Microquasars and The Power of Spin

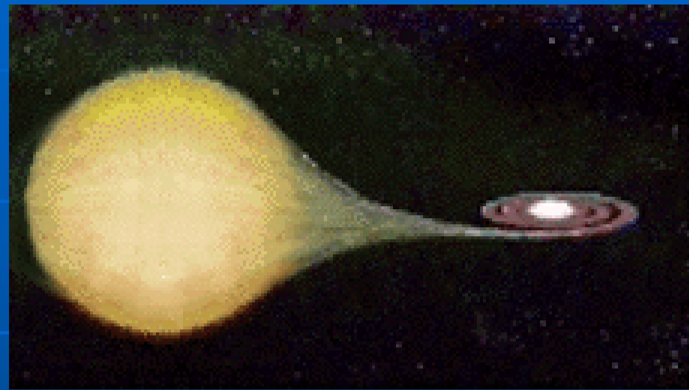
Ralph Spencer, Tony Rushton
with thanks to Mr Tony Blair

Overview

- What are Microquasars?
- A bit of history
- A gallery of objects
- The link to AGN
- A bit of theory of power generation
- Conclusion

X-ray Binary stars

- Many X-ray sources found to be in binaries – periods of several hrs to days ~300 in Milky Way
- Accretion onto a compact object formed by a supernova, releases gravitational energy and produces X-ray emitting binary star
- ~ 50 found to have radio emission (REXRB) : jets produced in some objects- **microquasars**



Accretion

Jets From SS433
Credit: NASA Artist's Visualization

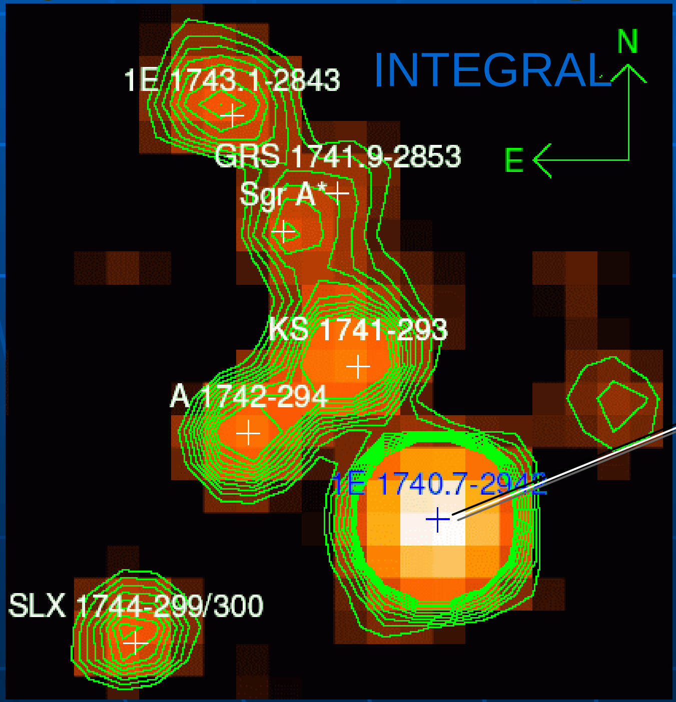
Jets produced

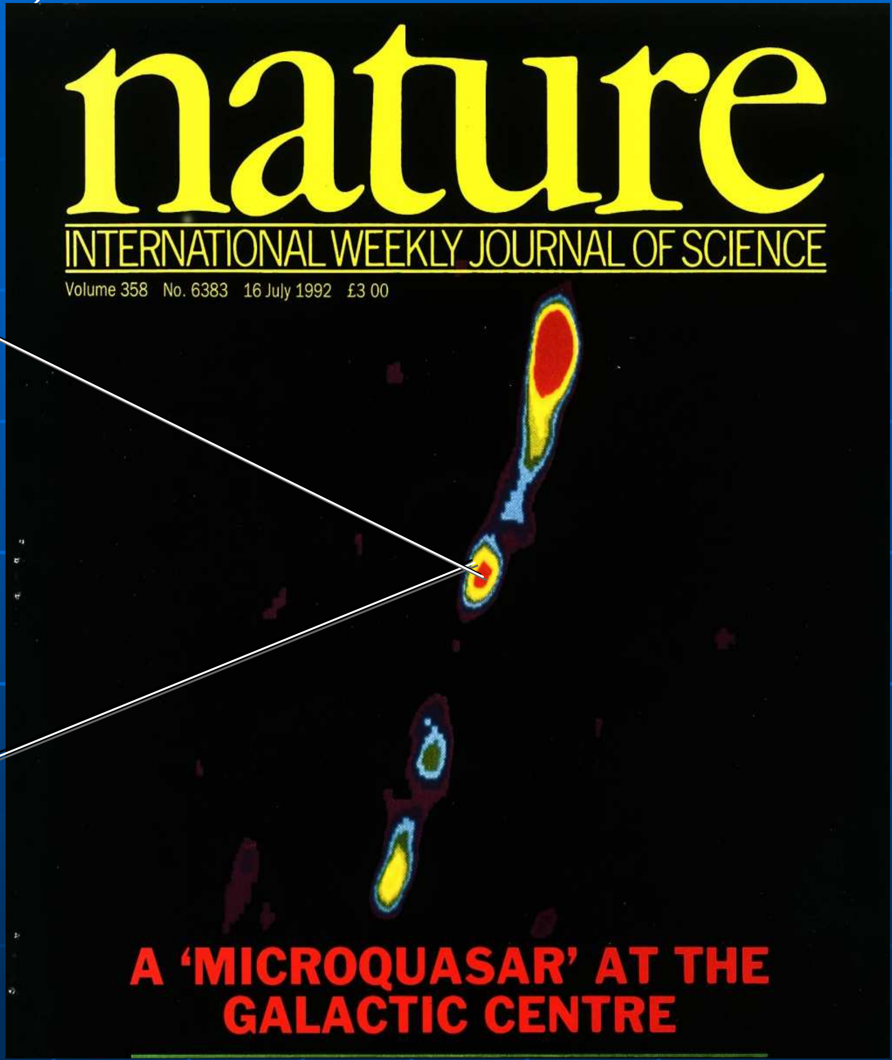
A "MICROQUASAR" AT THE GALACTIC CENTRE REGION

Wang et al. ApJ 2002

F. Mirabel., L.F.Rodríguez, Paul, Cordier, Lebrun (1992)

Belanger, Goldwurm, Goldoni, ApJ 2006

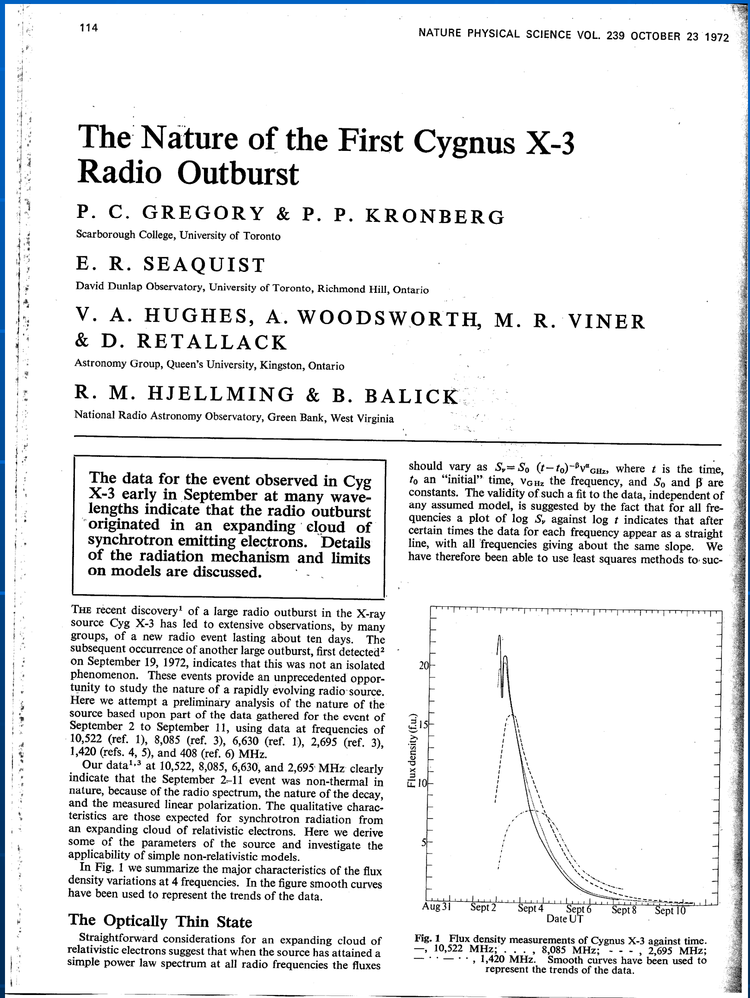




History

- 1970's – search for counterparts to the newly discovered X-ray sources
- 1971 Braes and Miley detection of compact radio emission from Cyg X-1 and Sco X-1 with the GB interferometer
- 1972 – Giant outburst on Cyg X-3 Nat. Phys. Sci. 239 114-

Cyg X-3 1972 Outburst –- 21 papers in Nature



The Nature of the First Cygnus X-3 Radio Outburst

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The data for the event observed in Cyg X-3 early in September at many wavelengths indicate that the radio outburst originated in an expanding cloud of synchrotron emitting electrons. Details of the radiation mechanism and limits on models are discussed.

THE recent discovery[1] of a large radio outburst in the X-ray source Cyg X-3 has led to extensive observations, by many groups, of a new radio event lasting about ten days. The subsequent occurrence of another large outburst, first detected[2] on September 19, 1972, indicates that this was not an isolated phenomenon. These events provide an unprecedented opportunity to study the nature of a rapidly evolving radio source. Here we attempt a preliminary analysis of the nature of the source based upon part of the data gathered for the event of September 2 to September 11, using data at frequencies of 10,522 (ref. 1), 8,085 (ref. 3), 6,630 (ref. 1), 2,695 (ref. 3), 1,420 (refs. 4, 5), and 408 (ref. 6) MHz.

Our data[1,3] at 10,522, 8,085, 6,630, and 2,695 MHz clearly indicate that the September 2–11 event was non-thermal in nature, because of the radio spectrum, the nature of the decay, and the measured linear polarization. The qualitative characteristics are those expected for synchrotron radiation from an expanding cloud of relativistic electrons. Here we derive some of the parameters of the source and investigate the applicability of simple non-relativistic models.

In Fig. 1 we summarize the major characteristics of the flux density variations at 4 frequencies. In the figure smooth curves have been used to represent the trends of the data.

The Optically Thin State

Straightforward considerations for an expanding cloud of relativistic electrons suggest that when the source has attained a simple power law spectrum at all radio frequencies the fluxes should vary as $S_\nu = S_0\ (t-t_0)^{-\beta}\nu^{\alpha}_{GHz}$, where t is the time, t_0 an "initial" time, ν_{GHz} the frequency, and S_0 and β are constants. The validity of such a fit to the data, independent of any assumed model, is suggested by the fact that for all frequencies a plot of log S_ν against log t indicates that after certain times the data for each frequency appear as a straight line, with all frequencies giving about the same slope. We have therefore been able to use least squares methods to suc-

Fig. 1 Flux density measurements of Cygnus X-3 against time. —, 10,522 MHz; . . . . , 8,085 MHz; - - - , 2,695 MHz; — · · — · · , 1,420 MHz. Smooth curves have been used to represent the trends of the data.

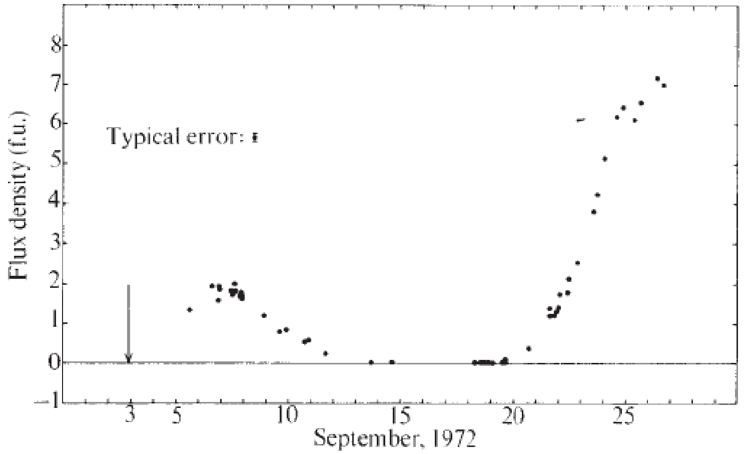


Fig. 2 The variation of the flux density at 408 MHz during September 1972. The time of the first reported detection on September 2 is shown. From Anderson *et al.*, *Nature Physical Science*, October 23 (1972).

Anderson et al. MkI-Defford 408 MHz

History contd.

- 1975 Radio emision from X-ray transient A0620-00 Davis et al 1975
  - Kuulkers et al. 1999 – we found the old 1975 data – was in fact extended ~ 3″ – a jet?
- 1980’s: Images of the radio bright objects
- 1990’s: More sensitive surveys, jet expansion measured
- 2000’s: Findamental plane, X-ray-Radio correlations, X-ray state dependence

A0620-00 Monoceros X-1

->

Kuulkers et al 1999

Davis et al 1972

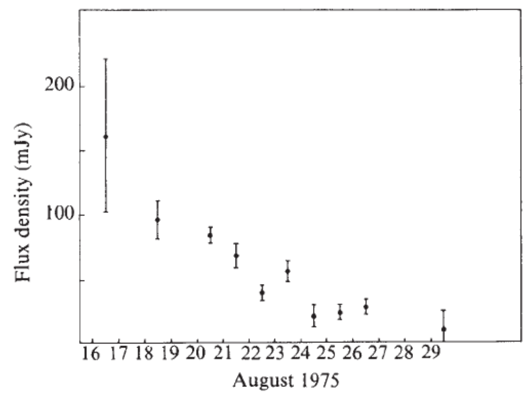


Fig. 1 Flux density of A0620 – 00 at 962 MHz with a resolution of 3″

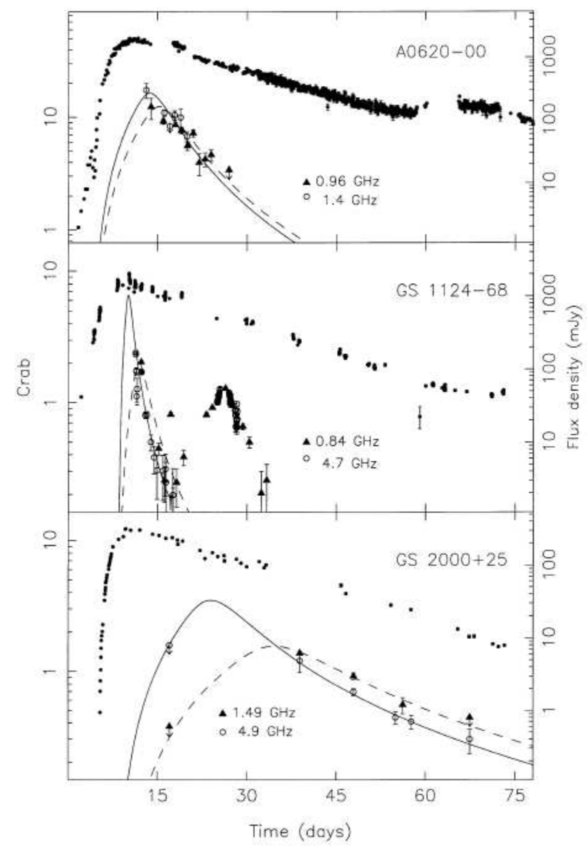
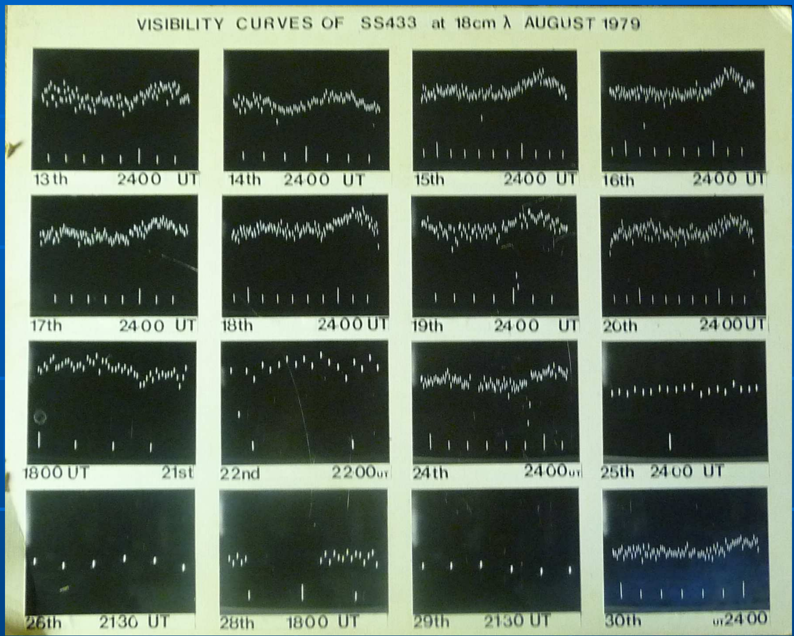
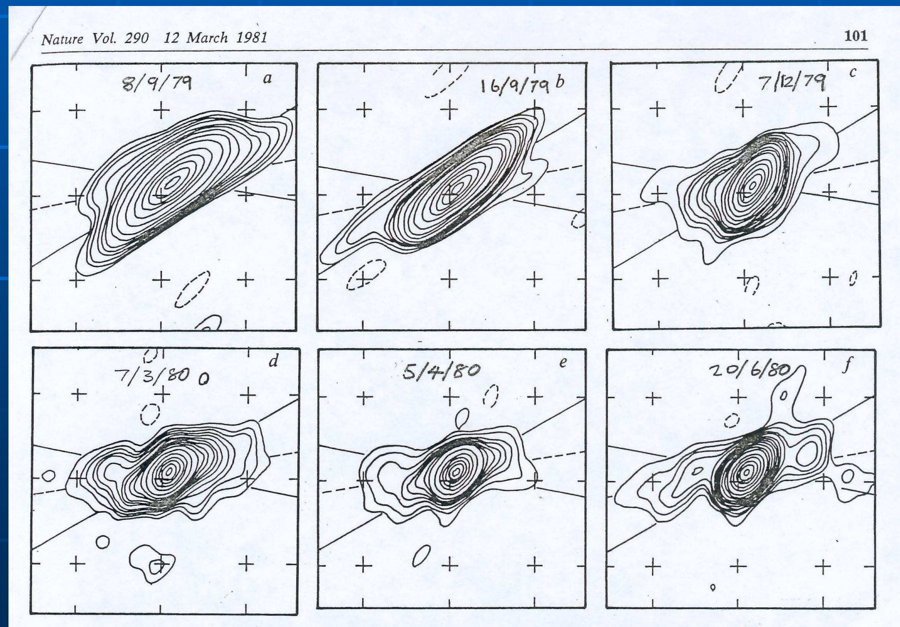


Figure 4. X-ray and radio light curves of A0620−00 (top), GS 1124−68 (middle) and GS 2000+25 (bottom). The X-ray measurements of A0620−00 are those obtained by the *Ariel V* SSE (2–18 keV), *Ariel V* ASM (3–6 keV) and *SAS-3* CSL-A (1.5–6 keV), see Kuulkers (1998). The *Ariel V* SSE and ASM light curves have been scaled to match the *SAS-3* CSL-A light curve. The X-ray measurements of GS 1124−68 are those obtained with the *Ginga* LAC (1.2–37 keV; Ebisawa et al. 1994) and the *Ginga* ASM (1–20 keV; Kitamoto et al. 1992). The rise of the X-ray outburst of GS 2000+25 is taken from Tsunemi et al. (1989), while the rest of the light curve is from Kitamoto et al. (1992). For the radio light curves we have plotted the measurements at two frequencies. The radio measurements of A0620−00 are tabulated in Table 1, the GS 1124−68 measurements are from Ball et al. (1995) and those of GS 2000+25 are obtained by Hjellming et al. (1988). Drawn with solid and dashed lines are fits to the lowest and highest radio frequency measurements, respectively, with single-synchrotron bubble models as presented by Hjellming et al. (1988) and Ball et al. (1995).

SS433

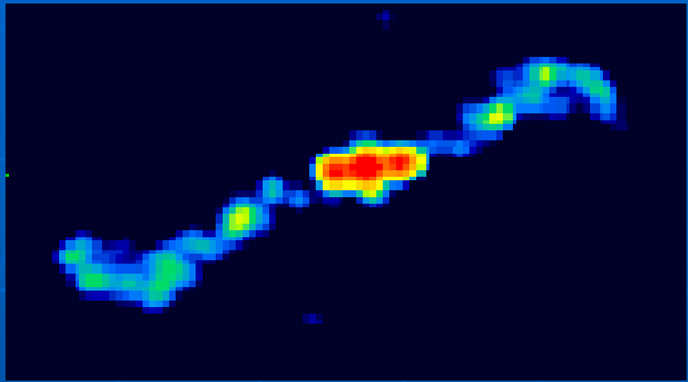


-Discovery of a radio jet,
- Spencer Nature 1979, 282 483



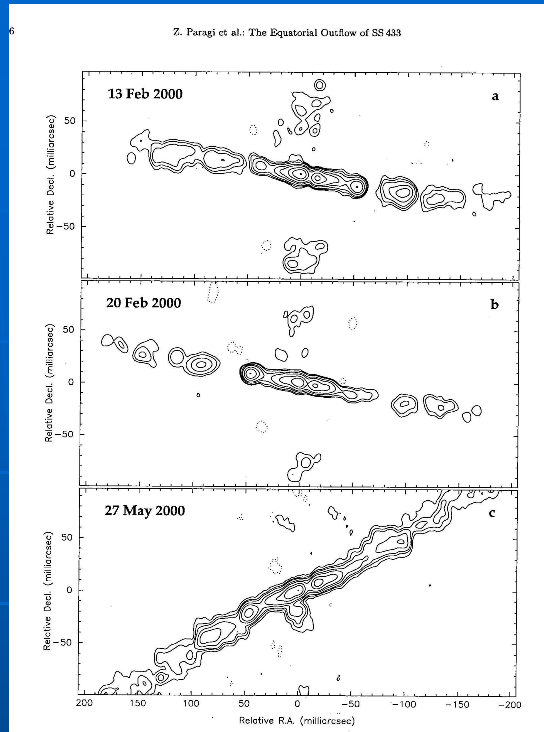
Hjellming and Johnston 1981

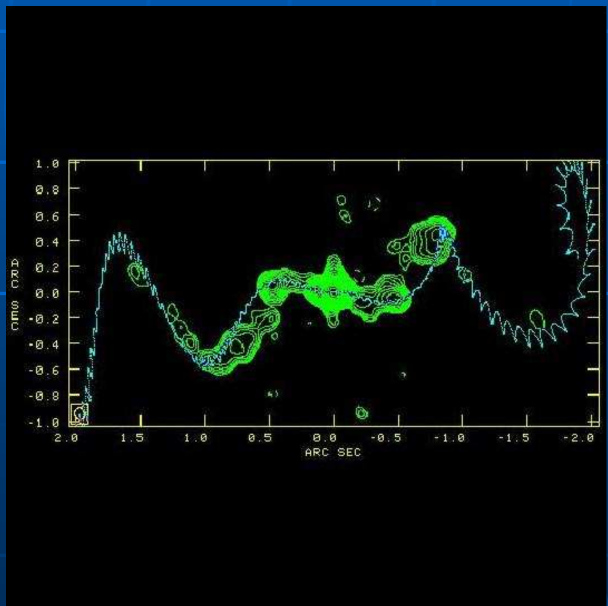
Gallery: SS433

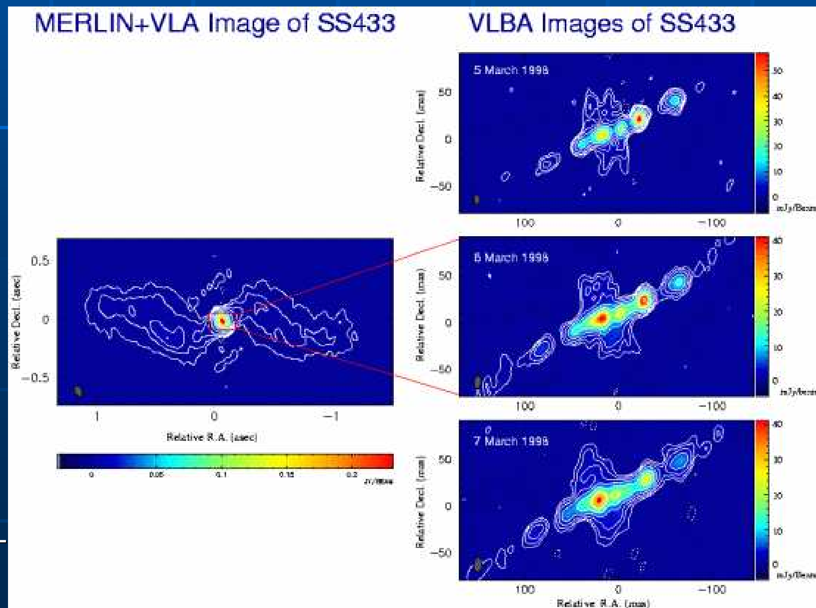


-MERLIN

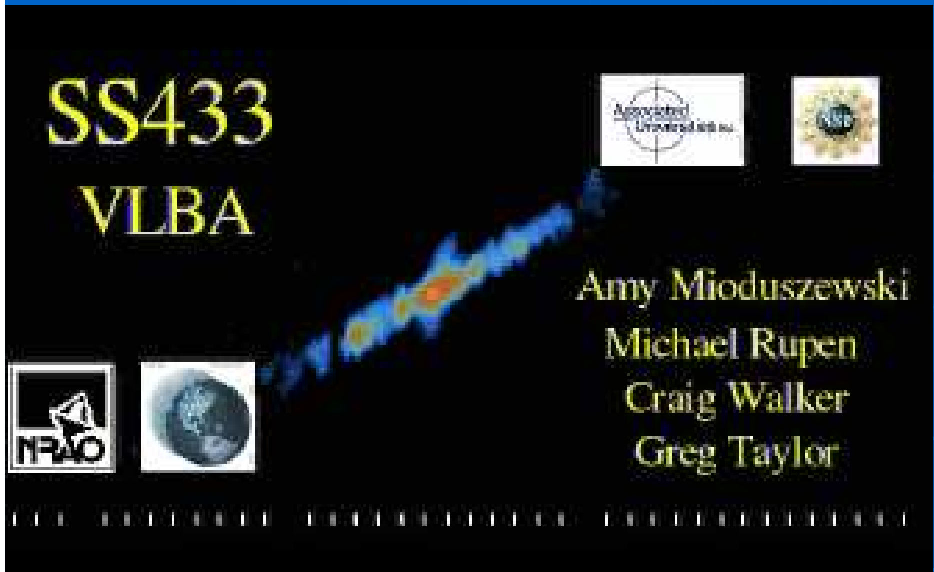
VLBI --







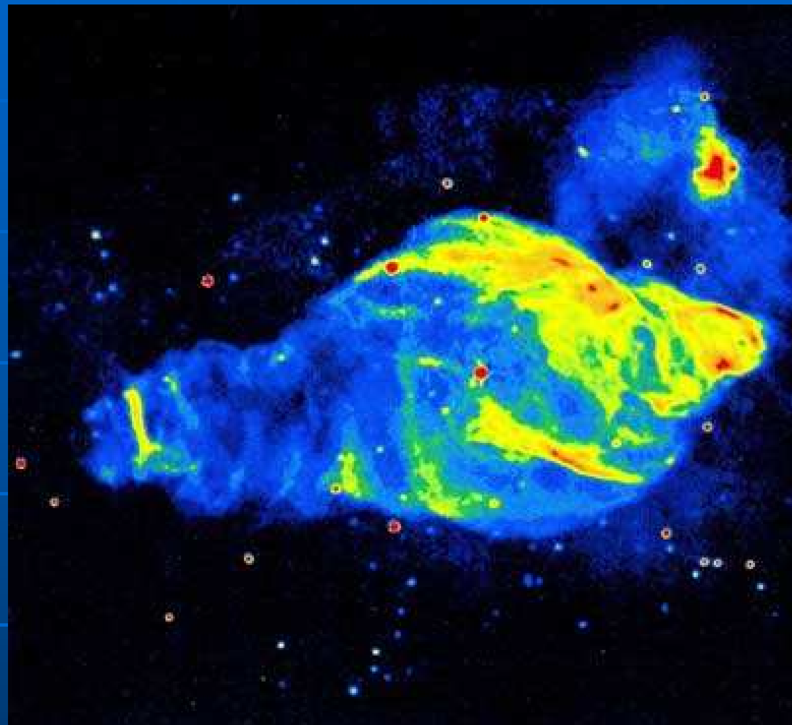
POWERFUL DARK JETS FROM BLACK HOLES



1arcsec

1^{o} = 60 pc

Radio (Dubner et al); X-rays: (Brinkmann et al)



W50

- Moving H α lines : matter moving at 0.26 c
- In precessing jets, period 162.5 days

SUPERLUMINAL EJECTION IN A μQSO

- GRS 1915+105 (discovered with GRANAT)

Mirabel. & L.F. Rodriguez, 1994

- 1 $M_{\odot}$ red giant orbiting a 14 $M_{\odot}$ BH (Greiner et al.)

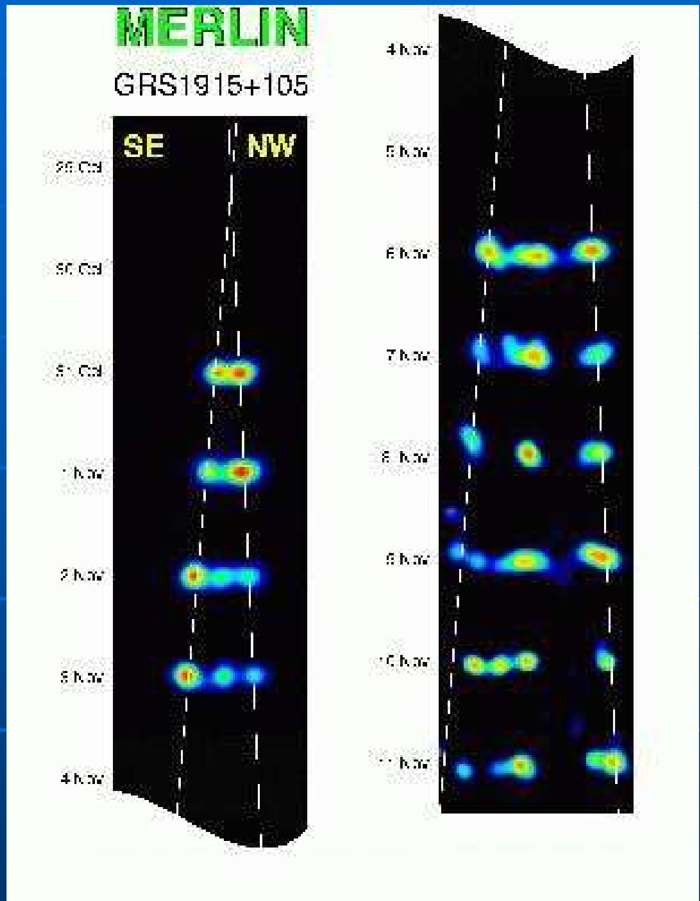
1 arcsec

GRS 1915+105

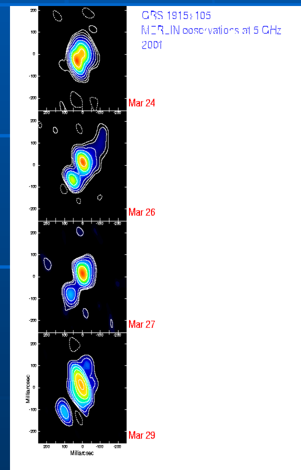
$V_{app} > C$ ---Jets have apparent superluminal motions

GRS1915+105 – blob ejection!

Radio Outburst:
5 GHz Merlin
Oct 1997
d=11 kpc,
v/c=0.98
$\theta=66^{o}$

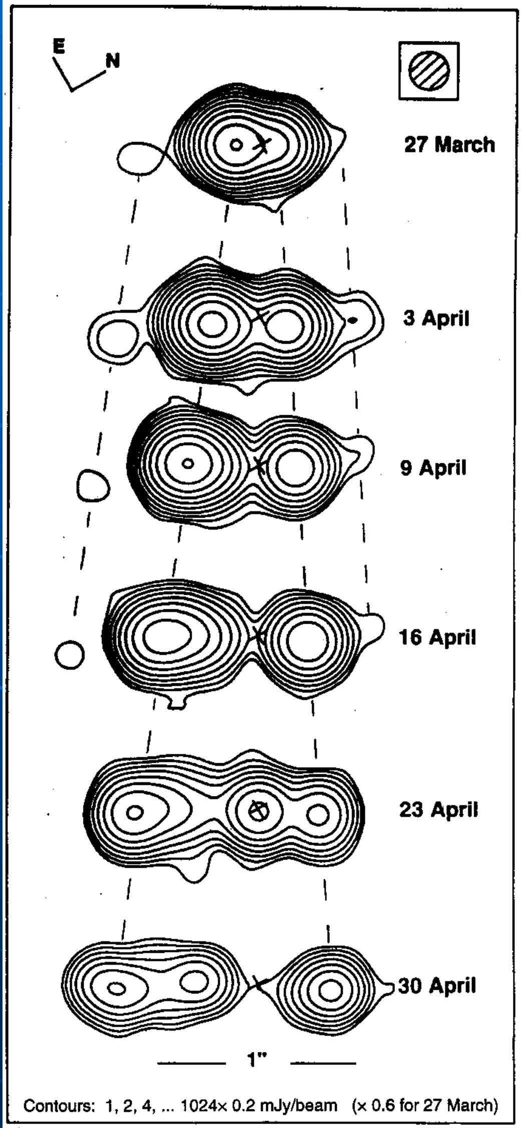


And again In March 2001 (plus another 7 Epochs)



NB the images have been rotated in the above

1994 and 1997 results compared

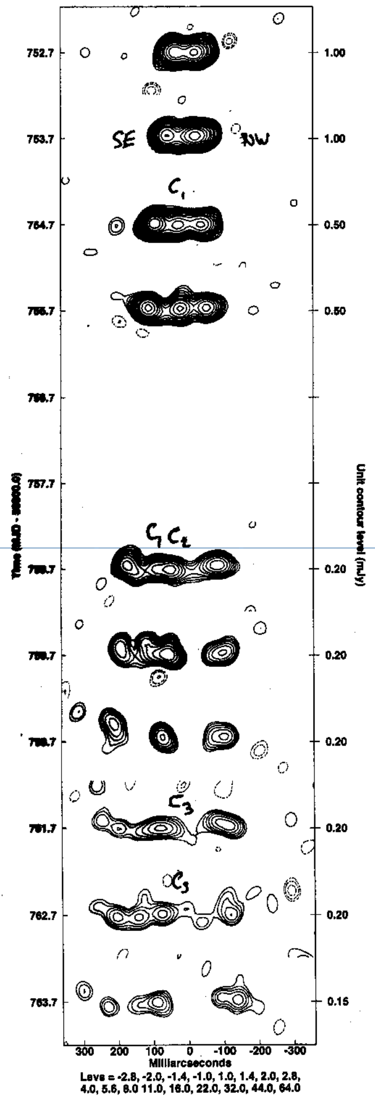


1994

- *Mirabel & Rodriguez*
- Nature, **341**, 46–48, 1994
- VLA observations
- 6 epochs
- $\lambda = 3.5$ cm

- Component velocities (mas/d)
  $\mu_{app} = 17.6 \pm 0.4$
  $\mu_{rec} = 9.0 \pm 0.1$

- D = 12.5 ± 1.5 kpc
- $v = 0.92 \pm 0.08c$
- $\theta = 70 \pm 2°$



1997

- MERLIN observations
- 10 epochs
- $\nu = 4994.0$ MHz
- $\lambda = 6.0$ cm
- $\Delta\nu = 14$ MHz
- Dual polarisation

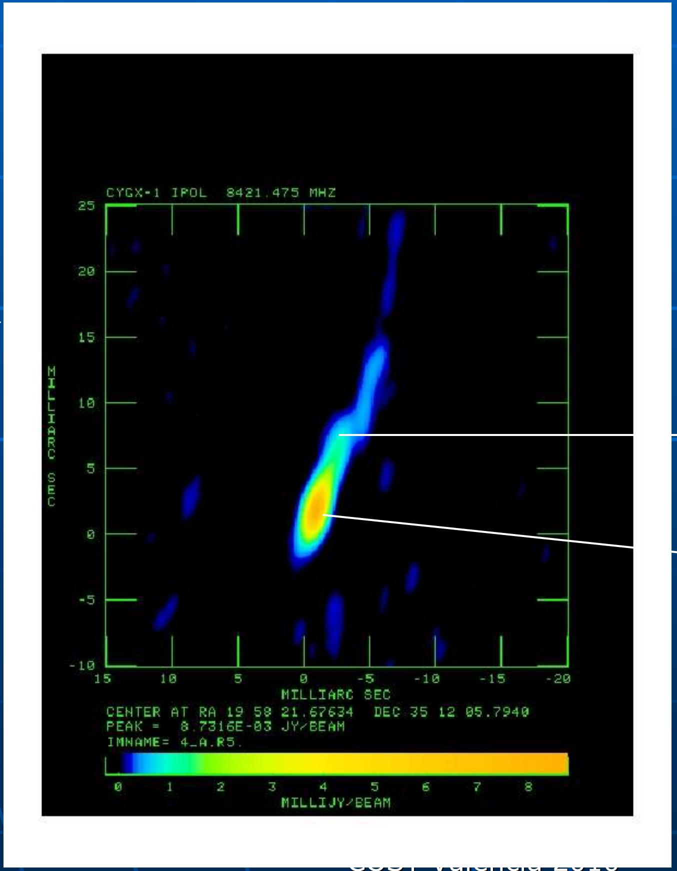
- Component velocities
  (2c) $\mu_{app} = 23.6 \pm 0.5$ mas/d
  (c) $\mu_{rec} = 10.0 \pm 0.5$ mas/d

- $\beta\cos\theta > 0.4c$
  $\therefore\ \theta \leq 66°$, and
  D < 11.2 kpc
- HII region, G4546+0.06
  $\Rightarrow$ D > 8.8 kpc
  $\therefore\ \theta \geq 62°$, and
  $v > 0.84c$

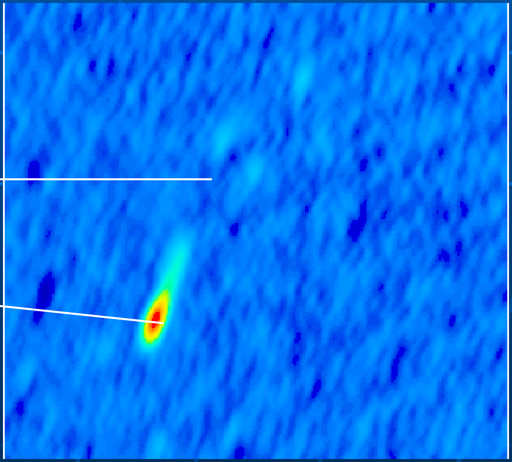
- $62° \leq \theta \leq 66°$
- $0.84c \leq v < 1.0c$

Cygnus X-1 – a radio jet in a persistent black hole XRB

VLBA 8.4 GHz
August 1998
-discovery of jet
in Cyg X-1 on
~15 mas scale
(Stirling et al 2001)

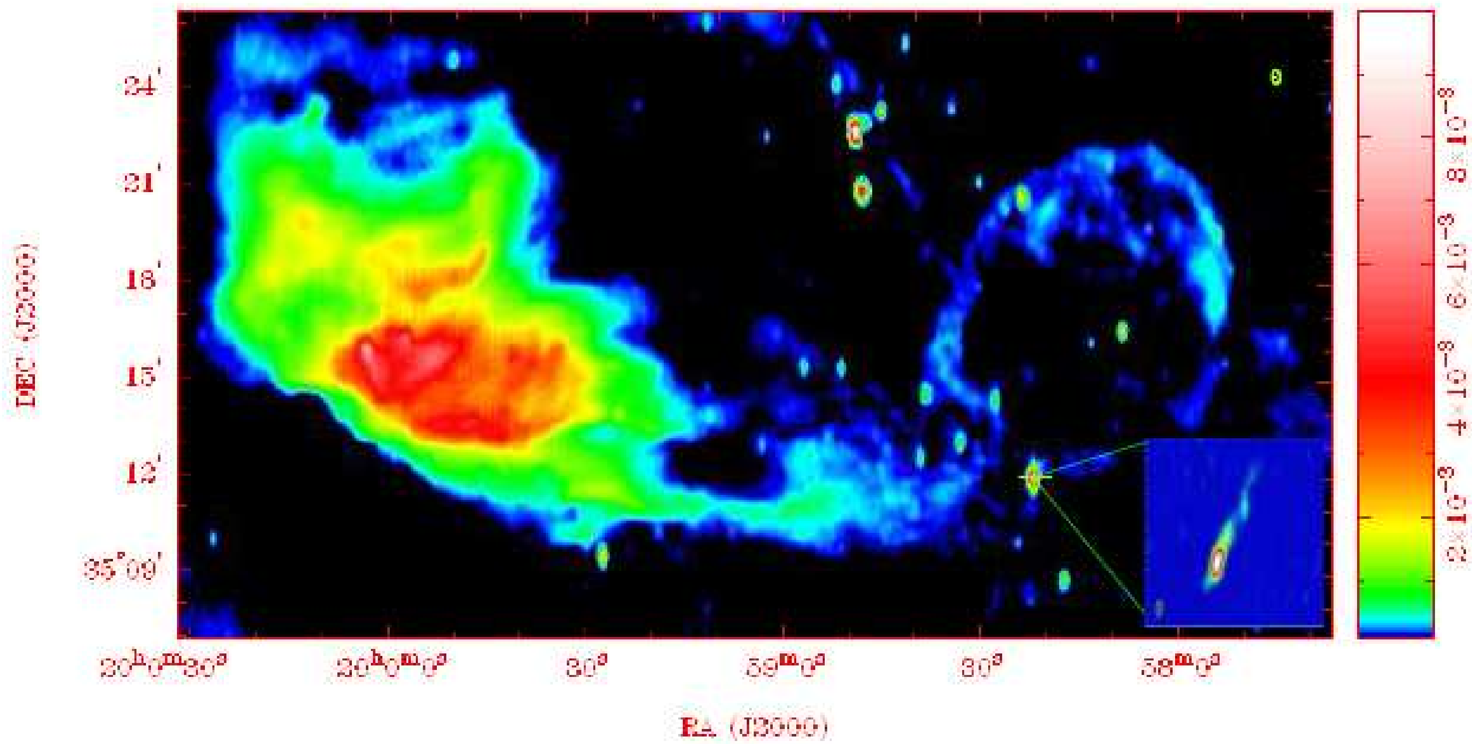


VLBA 15 GHz
Showing compact jet
~3 mas long



(in low/hard X-ray state)

Cygnus X-1 Bubble



(Russell, Fender et al. 2007)

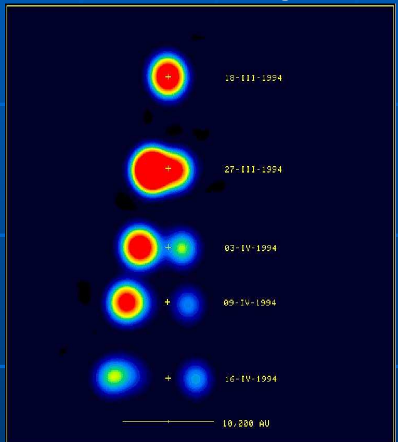
UNIVERSAL DISK-JET COUPLING IN BLACK HOLES

Fender et al. (2006); Corbel et al. (2006); J. Rodriguez et al. (2004-2009)

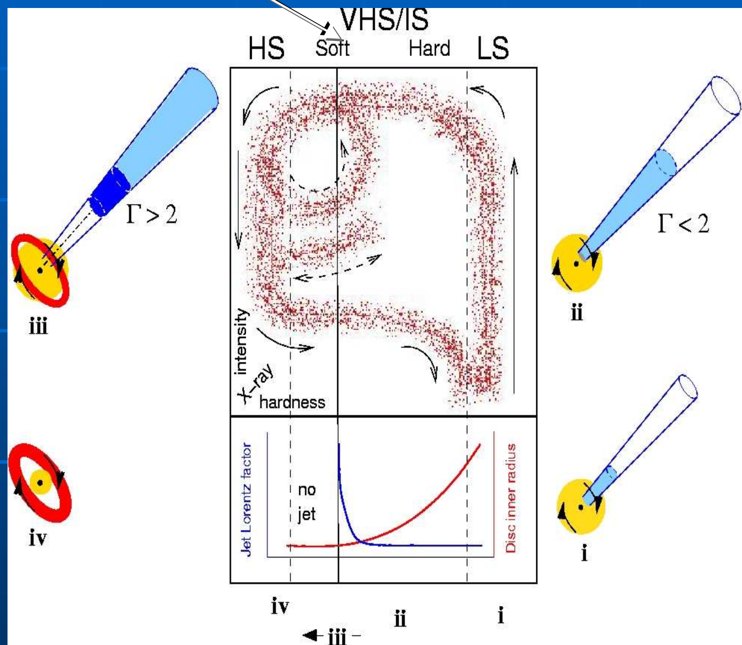
Outburst with rapid transition from hard to soft X-ray state

M., Chaty et al. (2005)

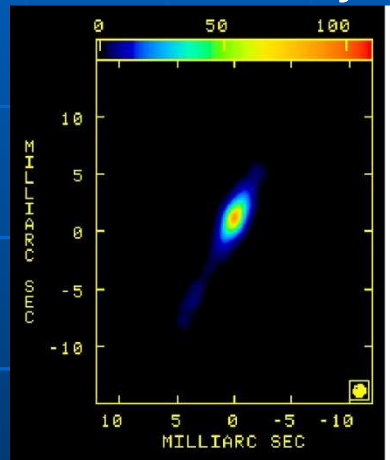
Soft X-rays



Transient, optically thin radio jets: Γ **> 2**

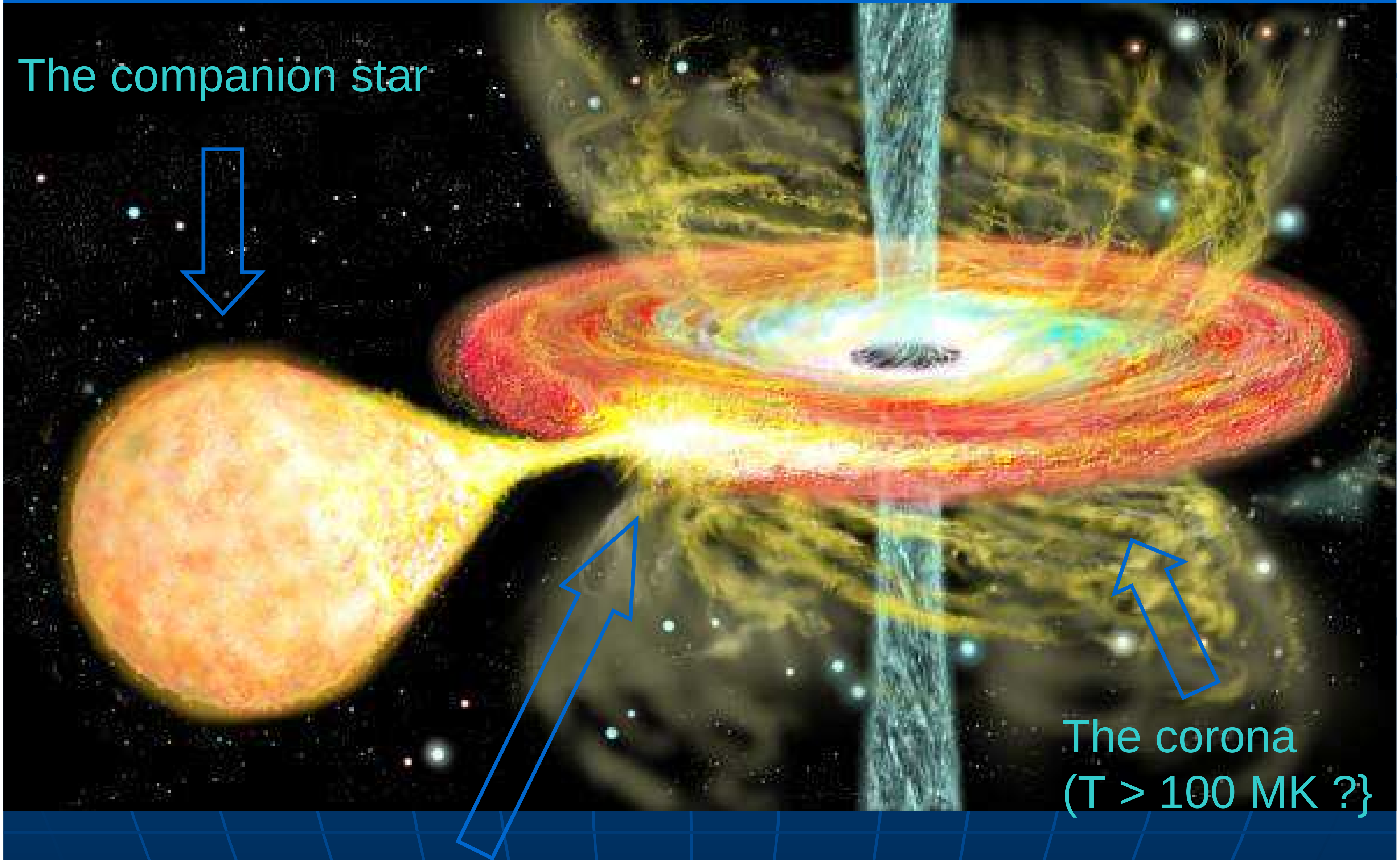


Low-hard X-rays



Persistent, flat spectrum radio source: $\Gamma < 2$

- Disk-jet coupling also observed in QSOs (Marscher et al Nature 2004)
- How are BH binary states related to AGN types ? (Köerding et al.)
- The transient radio jets produced by internal shocks (as in GRBs)

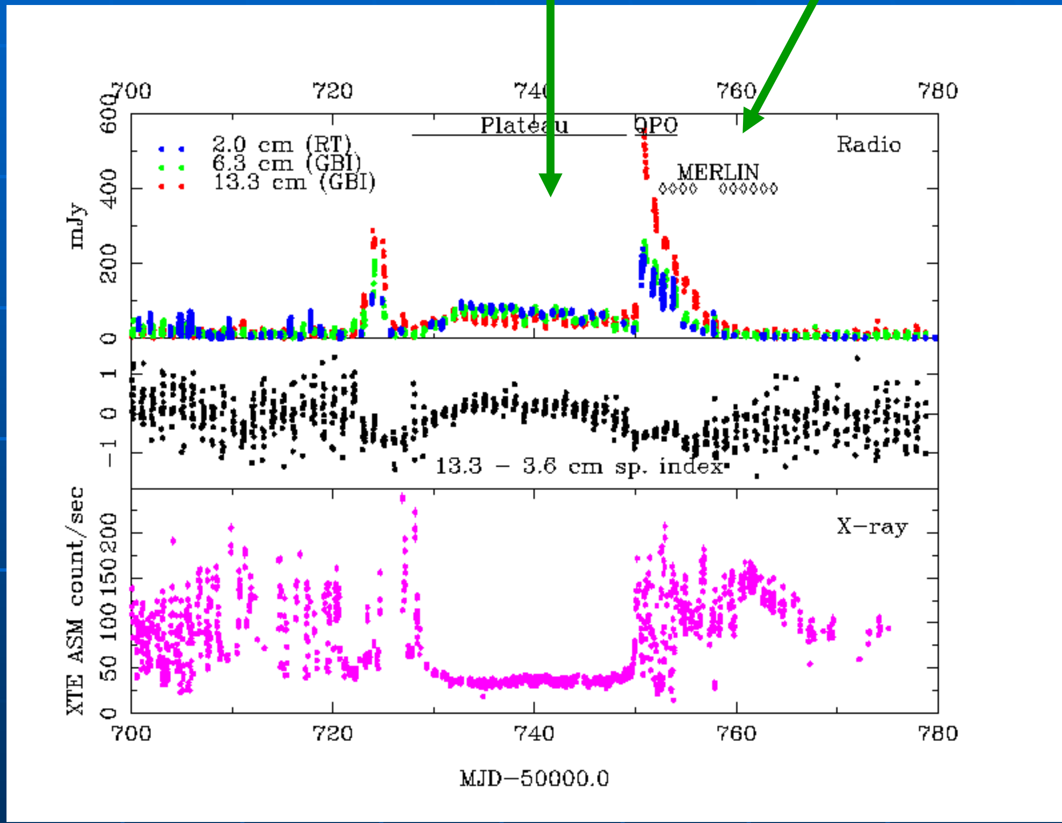

The companion star
The corona
(T > 100 MK ?}
The accretion disc
(1000 K < T < 10,000,000 K)
The jet
(v ~ c)

Jets and the X-ray state

- 1997 outburst on GRS1915+105
- Big flare and ejection followed plateau low/hard X-ray state
- Small, (50 au) VLBI scale weak jet present in plateau state

Merlin obs

VLBI mini-jet



Plateau state

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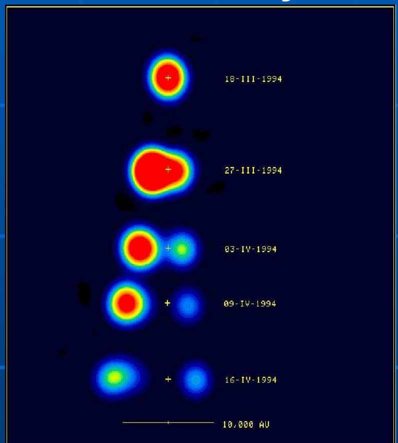
Soft X-rays



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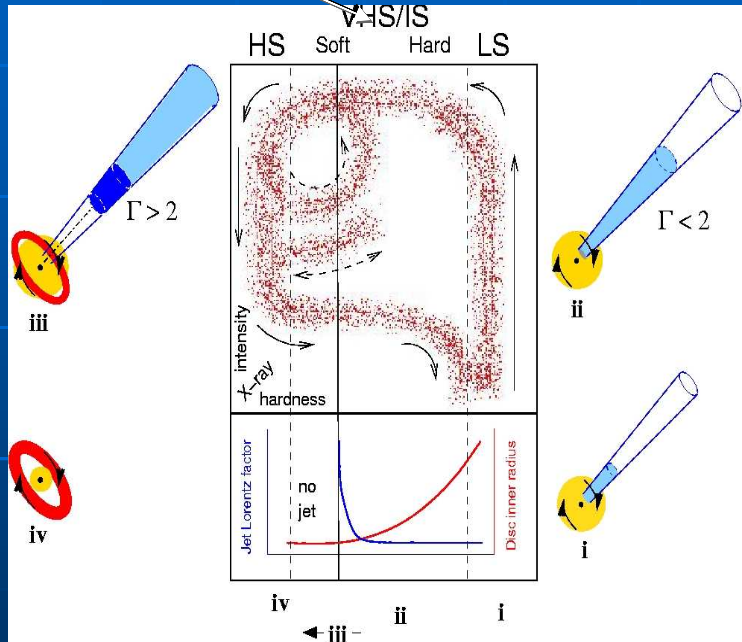
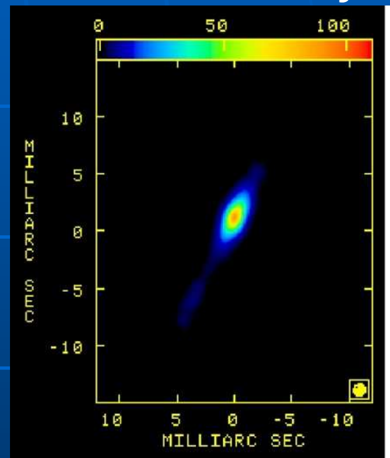


Low-hard X-rays



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The Fundamental Plane

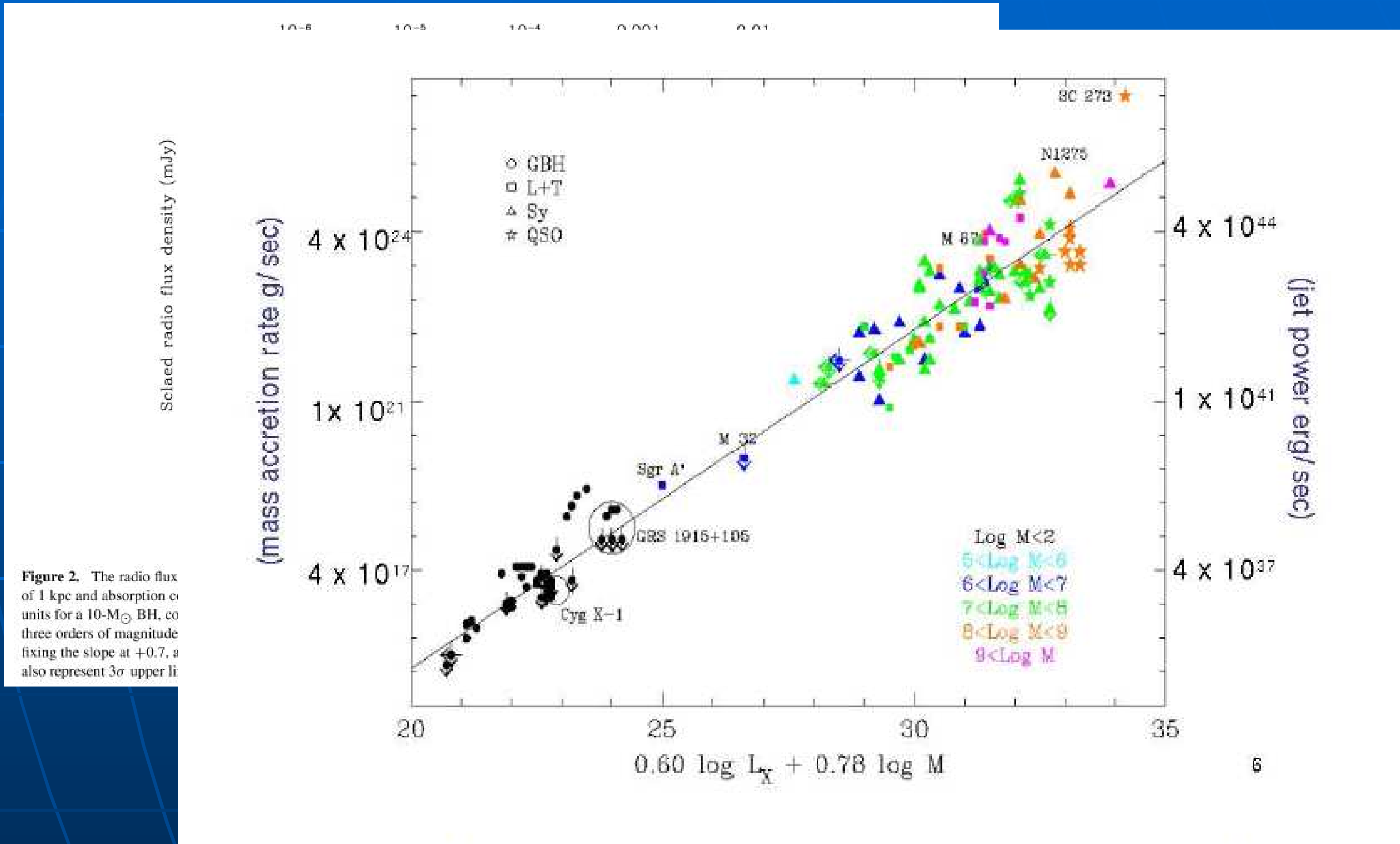


Figure 3: The 'calibrated' fundamental plane, where radio luminosity can be replaced by total jet power and/or mass accretion rate (see Fig 2), which are more physically useful numbers.

Spin: Power Generation

- Blandford and Znajek 1977: energy released from the accretion disk/black-hole system from BH spin: power in the jet is

$$P = 10^{35} \left(\frac{J}{J_{max}} \right)^2 \left(\frac{M}{M_{sun}} \right)^2 \left(\frac{B}{10^8} \right)^2$$

(In ergs/sec, J is spin of BH, B in gauss)

What's the value of B?

Typical jet luminosities suggest B~ 10^8 gauss or more

Equate pressure in the magnetic field

to the ram pressure of material in the ISCO

$$\frac{B^2}{8\pi} = \rho v^2 \text{ where v is the velocity } = \left(\frac{2GM}{r}\right)^{1/2}$$

Density given by the inflow through the disc

$$\rho = \frac{\dot{M}}{4\pi r^2 v}$$

But the X-ray luminosity depends on accretion rate Mdot

$$L_x = \dot{M}c^2 \left(\frac{r_g}{r}\right)$$

where r_g is the gravitational radius and r the ISCO radius

Gives:

$$P = 4 \times 10^{35} \left(\frac{J}{J_{\max}}\right)^2 \left(\frac{r}{r_g}\right)^{-1.5} \left(\frac{L_x}{10^{38}}\right)$$

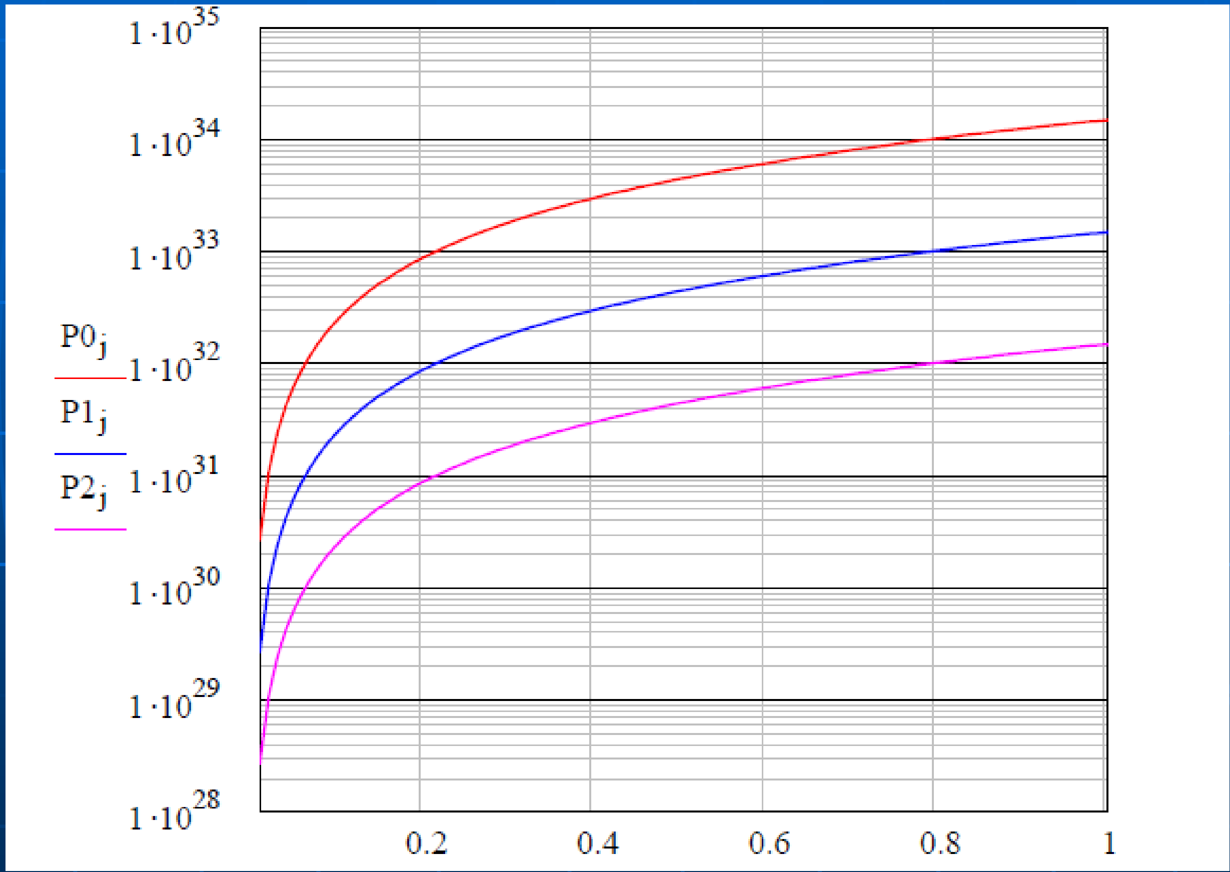
The data: (Jet power from radio synchrotron minimum energy and length of jet, Lx from X-ray counts)

Name	Type	D kpc	beta	tjet secs	E ergs	Gamma	Overall gamma x L	S X max	L X max
A0620-00	L	1.2	0.9	2.60E+06	1.30E+41	2.30E+00	1.15E+35	50000	1.87E+38
J1655-40	L	3.2	0.92	1.70E+06	3.00E+42	2.60E+00	4.68E+36	1600	4.26E+37
GX339-4	L	8	0.5	9.30E+06	3.50E+41	1.16E+00	4.41E+34	899	1.5E+38
1E1740.7-2942	L	8.5	0.5	7.90E+08	2.00E+43	1.16E+00	2.90E+34	30	5.64E+36
GRS1758-258	L	8.5	0.5	7.90E+08	4.70E+44	1.16E+00	6.84E+35	20	3.76E+36
LS5039	H	3.2	0.5	6.00E+04	3.70E+39	1.16E+00	4.41E+35	0.3	7.99E+33
SS433	H	4.9	0.26	1.90E+07	5.60E+43	1.04E+00	2.70E+34	10	6.24E+35
GRS1915+105	L	11	0.9	7.10E+06	3.00E+43	2.30E+00	9.66E+36	300	9.44E+37
Cygnus X-1	H	2.1	0.9	1.40E+04	9.00E+38	2.30E+00	1.47E+35	1320	1.51E+37
Cygnus X-3	H	10	0.6	5.80E+06	1.00E+43	1.25E+00	2.13E+36	430	1.12E+38

Counter-rotating BH

Jet Luminosity

Lx:
10^{38} -
10^{37} -
10^{36} -
ergs/sec

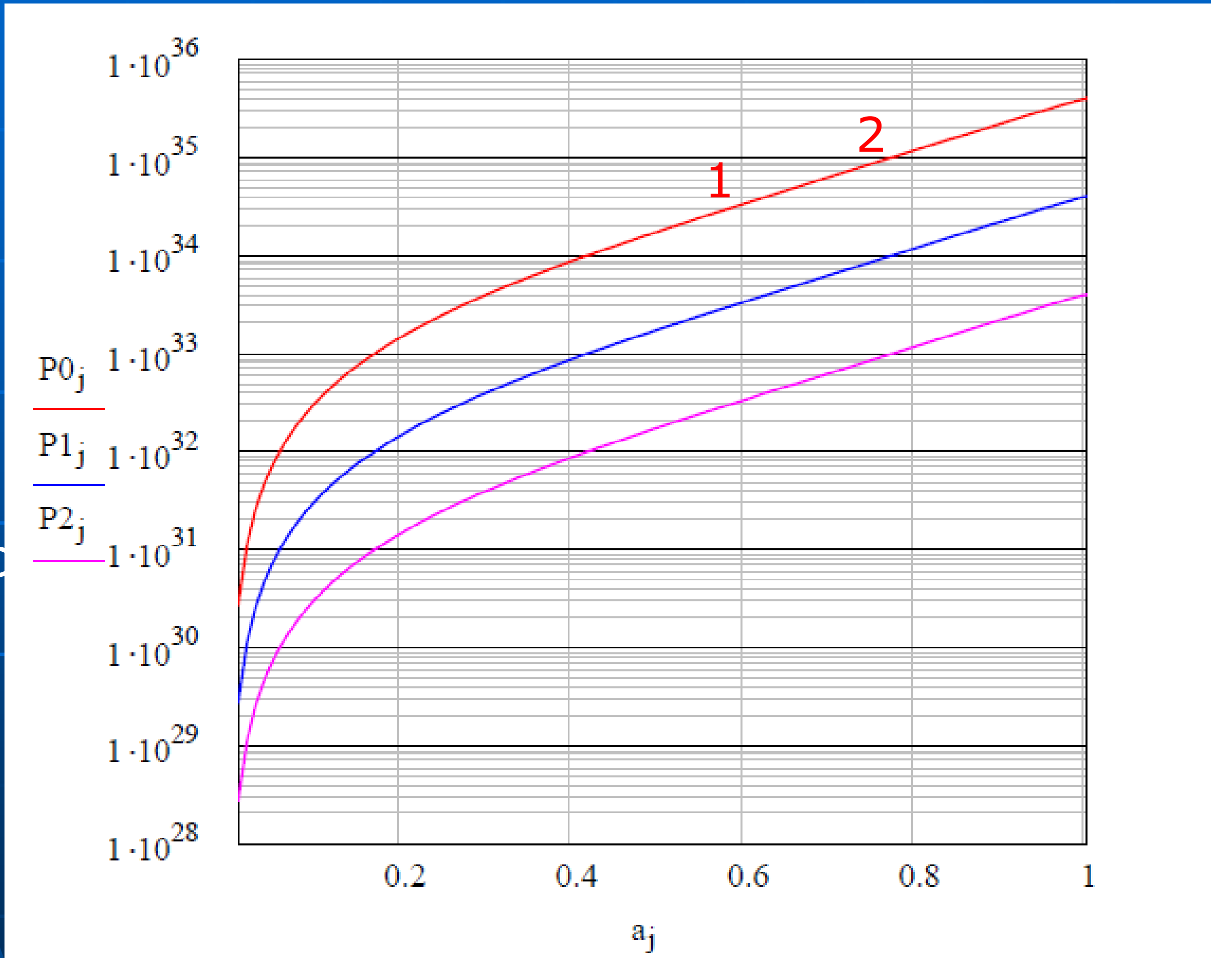


Spin Parameter

Co-rotating:

Jet Lum.

10^{38}
10^{37}
10^{36}
ergs/sec



1 GX339-4

2 A0620-00

Rest are off the chart !

Spin parameter J/Jmax

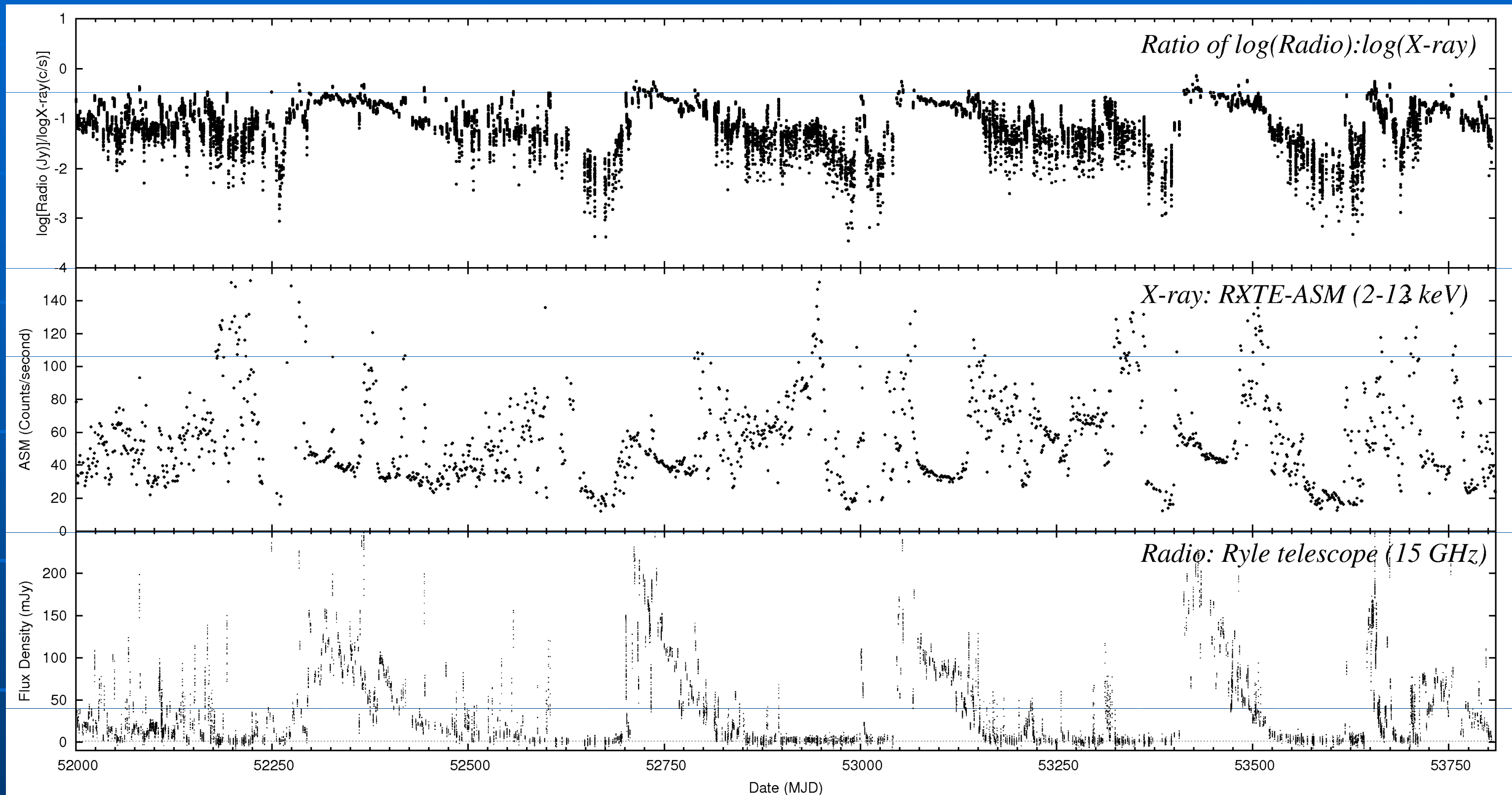
GRS1915+105

Log(radio)

Log(X-ray(

X-ray ASM

15 GHz
Radio



1999 2005

Rushton et al 2010 A&A in press.

GRS1915

- 3 phases:
  - Quenching X: 20 c/s R: < 5 mJy
  - Plateau X:50-40 c/s   R: 150-50 mJy
  - Flaring X: 40-100 c/s R: 40-100 mJy

- Still off the chart!

Conclusions

- My rubbish theory!
  - doesn't fit the mass dependence
  - not efficient enough – radio power in the jet sometimes > X-ray luminosity – is spin all there is?
  - simulations by McKinney and others more relevant!
- Are there other jet formation mechanisms?
- How does the material get accelerated Why is the velocity in SS433 so constant (0.26c)?
- How does the jet formation process impact on the accretion disk in detail?
- Where are the intermediate mass objects – ULX's – do they have jets?

Acknowledgements

- Felix Mirabel for some slides
- Zsolt, Rob, Guy, Al, Tasso, Tom, Vivek, MERLIN team, etc.


Questions ?