Microquasars

Vivek Dhawan

NRAO Socorro

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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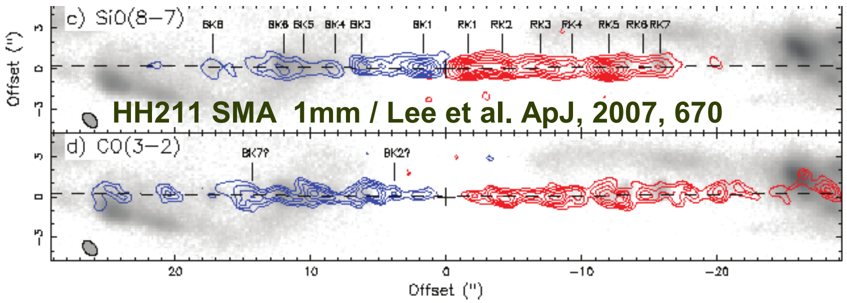
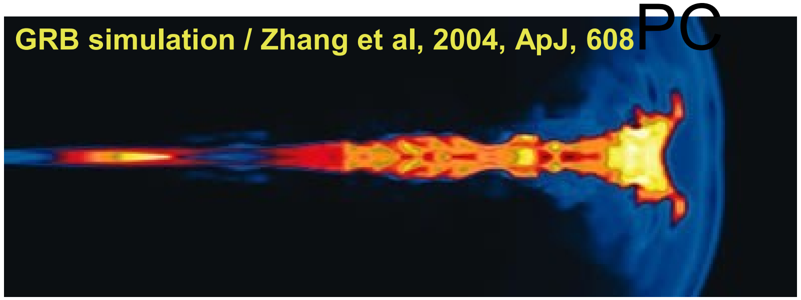
Accretion & Outflow are common.

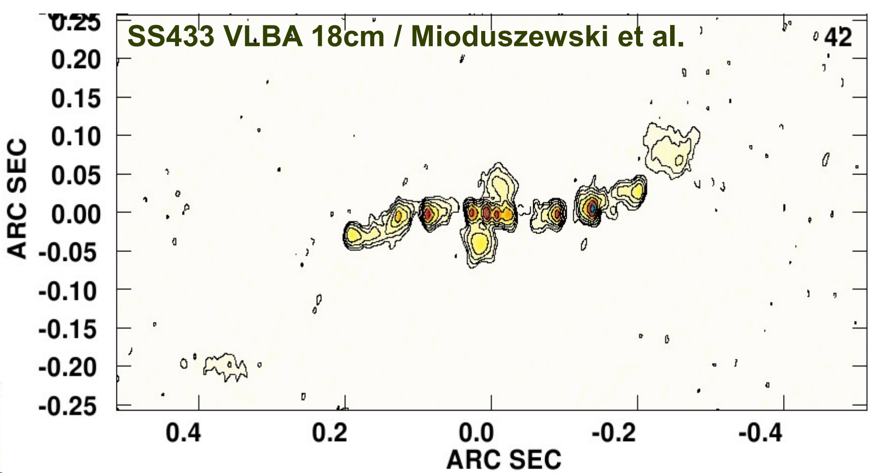


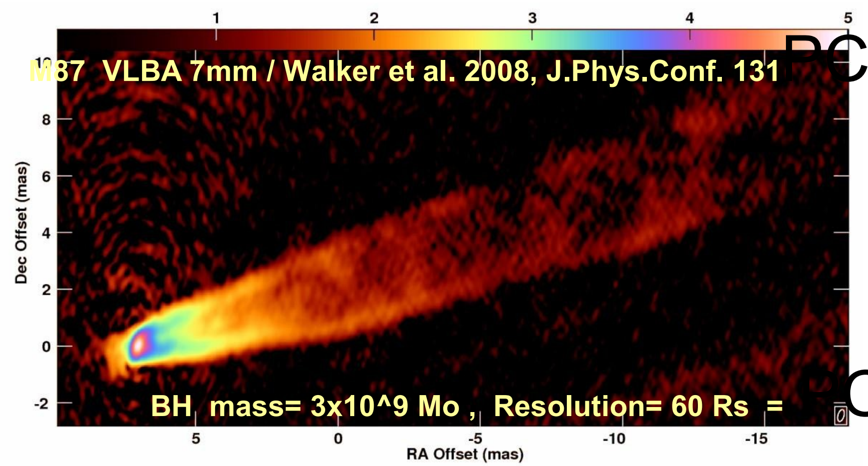


- Protostars (YSO)
- Core Collapse SN (GRB)
- Stellar corpses (XRB, CV)
- Massive BH (AGN)

...All produce jets when they taste the Elixir of Accretion.

- Microquasars: *e-coli of jet production*

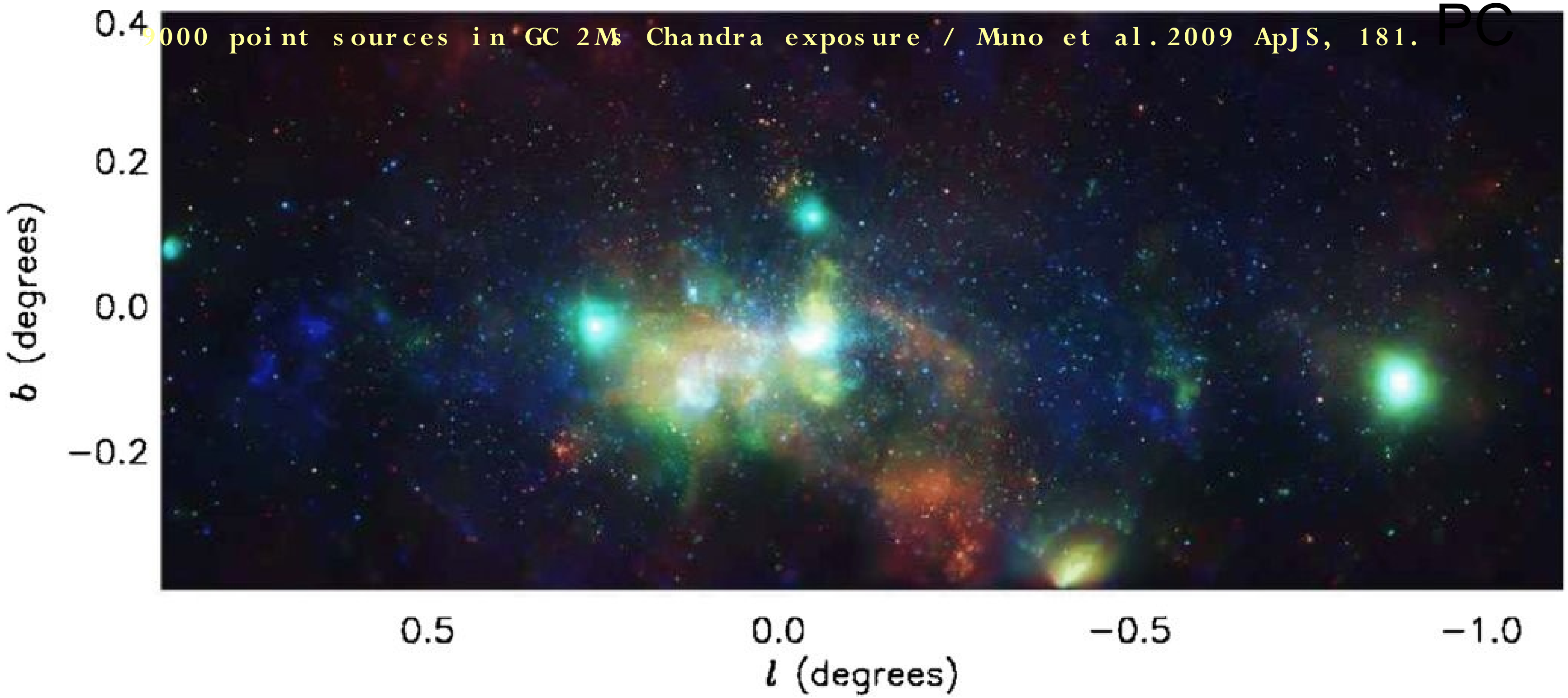




However: not all X-rays are from accretion

9000 point sources in GC 2Ms Chandra exposure / Muno et al. 2009 ApJS, 181.

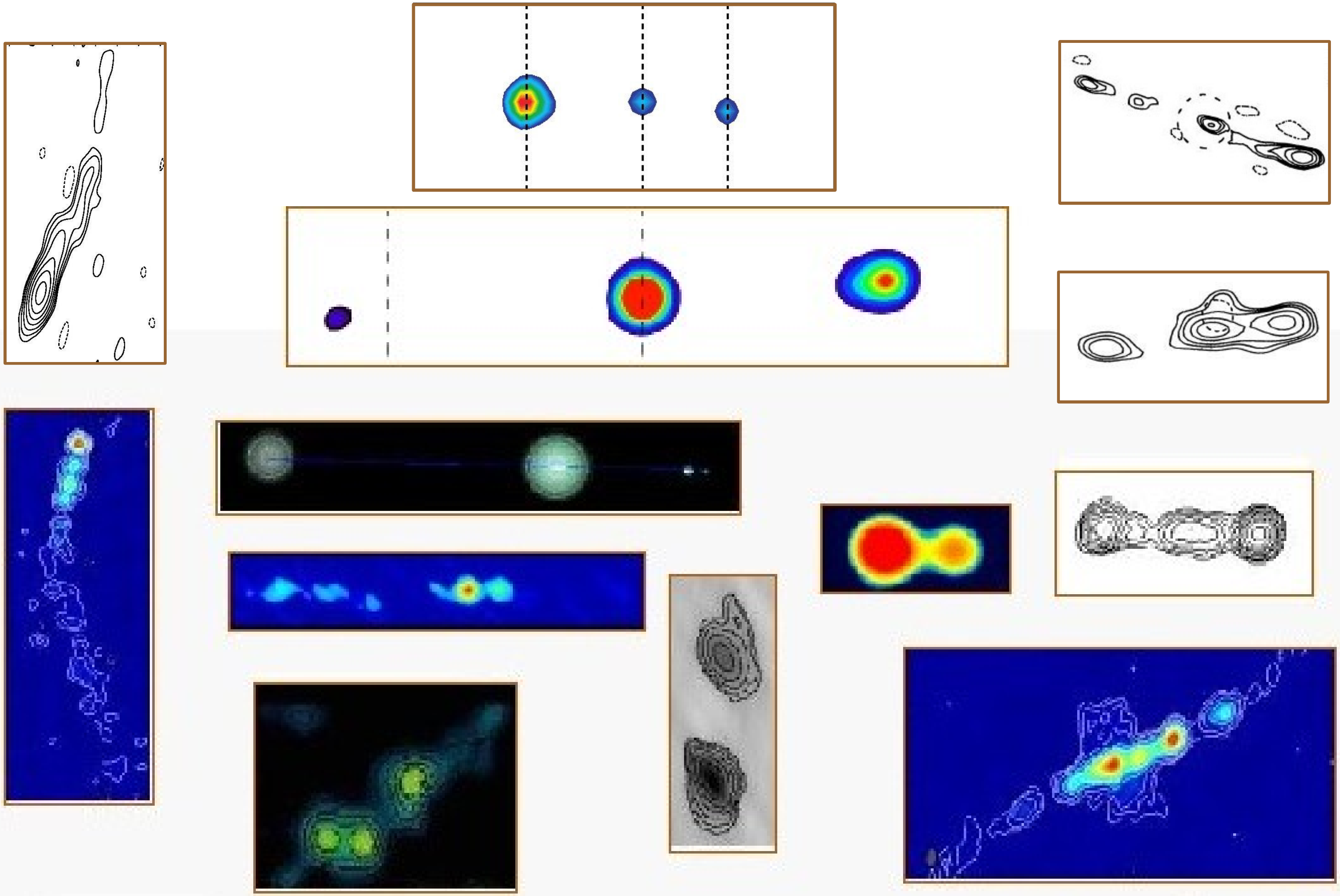
PC



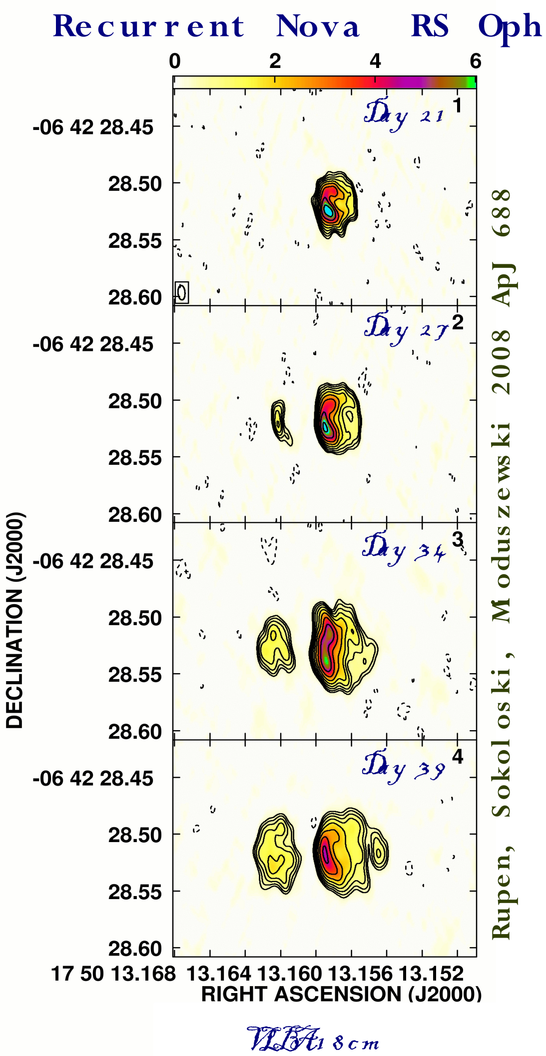
And not all radio, even high T_b, is from jets

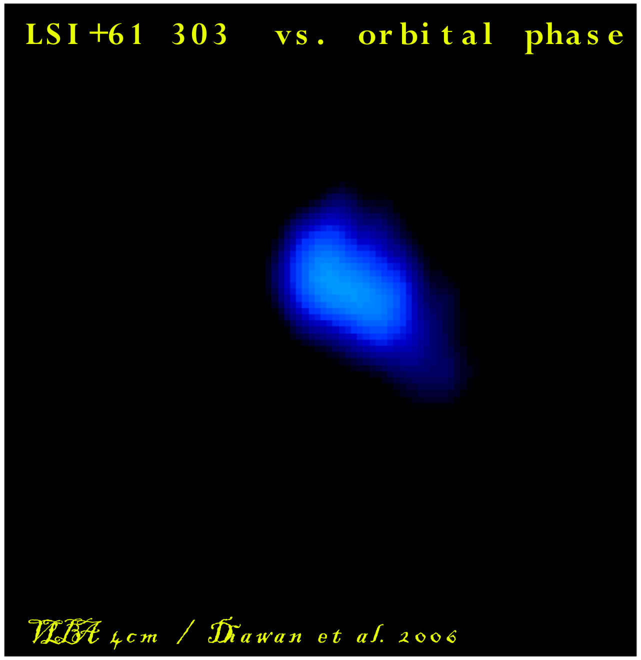
Need VLB images – see examples

Examples: bona fide microquasar jets



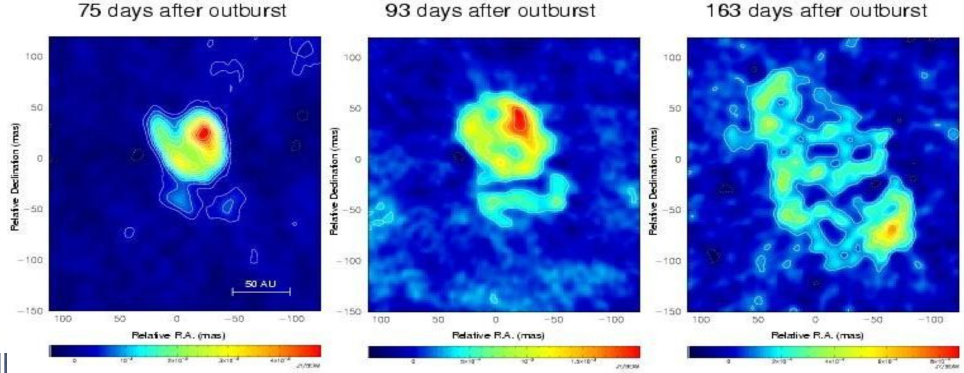
Muffled jets; non-jets (pulsar nebulae)





VLBA Images of X-ray Nova CI Cam

Mioduszewski & Rupen 2004 ApJ 615



Microquasars: X-ray binaries with jets.

- XRB = NS or BH, X-rays from hot accretion disk.
  - HMXB accretion by wind capture ~150 known.
  - LMXB accretion by Roche lobe overflow ~150.
  - 15-20% emit radio, mostly transients, not all jets.
- Bright, Fast, Close: Model systems for jet formation.
  - Prospects for controlled experiments e.g.
  - Effect of surface vs. event horizon.
  - Measure spin of compact object.
  - Matter content of jet & disk via spectroscopy.
  - B via cyclotron lines (Xray); Faraday, Zeeman (radio).
  - Resolution in units of Rs better by 10^4 on AGN
  - (Lradio/Lxray) ~ M1.4, higher by ~10^4 in AGN
- Probe ISM via large-scale interactions
- Radio: low obscuration; astrometry, PM, parallax

Liu et al 2006; 2007

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Black Hole X-ray Binaries

- ~ 20 dynamically confirmed BH systems
- ~20 candidates

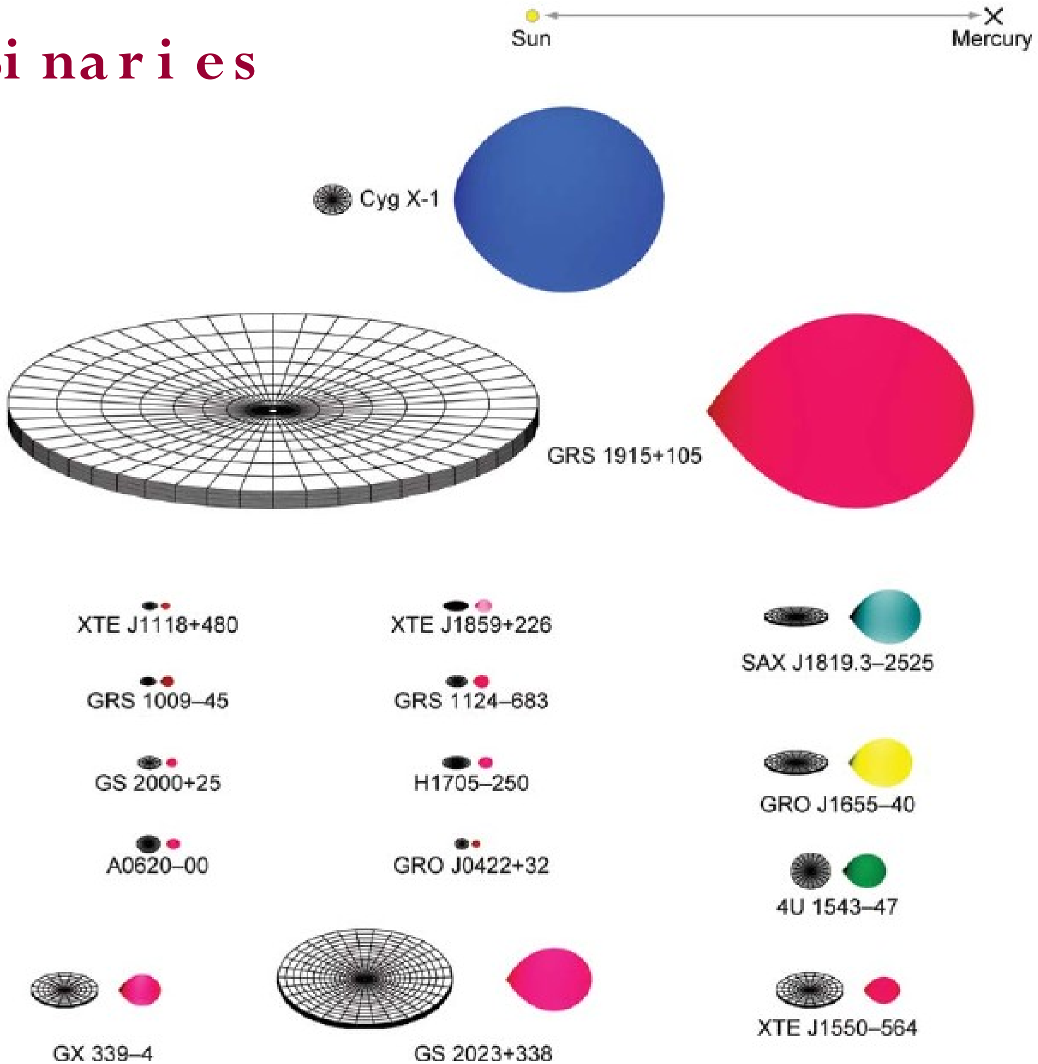

Figure 1

Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature.

J. Orosz / Remillard & McClintock, ARAA, 2006, 44

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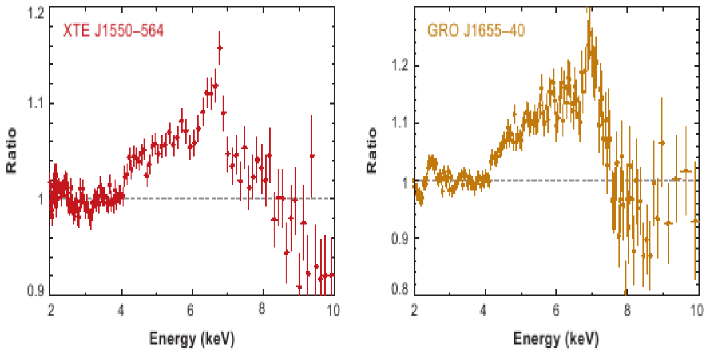
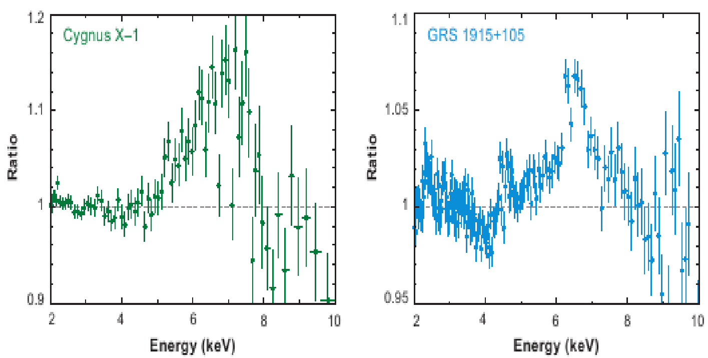
Measurement of BH spin (High spin ?= strong jet)

a) Fit X-ray continuum of inner disk (high spin --> small ISCO --> hotter continuum - see later)

b) Line profile distorted by GR effects in inner disk.

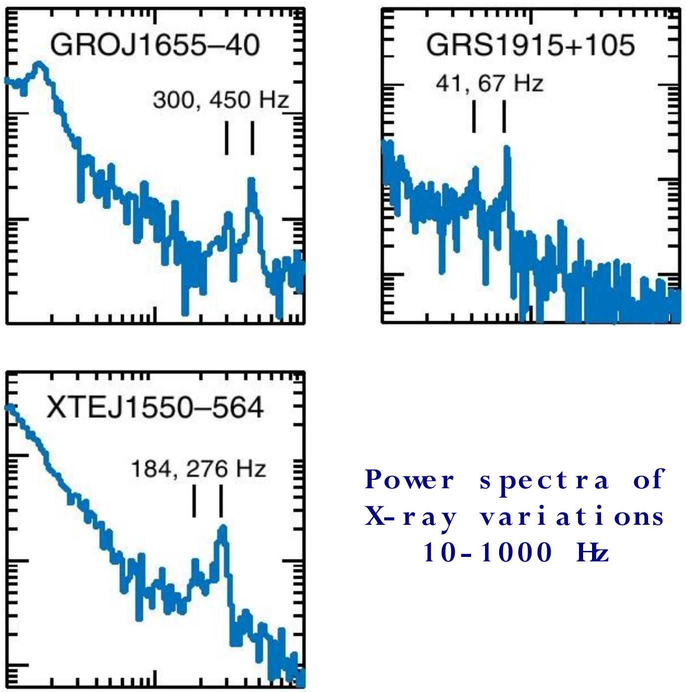


6.4 keV Fe fluorescence line



J.M. Miller, ARAA, 2007, 45

c) QPO frequencies ~100Hz, ratios of 3:2, maybe GR diagnostic (if a model is agreed upon!)



Power spectra of X-ray variations 10-1000 Hz

Remillard & McClintock, ARAA, 2006, 44

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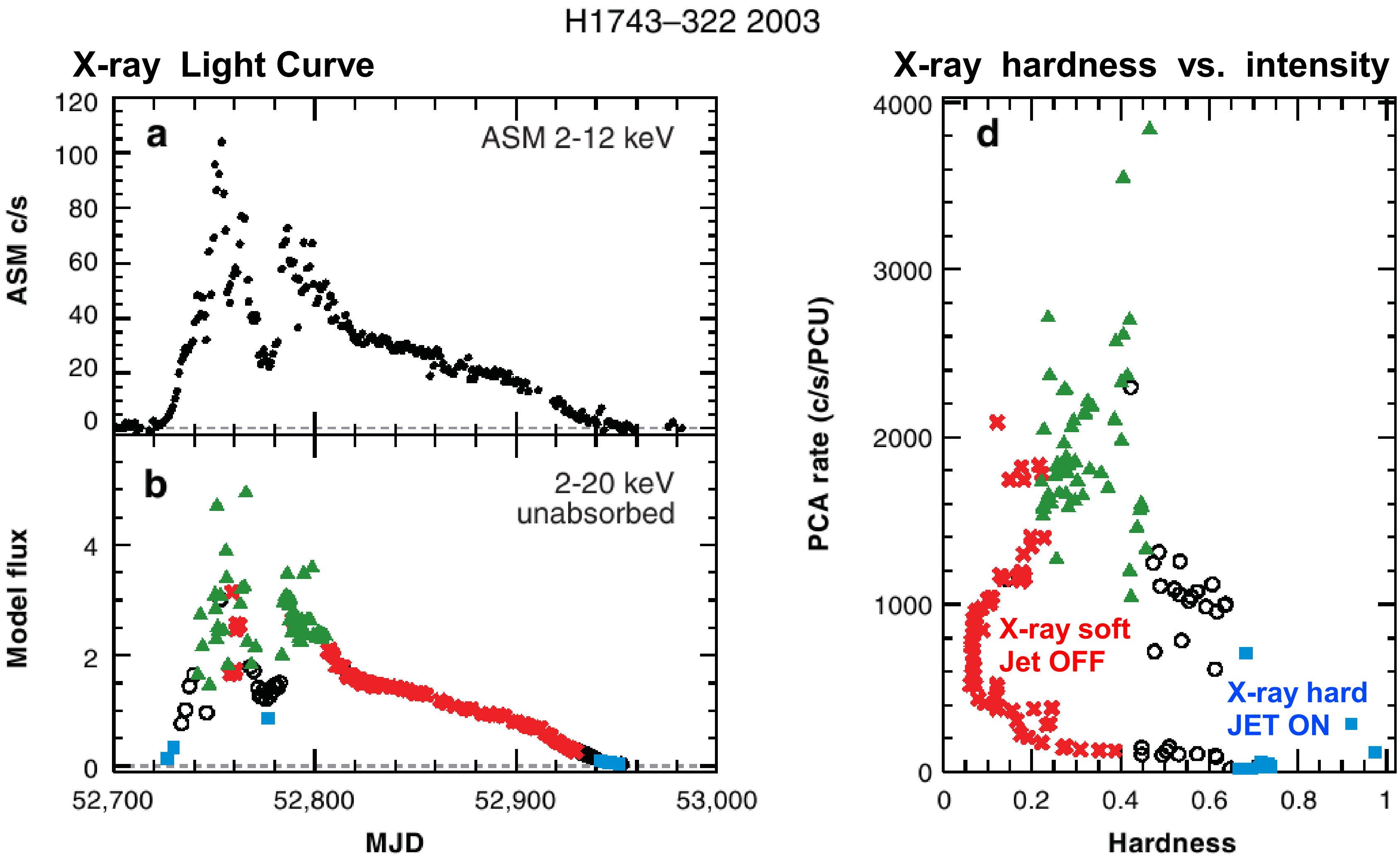
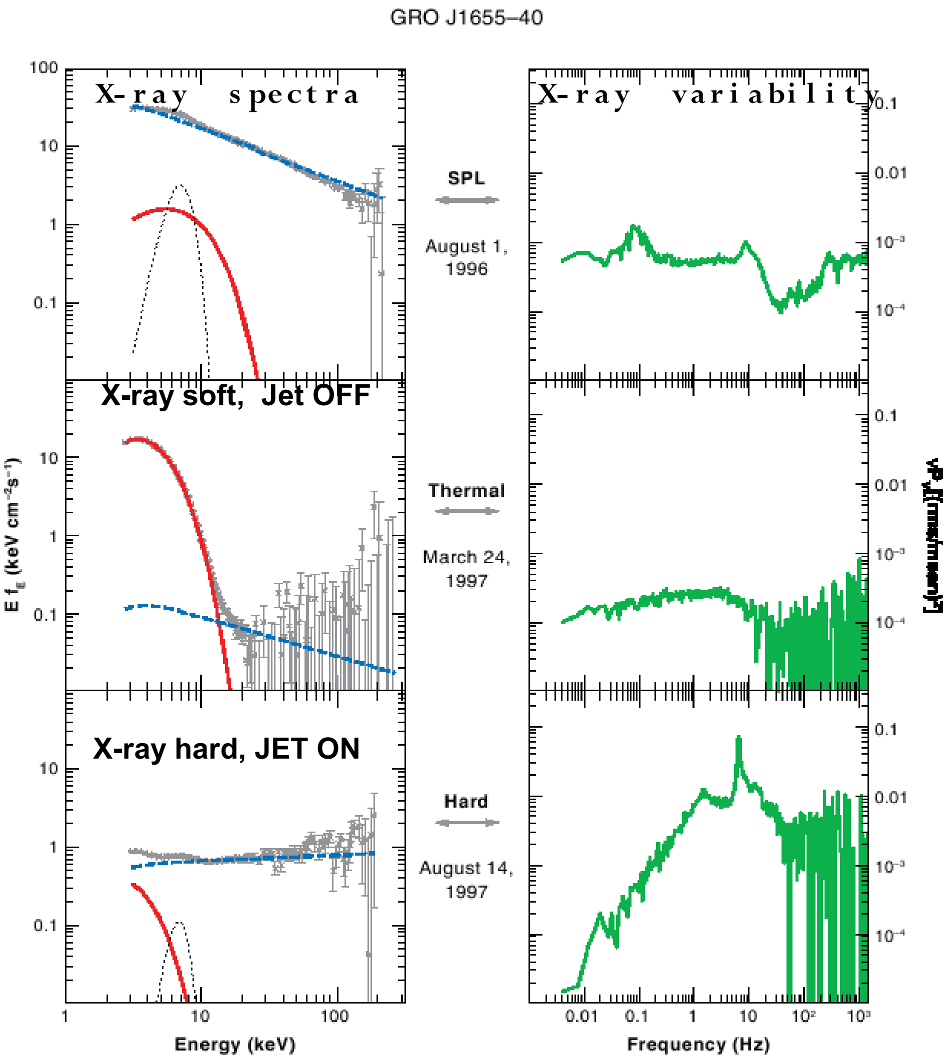
Variable Accretion & X-ray State Changes



Remillard & McClintock, 2006, ARAA, 44, 49

State Changes: physical basis



Remillard & McClintock, 2006, ARAA, 44, 49

Figure 2

Sample spectra of black-hole binary GRO J1655–40 illustrating the three outburst states: steep power law, thermal, and hard. Each state is characterized by a pair of panels. Left panels show the spectral energy distribution decomposed into three components: thermal (*red, solid line*), power-law (*blue, dashed line*), and a relativistically broadened Fe Kα line (*black, dotted line*). Right panels show the PDSs plotted as log($\nu \times P_\nu$) versus logν.

- **Thermal:** ~1 keV multi-temperature Keplerian accretion disk
- **Power-law** (non-thermal): Compton up-scattering of disk photons by relativistic electrons
- **Radio:** synchrotron jet emission

Radio flares at X-ray state transitions

GRS 1915+105

G.G. Pooley, MRAO

Steady jets in the low/hard state

Lx/Ledd ~ (m/m_edd)^2 For RIAF type accretion

Lradio ~ m^1.4 Empirically determined

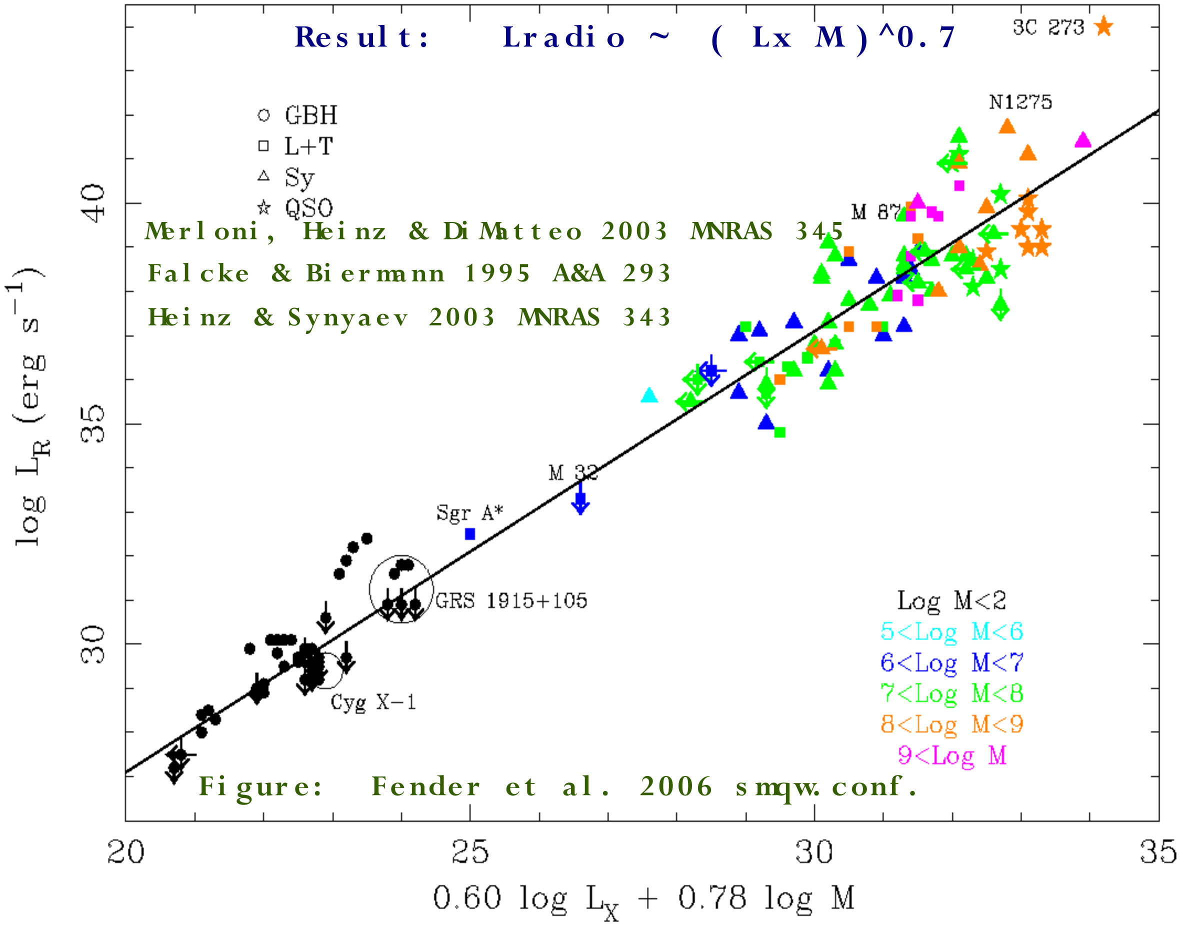
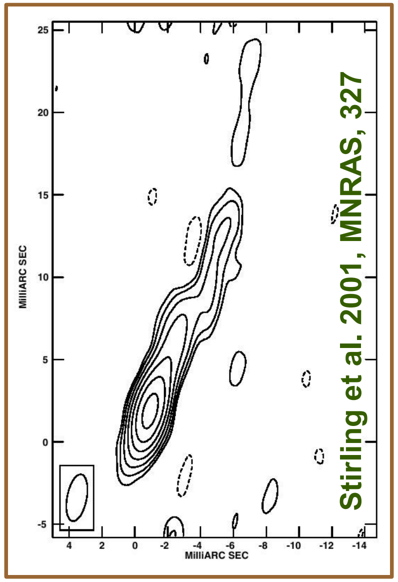
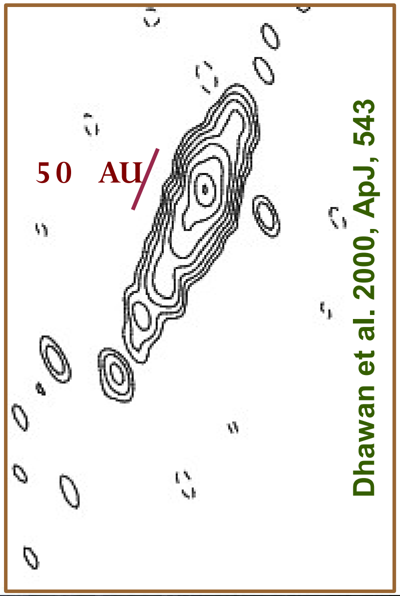


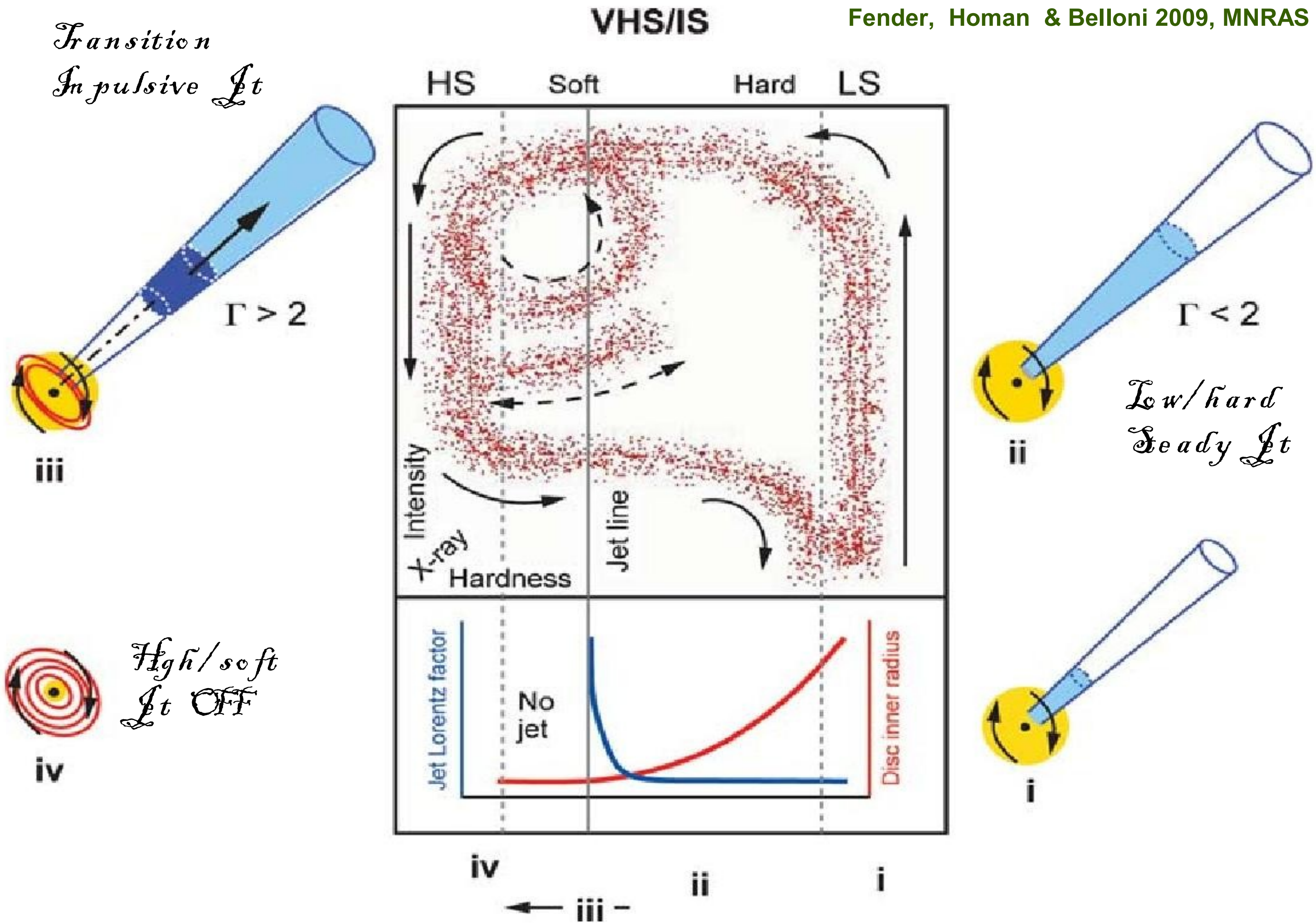
Figure 1: The fundamental plane of black hole activity, relating radio luminosity, X-ray luminosity and mass over more than eight orders of magnitude in black hole mass. A major step forward in the unification





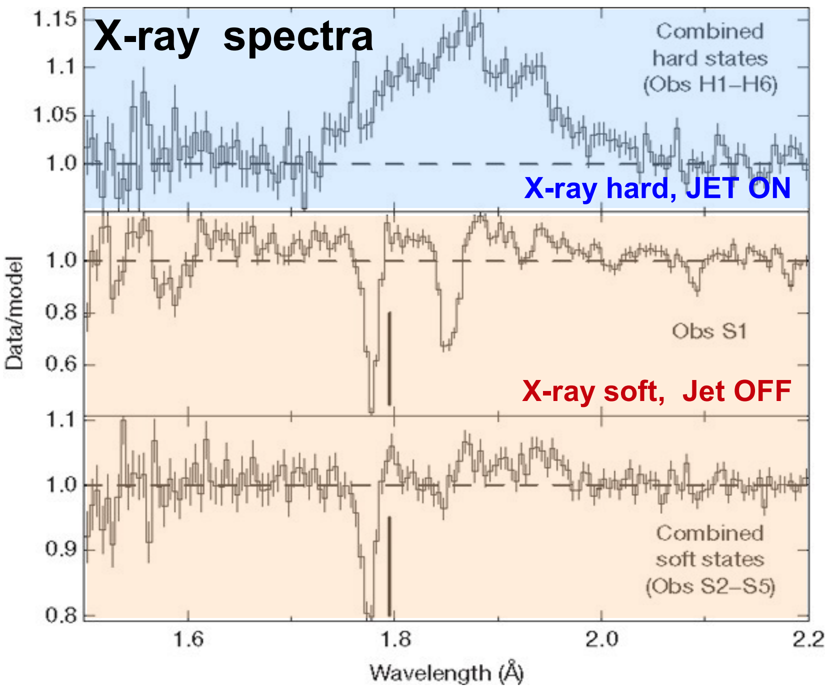
Making sense of the disk/jet coupling

Fender, Belloni & Gallo 2004 MNRAS, 355
Fender, Homan & Belloni 2009, MNRAS

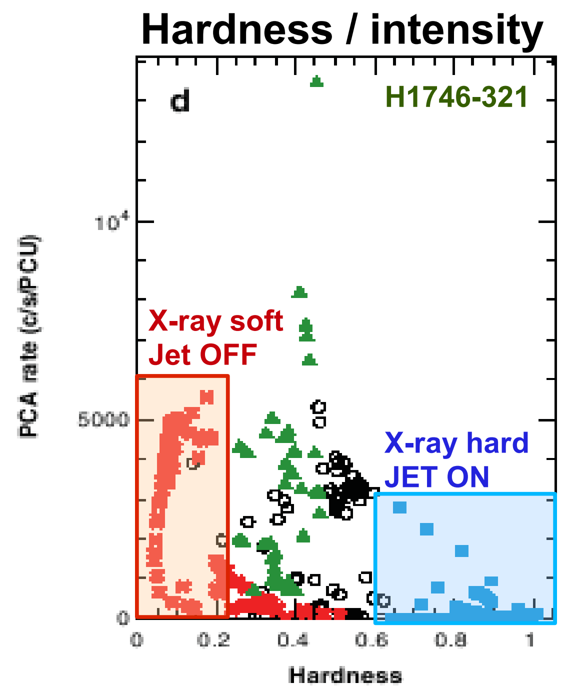


Jet suppressed by disk wind?

GRS 1915+105



Neilsen & Lee, 2009, Nature, 458, 481



- **Hard state:** *Jet ON – broad reflection line from disk.*
- **Soft state:** *Jet OFF – narrow absorption line from wind.*
- **Claim:** *intense Xrays shut off jet, by diverting the accretion fuel into wind outflow.*

Jet launch: MHD simulations & Theory

Simulations of MDAFs: magnetically dominated accretion flows.

Meier & Nakamura, 2006, ASP Conf. Ser. 350
Meier et al. 2001, Science, 291
Koide et al. 2002, Science, 292

Jets and Accretion Flows

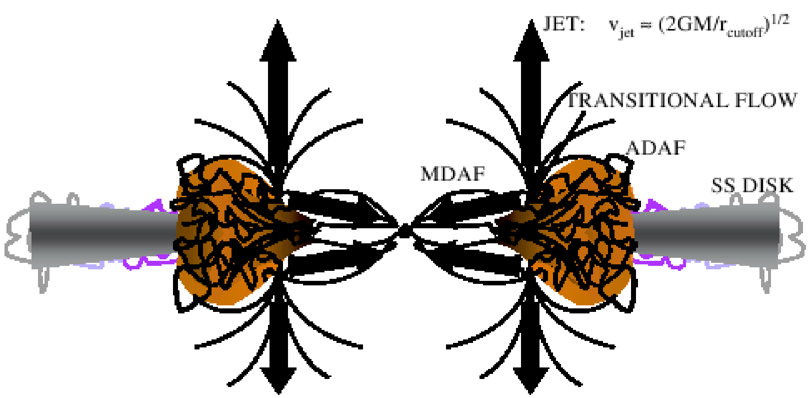


Figure 2. Equatorial view of the MDAF model of the plateau state. Outside a radius of $r_{cutoff} \sim 50 r_{Sch}$ the model is identical to current concepts: a Shakura & Sunyaev disk, truncated at several hundred r_{Sch} of so to a geometrically thick, optically thin ADAF. Interior to r_{cutoff} a magnetosphere develops, with accretion flow along strong field lines inward and outward jet flow.

Magnetic reconnection events trigger the jet flares.

De Gouveia dal Pino & Lazarian, 2005, A&A, 441

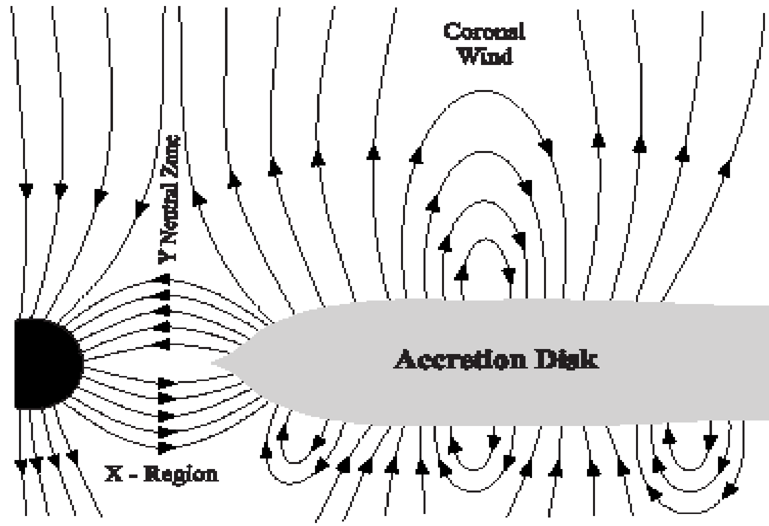


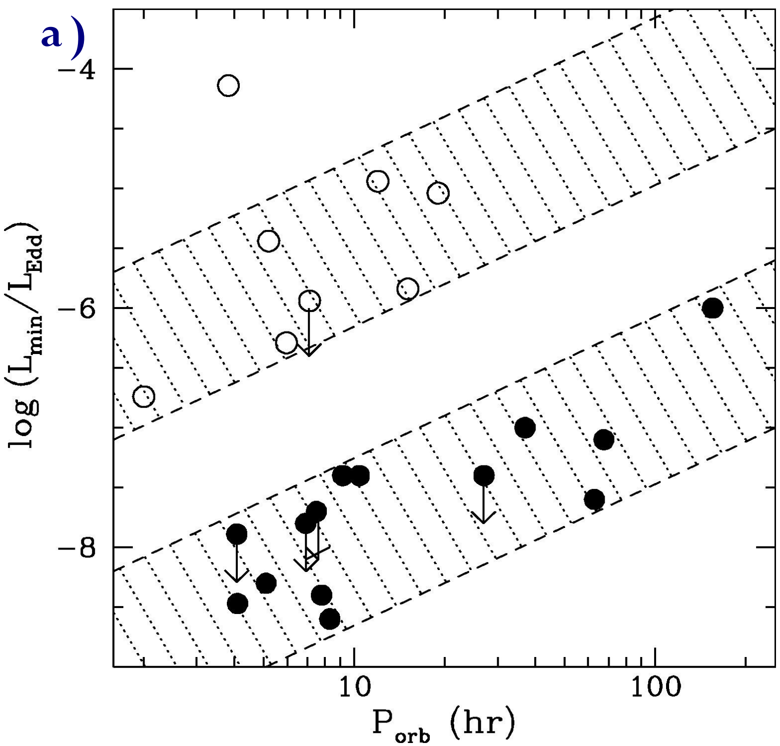
Fig. 1. Schematic drawing of the magnetic field geometry in the inner disk region at R_X. The acceleration occurs in the magnetic reconnection site at the Y type neutral zone (see the text).

BH vs. NS: evidence for ADAFs & event horizons

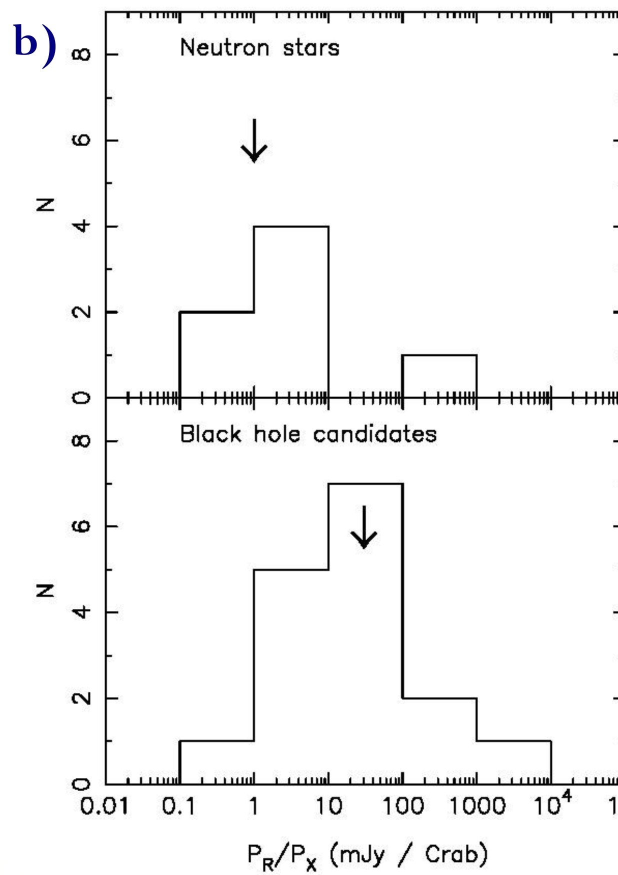
a) BH: L_x faint compared to NS at the same M_dot.

b) BH: L_Jet falls slower with M_dot than L_x (ADAF/RIAF).

- Jet emission dominates L_x at very low M_dot.



Narayan & McClintock 2008, NewAR, 51, 733



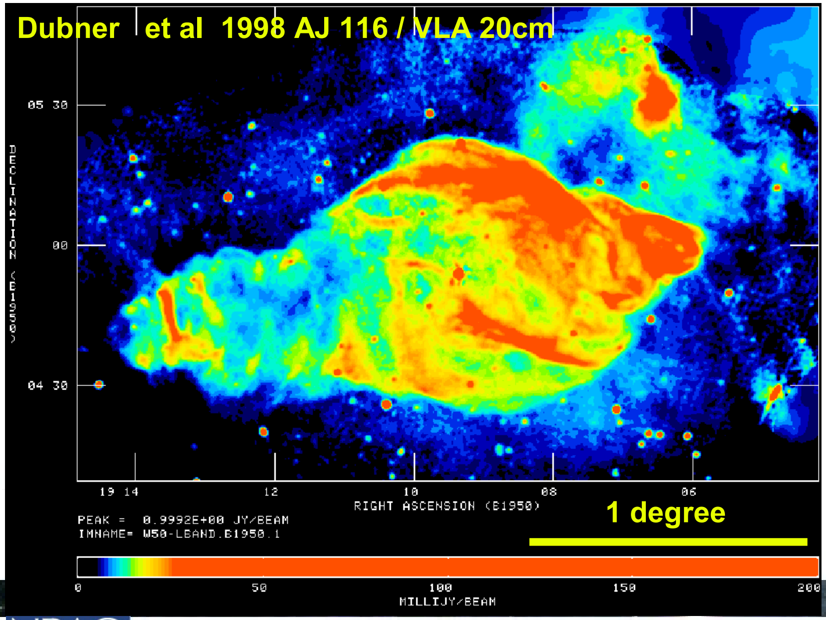
Fender & Kuulkers 2001, MNRAS, 324

Migliari & Fender 2006, MNRAS, 366

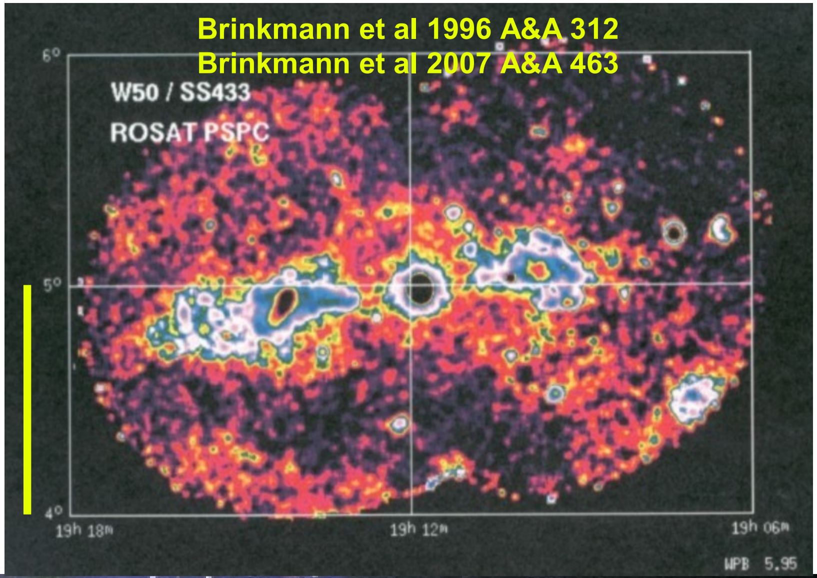
Large-scale impact – a jet plows through

- Interactions = Calorimetry & Densitometry
  - *Jet energy & composition*
  - *Jet lifetime, particle acceleration – Xray jets*
  - *ISM heating*
  - *Cosmic ray acceleration*

RADIO: SNR shaped by jet drill with 10^51 ergs

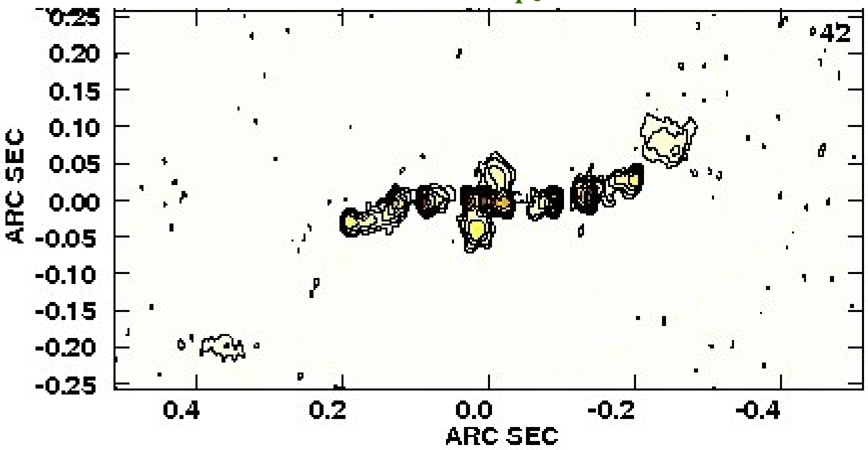


X-RAY: Gas supplied by stellar wind energy supplied by jet.

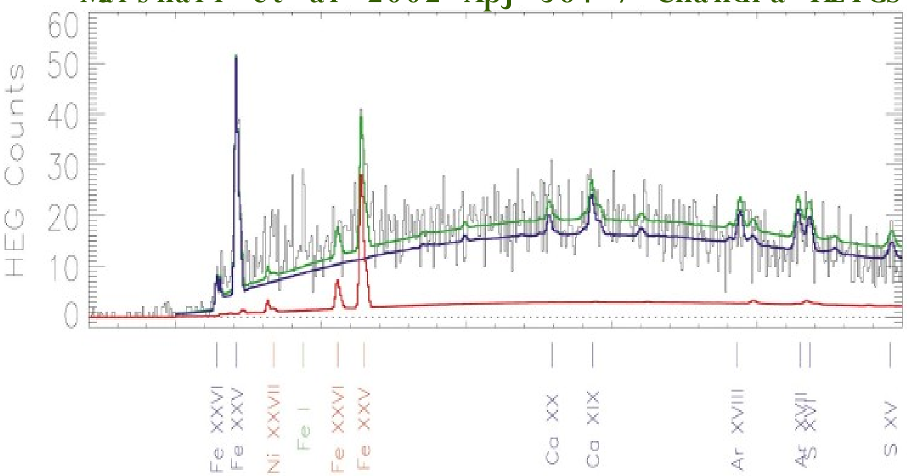


SS 433 - outflows everywhere

Blundell et al 2001 ApJ 562 / VLBA 18cm



Marshall et al 2002 ApJ 564 / Chandra HETGS



- Hot inner jet: X-ray lines
  $T = 10^8$ K @ $r = 10^{11}$ cm, $v = 0.27c$
- Cold jet: optical lines $T = 10^4$ K @ $r = 10^{15}$ cm, $v = 0.26c$
- X-ray lines downstream re-heated by jet $T = 10^7$ K @ $r = 10^{17}$
- Jet $r = 10^{11}$ … 20 … L_{mech} 10^{38}

  Migliari et al 2002 Science 297

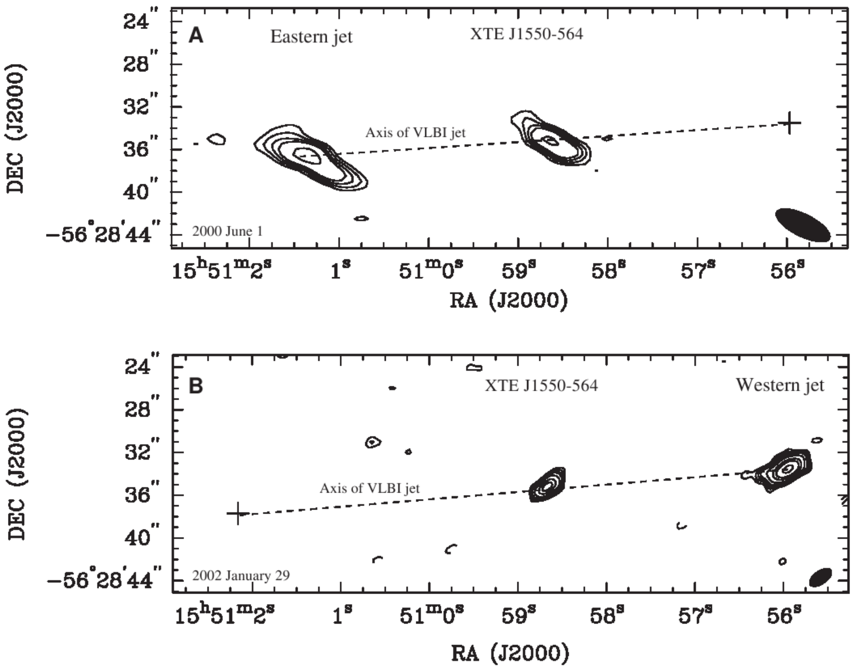
- Heavy mass loss (ring?) hides binary parameters 10^{-4} M/yr V = 200-300km/s
- Try radio lines

  Blundell et al 2008 ApJ 678

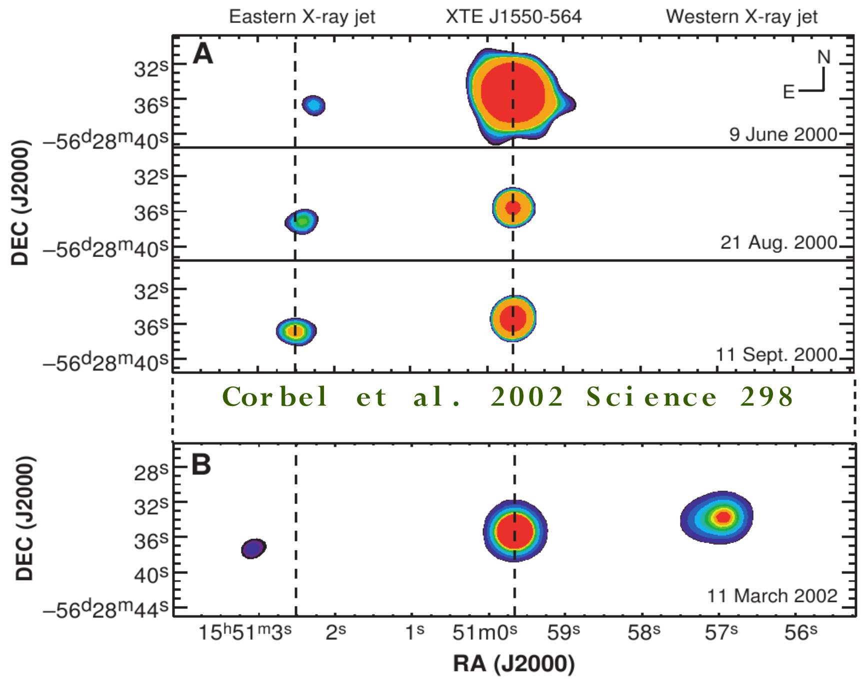
  - Lines from gas entrained by jets? 0.26c = 10GHz @ 1cm
  - Shock-excited by jets as they plow through? Any molecular lines? RRL?

X-ray knots contain TeV electrons

Radio jet / ATCA



X-ray jet / Chandra



Corbel et al. 2002 Science 298

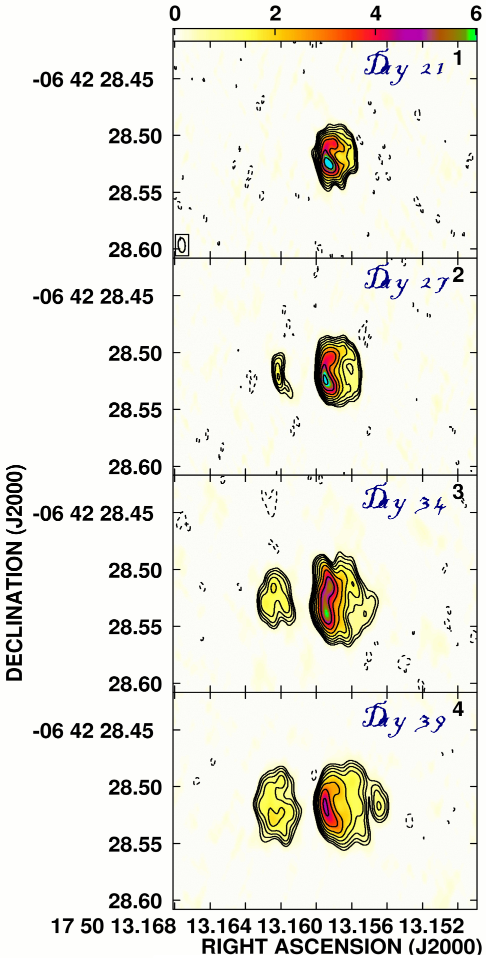
- XTE J550-560 flared in 1998, VLB source detected (v~2c)
- Xray & radio knots seen in 2002, gradually decelerated.
- Radio to Xray synchrotron spectrum --> TeV electrons in knots, generated by shock interaction with ISM
- H1746-322: another one, very similar

Corbel et al. 2005 ApJ 632

- Why do other jets fade in days – this one lit up after 4 yrs?

Muffled jets: circumstellar smothering.

Recurrent Nova RS Oph



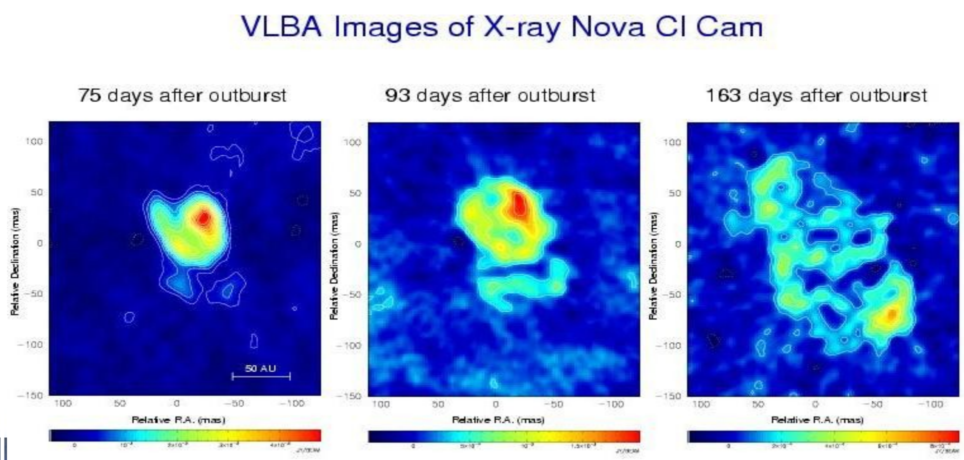
Rupen, Sokoloski, Mudszewski 2008 ApJ 688

VLBA 18cm

CI Cam

Mudszewski & Rupen 2004 ApJ 615

- Xray nova + usual jet signature, radio flare etc...
- But no jet.
- Variable Xray absorption- N_H went $10^{22}/cm^2$ to ~0 in days; evidence of dense circumstellar material
- Expanding shock allowed measure-ment of jet mechanical energy $E_{jet} \sim 10^{46}$ erg ~ $E_{bolometric}$



Astrometry of X-ray binaries

- **VLB PM + optical radial vel = 3d motion**
  - *Do BH get a birth kick like young pulsars?*
  - *Galactocentric orbit: disk, halo or bulge pop.?*
  - *Constrain mass loss in SN*
- **Parallaxes ? Yes, with effort**
  - *Parent population, massive starforming regions, being done. e.g. Reid et al 2009, ApJ 693.*
- **Feedback to detailed stellar evolution models:**
  - *Compact object formation and natal kicks* Willems et al.2005 ApJ 625; Fragos et al. 2009 ApJ 697
- **Who predicted VLBI impact on stellar evolution?**

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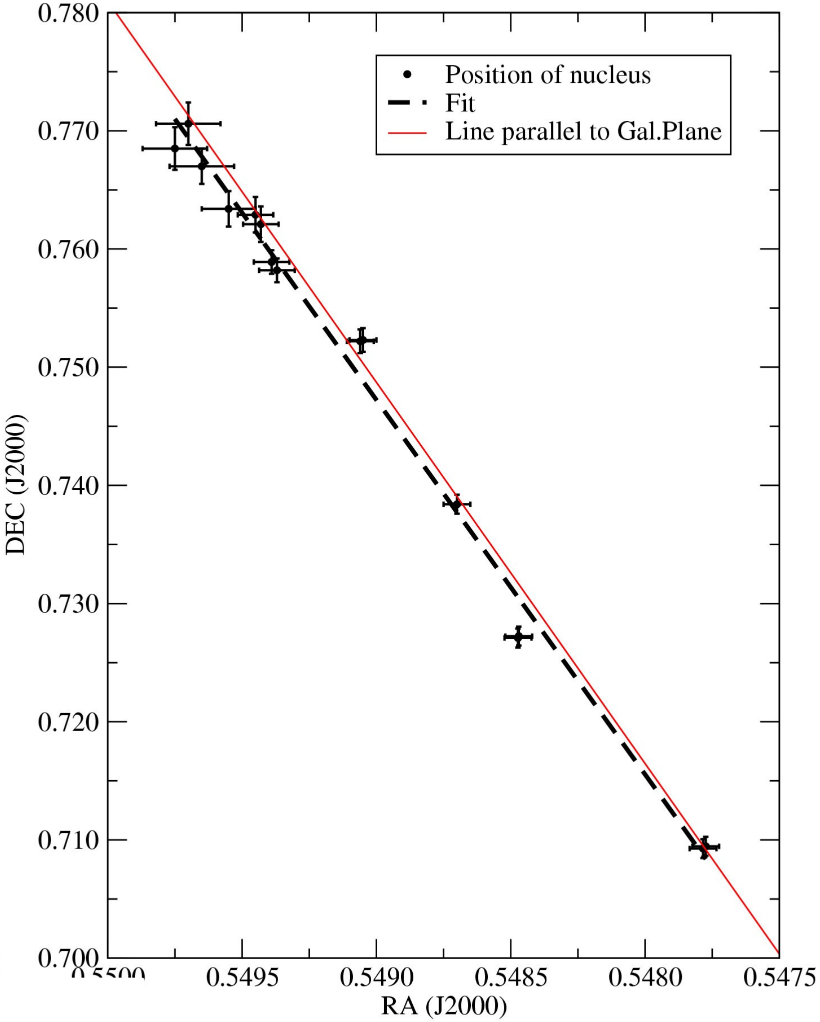
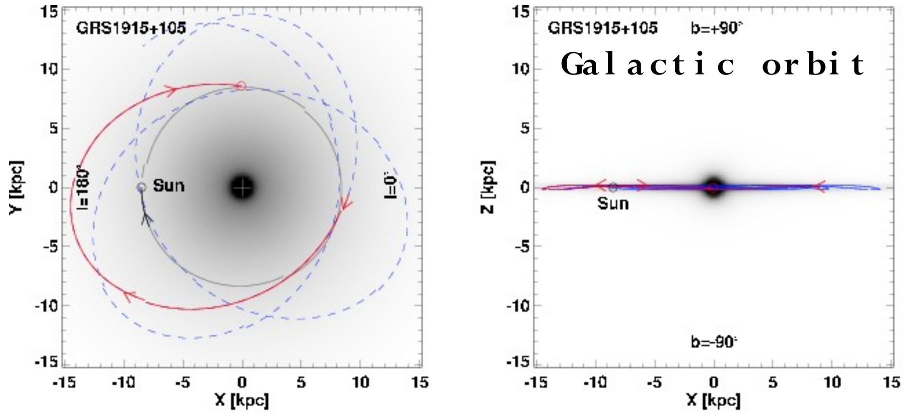
A $14 M_\odot$ BH: kicked or stirred ?

GRS 1915+105 Astrometry

Dhawan et al. 2007 ApJ, 668





- **Peculiar velocity is large**
  - $>$ 55 km/s in galactic plane momentum of pulsar @550 km/s
  - $<$ 10 km/s out of plane
- **Can we constrain SN kick?**
  - Hard to say -
  - Kick must be nearly in plane.
  - 15 Gy old, stirring by spiral arms could have done it with no SN kick.

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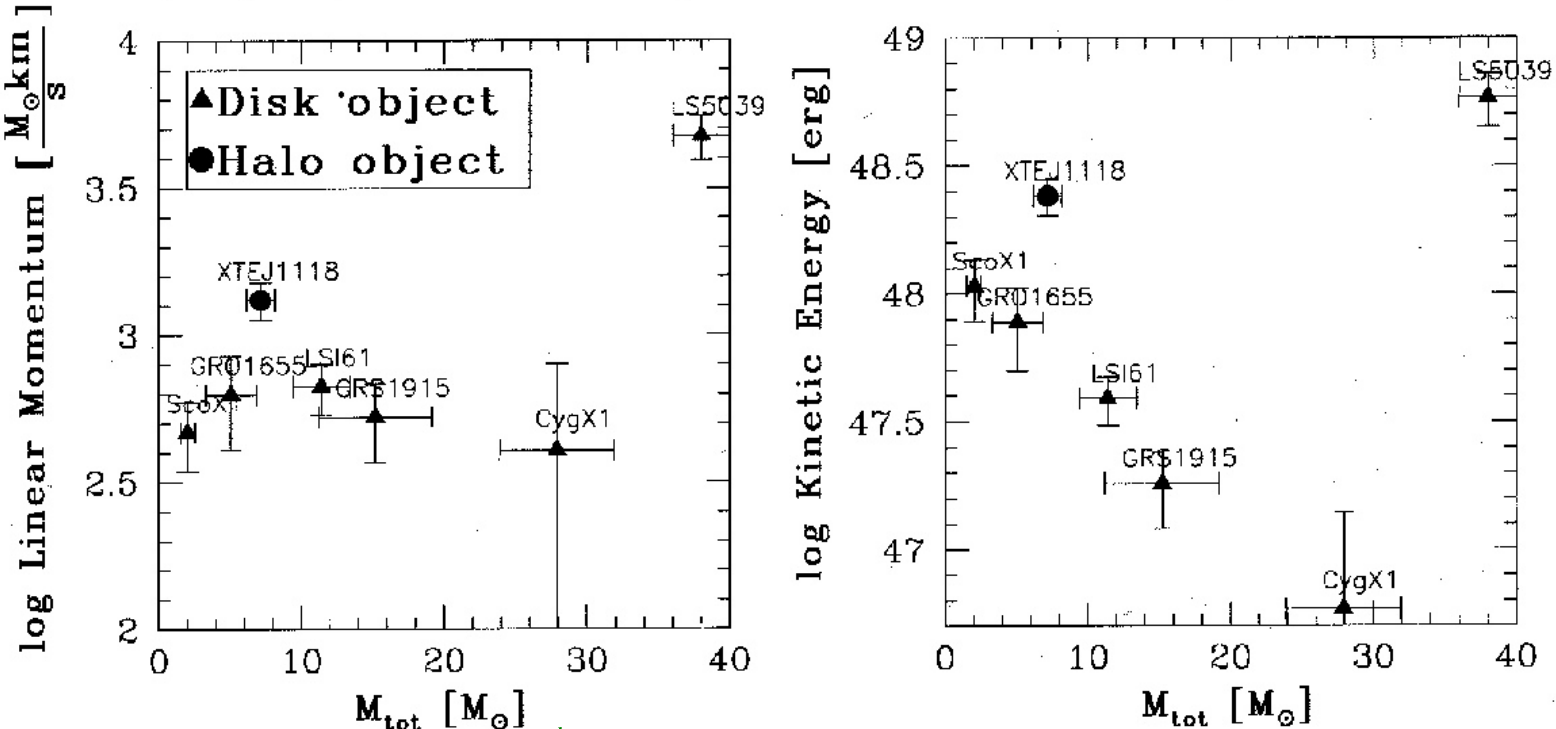
BH formation by implosion or explosion?



Mirabel & Rodrigues, 4th Microquasar Workshop, 2003 (Ed. Durouchoux)

Figure 7. **Linear momentum (left) and kinetic energy (right)** of the anomalous motion of X-ray binaries as function of the total mass (compact object plus donor star).

- *BH formation without SN explosion:*

Fryer & Kalogera 2001, ApJ, 554

Belczynski & Bulik 2002, ApJ, 574

Using realtime VLB - 1

- Timeline: trigger > coordinate > propose > find cals > record > correlate
  - *First stages - fix at institutional level*
- Calibrators: needed for phase ref + astrometry
  - *Use new arrays e.g. ATA for prefilter*
  - *Galactic plane, 4-8 GHz.*
  - *Flat 10% tax on everyone?*
- eVLB can do quick cal search
  - *~100 NVSS >50mJy < 2deg separation.*
  - *Typically >30% OK VLA A only 1+_1% >10mJy VLBA*
  - *FIRST better: >30% >2mJy @5GHz VLBA* Wrobel+ 2005 AJ 130.
  - *Filter + Tie to ICRF within 1 hr of trigger.*
  - *Need scheme for real-time obs update*
- VLBA 4 Gbps can use cals ~2mJy.

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Using realtime VLB - 2

- Trigger location may be poor – arcmin.
- Need widefield imaging – reuse disks.
  - Disks @ home, data by fiber.
  - Record corr output ~250 MB/s (0.1 s, 20 kHz)
  - ~3' FOV for imaging (~1 TB/hr < 10% smear).
  - Alternative to EVLA initial search.

- Adopt post-processing techniques from other high data rate arrays (EVLA, LOFAR)
  - W projection
  - CPU clusters

Widefield VLB already being done:
e.g. Garrett et al 2005, ApJ, 619

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SUMMARY

- Microquasars provide safe amusement to most brands of astro/physicsts
- VLB resolution & real-time nice to have
- Coordinated responses are key to progress – make better use of existing tools

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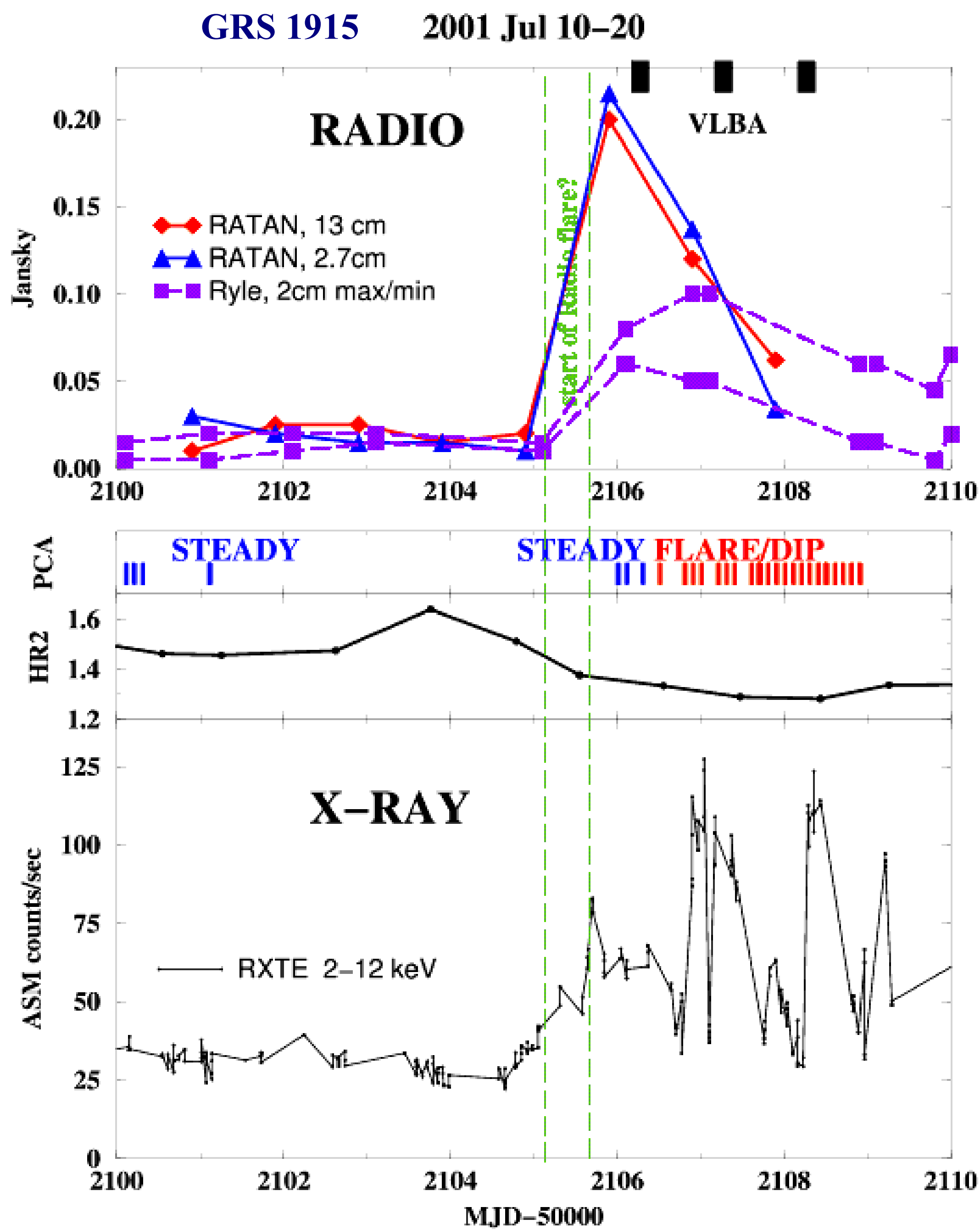
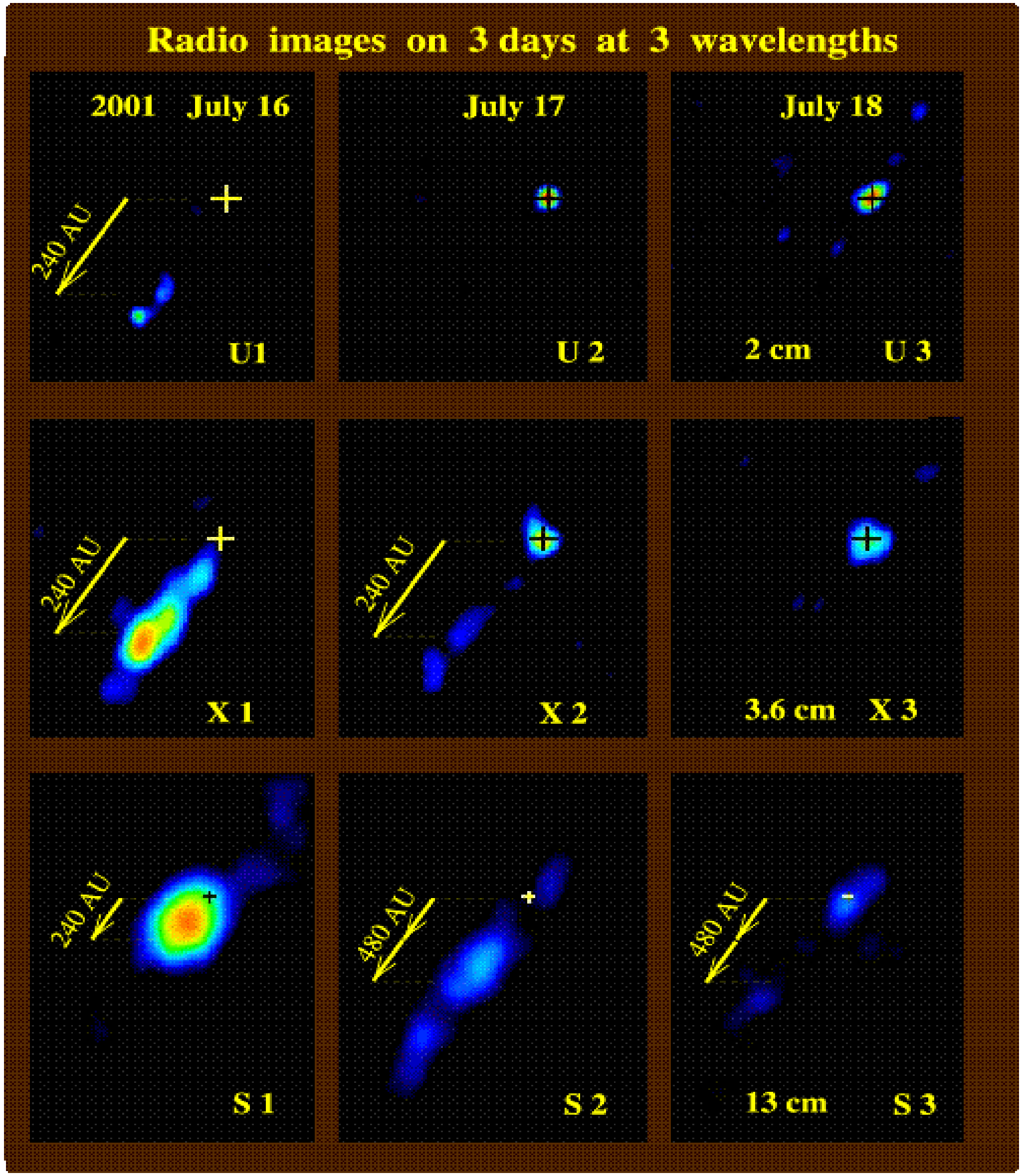
Jet birth



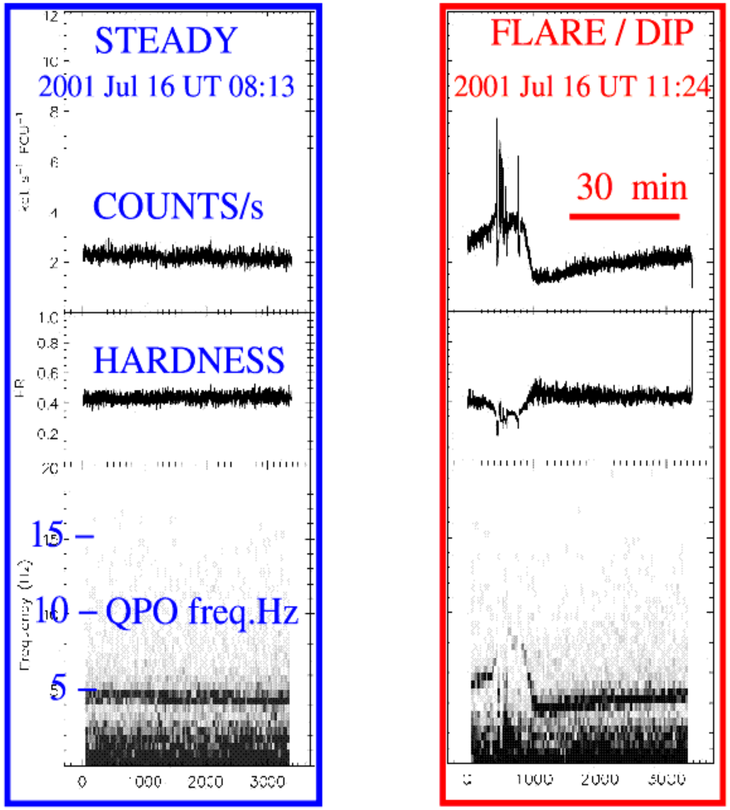
GRS 1915 2001 Jul 10–20
RADIO
VLBA
Jansky
0.20
0.15
0.10
0.05
0.00
RATAN, 13 cm
RATAN, 2.7cm
Ryle, 2cm max/min
start of Radio flare?
2100
2102
2104
2106
2108
2110
PCA
STEADY
STEADY
FLARE/DIP
HR2
1.6
1.4
1.2
X–RAY
ASM counts/sec
125
100
75
50
25
0
RXTE 2–12 keV
2100
2102
2104
2106
2108
2110
MJD–50000

Jet birth

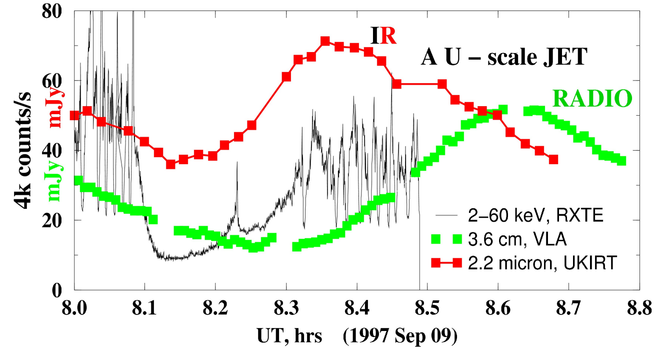

Radio images on 3 days at 3 wavelengths
2001 July 16
July 17
July 18
240 AU
U1
U 2
2 cm
U 3
240 AU
X 1
240 AU
X 2
3.6 cm
X 3
240 AU
S 1
480 AU
S 2
480 AU
13 cm
S 3

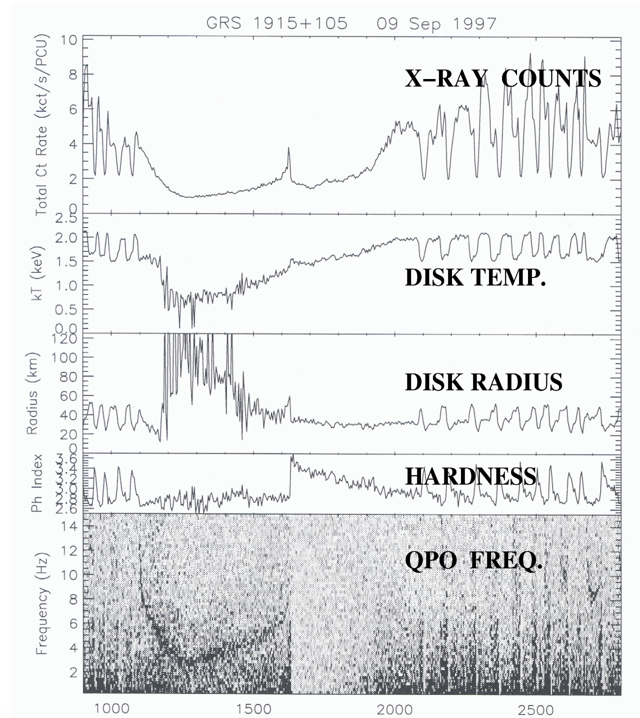
The data get even richer...

X–Ray PCA data across transition



Disk – Corona – Jet interplay





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