC 4151
massive black hole

Cyg X-1
stellar black hole

Sco X-1

Crab nebula
and pulsar

Cen X-3

Large Magellanic Cloud

GX 17+2

GX 1+4

GX 5-1

GX 349+2
neutron star

02/25/96

\[ \theta \sim \frac{\lambda}{D} \Rightarrow \text{large telescopes with small FoV, CV49=30\% at 20\alpha} \]

or

long wavelengths with lots of confusion absorption and 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 A-1
  - 4U 2316+61

- interferometric just starting: Homan et al. 2000
  - 2.5 on Gal Ctr @ 90cm
  - \( \Rightarrow \) XTE J1748-288
  - GCRT 1746-2757 (no X-rays)

Still mostly serendipitous: e.g. Gal Ctr. transient Zhao et al. 92 no X-rays!
\[ \Rightarrow \text{most radio work requires rough positions} \]

Radio follow-up of other X has been most productive

0 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?

\[ \Rightarrow \text{permission to observe (monitoring program, each 7-14 days)} \]
\[ \Rightarrow \text{to beg (NO BUMPING, esp. of non-NRAO)} \]

\[ \Rightarrow \text{response time < 1 day to a week} \]

\[ \Rightarrow \text{requires energy & persistence (\$\$ luck \$)} \]

n.b. no automated data reduction or scheduling
Radio follow-up monitoring of known X-ray sources selected by...

- previous transients: radio events NOT triggered by X-rays
  - 1118+480 (Z2)
  - 1464+585 2002 ← Chandra Too
  - GRS 1758-258 recently

b) Check sources chosen by X-ray "colors"
   Mirabel et al., e.g. GRS 1915+105
   Trasovsky et al., e.g. 51628-41

c) General location
   Nearby galaxies for IXOs (e.g. Sijouwerman, 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-10s
    Pe獭ak: detailed 15GHz lightcurves of bright B N sources Rk
    Cyg X-1 Cyg X-3 GRS 1915+105
Multij 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. \( 6 \times 17 + 1, 6 \times 13 + 2 \), etc.

if dwell, 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+044
  - response time: rega ~ 2 source, hours -> months

- imaging X-ray jets (1550-564) &
  - few extended enough
  - some too obscured (1748-288)
  - some seldom big enough (Cyg X-3)
  - a few are VERY fast (VY641 Sgr)

0.5 @ 10 kpc = 30/kpc days response time
  -> days VY641 Sgr
  weeks to months Cyg X-3
  (also 1655+40, 1915+208)
  years 1550

- Spectroscopy during jet ejections
  - the inner orbit is lined to ejection events
  - look for Doppler shifts: BARYO5, 55433, NMus(?), etc.
  - requires rapid response (by both instruments): days, usually
Radio Observation

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

VLBA & GBT 1.4 GHz
3 x 8 hours @ 256 Mbits/sec
Target: NOAO DWTS - Bootes
RMS NOISE ~ 9 microJy/beam

Garrett, Wrobel & Morganti

- 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/ xmmjj)
need rapid response on both ends

What's needed:
continuous monitoring of ALL X-ray sources (>5000s)
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

EVLRA - Phase I

- continuous frequency coverage 1-50 GHz > 10x sensitivity!
- 16 GHz (vs. 200 MHz) BW
- transients are a MAJOR part of the science case
  - dynamic scheduling
  - automate processing
- many more sources IXOs? 55433 in nearby gals.
- ridiculous light curves (w/ mult. v)
- instantaneous sp. indices (SED)
- higher v => 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: \[4 \text{ mas} @ 450 \text{ Hz}\]

NMA alone: PERFECT MONITORING ARRAY
- 5-50 mas @ - 100% of the time
- 0 - current VLA
- very good imaging

NMA + VLA-I: mas imaging of thermal sources
(\[0-30 \text{ mas}\])

Proposal goes in early next year (400M)
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

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

- 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

Pulsars with distances measurable to 3 kpc and 8 kpc

M.P. Rupen
SPIE 22 August 2002
A New Era for Radio Astronomy

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!!