MERLIN

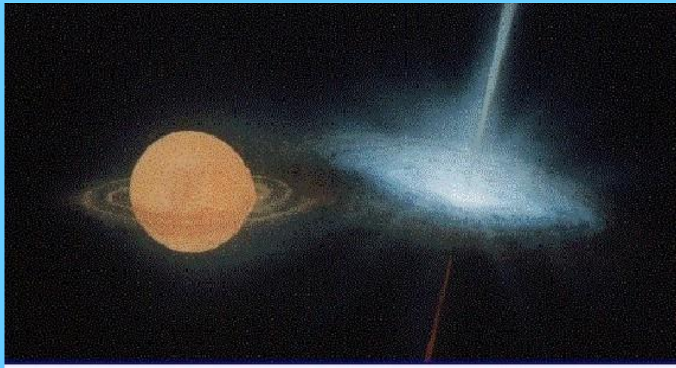
THE UNIVERSITY of MANCHESTER

Microquasars 3

R. E. Spencer

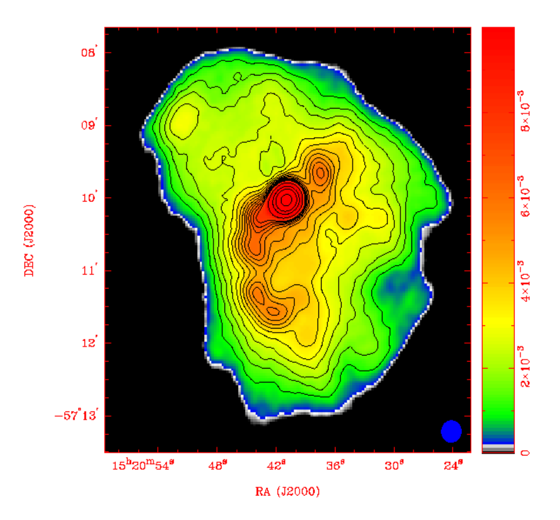
Frontiers in Astrophysics

Nov 2003

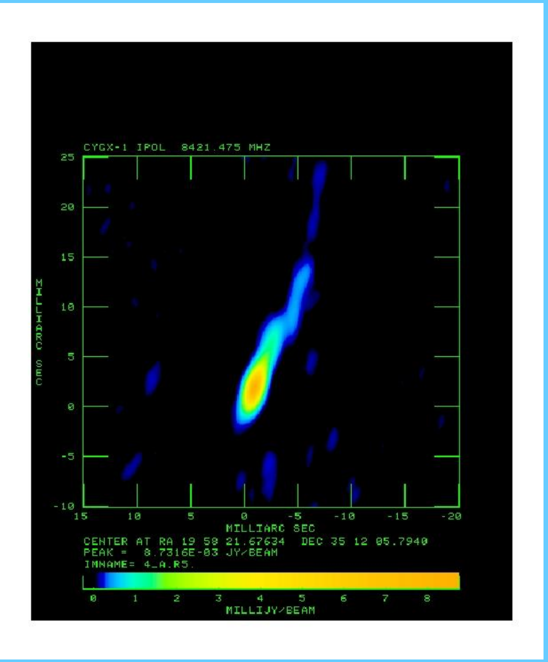


Lecture 3- some examples

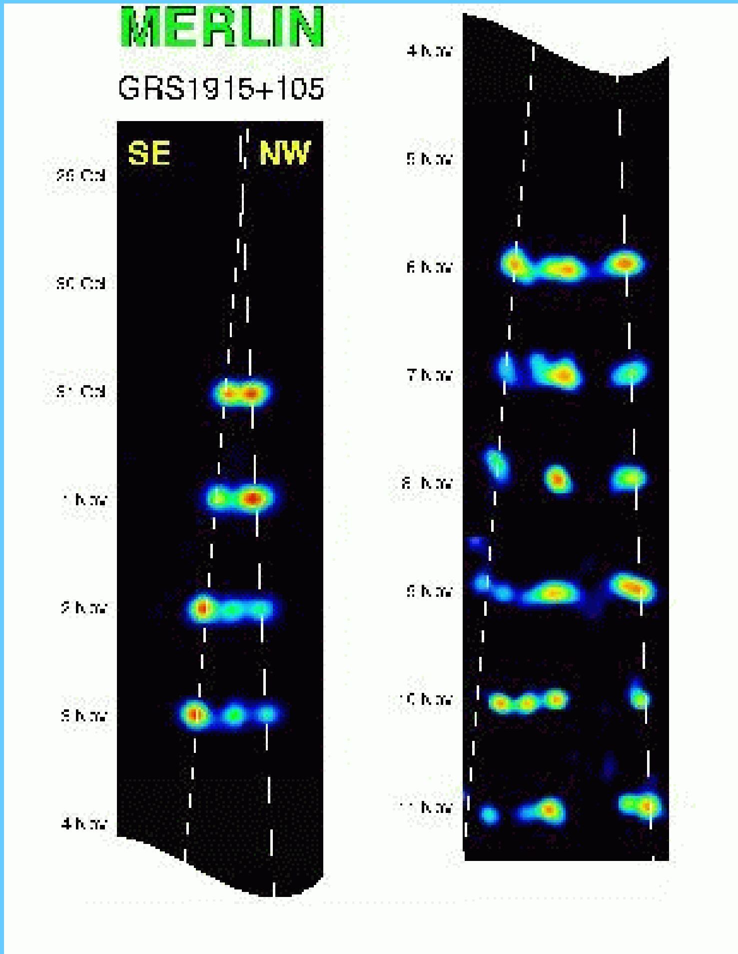
Circinus X-1
Cygnus X-1
GRS1915+015



Circinus X-1 Nebula

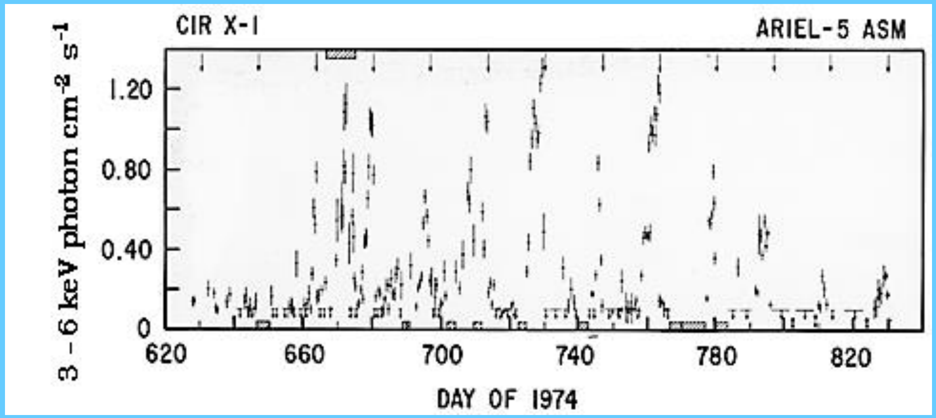


Cygnus X-1 4cm radio

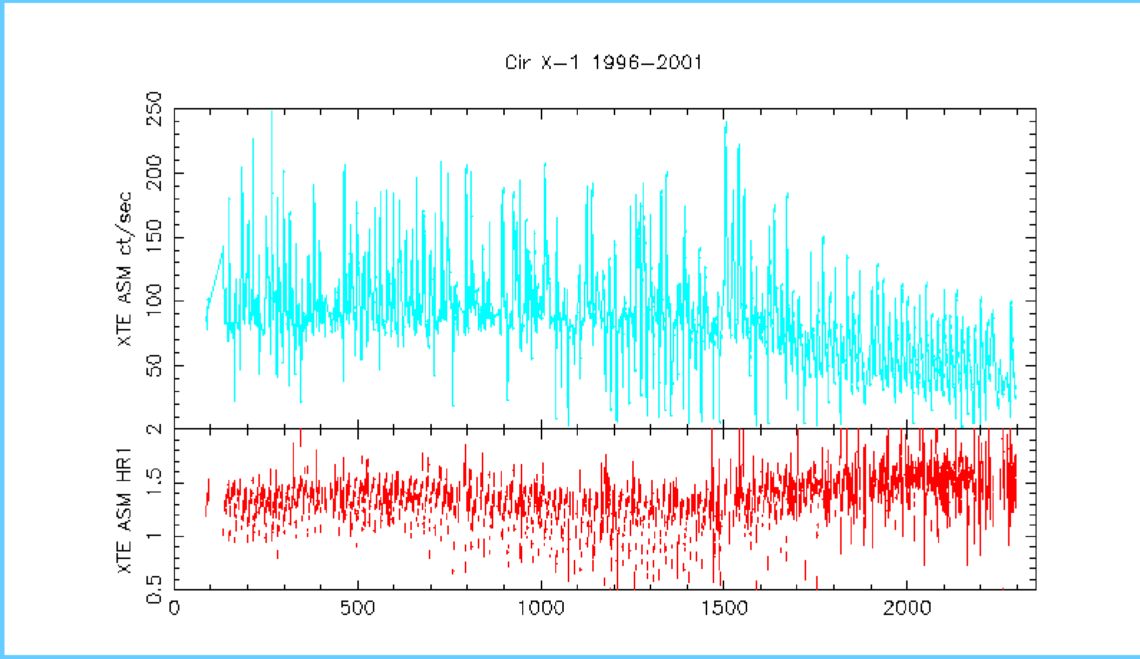


Circinus X-1

- Highly variable X-ray binary, period 16.6 d at dec –57º –studied by in the radio by ATCA in Australia
- Intense radio flares (~1 Jy) in 1970’s and changes in X-ray emission as stars approach periastron.
- RXTE shows evolving X-ray states :-

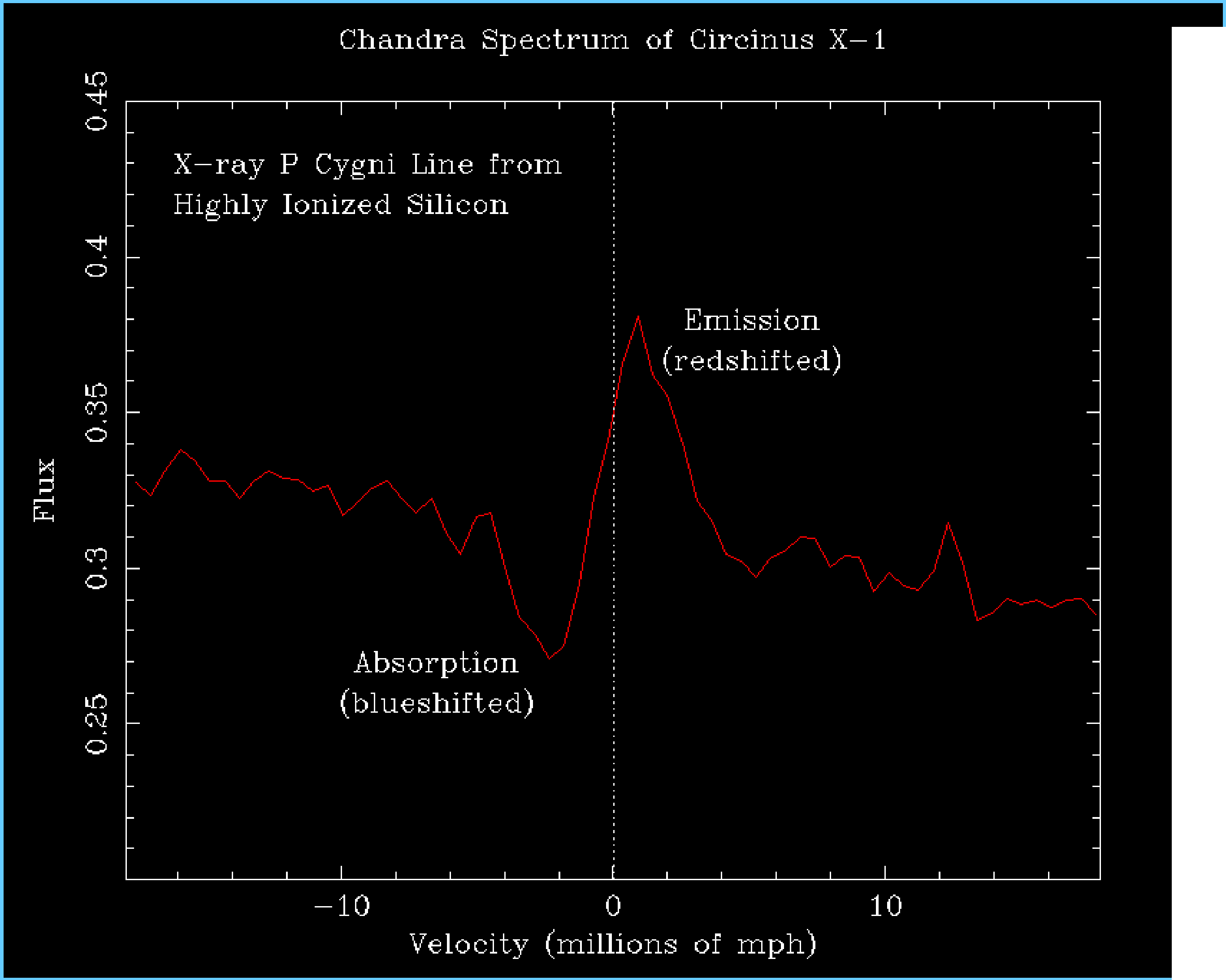


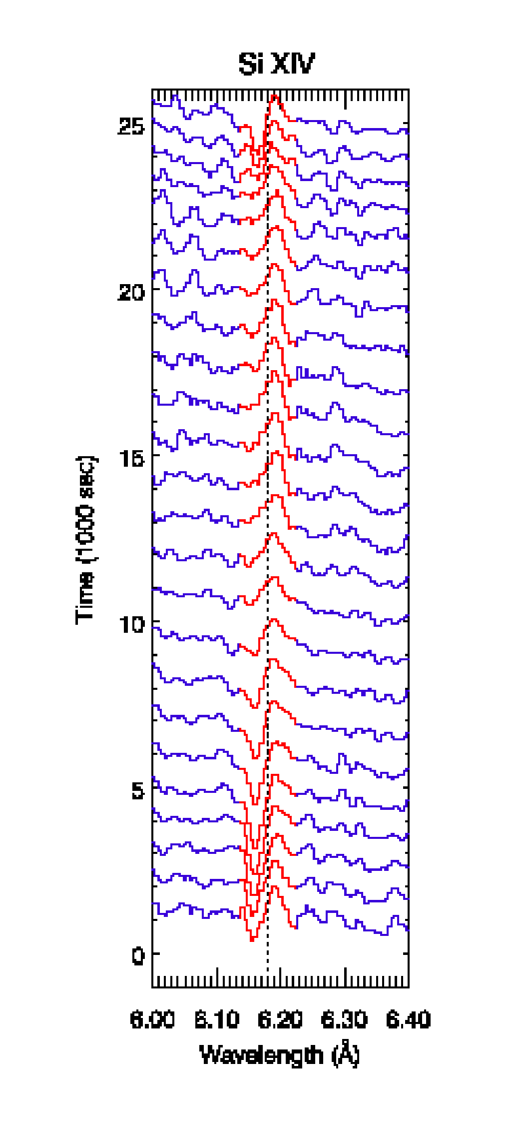
Type I bursts in 1970’s indicate neutron star



Now evolving to a low-hard X-ray state

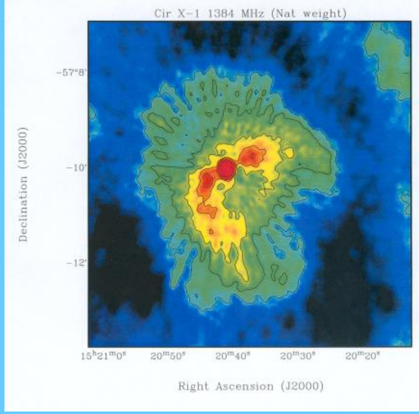
P-Cygni profile in Circ X-1





Chandra obs. show a hot wind at 2000 km/sec

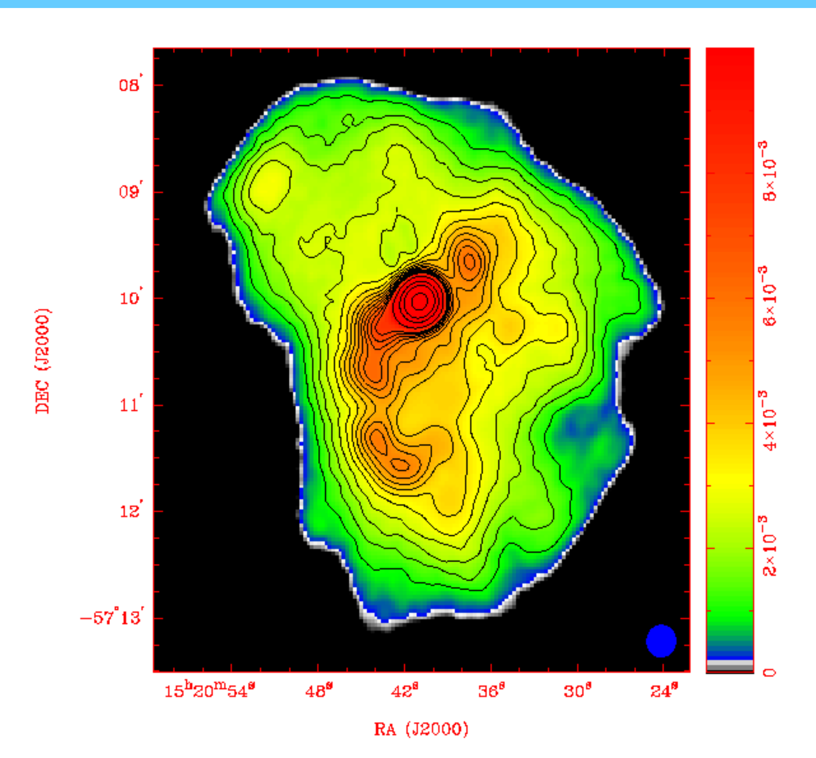
Circ X-1 Nebula.



- 21 cm HI absorption indicates distance of 8 kpc, reassessed to be ~6.5 kpc
- Close to the centre of a large diffuse radio nebula, outside of a possibly associated supernova remnant G 321.9-0.3 – moving at 500 km/sec if 10^5 yrs old
- Newly discovered wind from the X-ray source may drive the nebula?
- Extended radio jets emerge from a compact object and curl round after ~35 arc sec as though deflected by motion through the ISM
- Nebula and jets emitting by synchrotron radiation (since polarised)

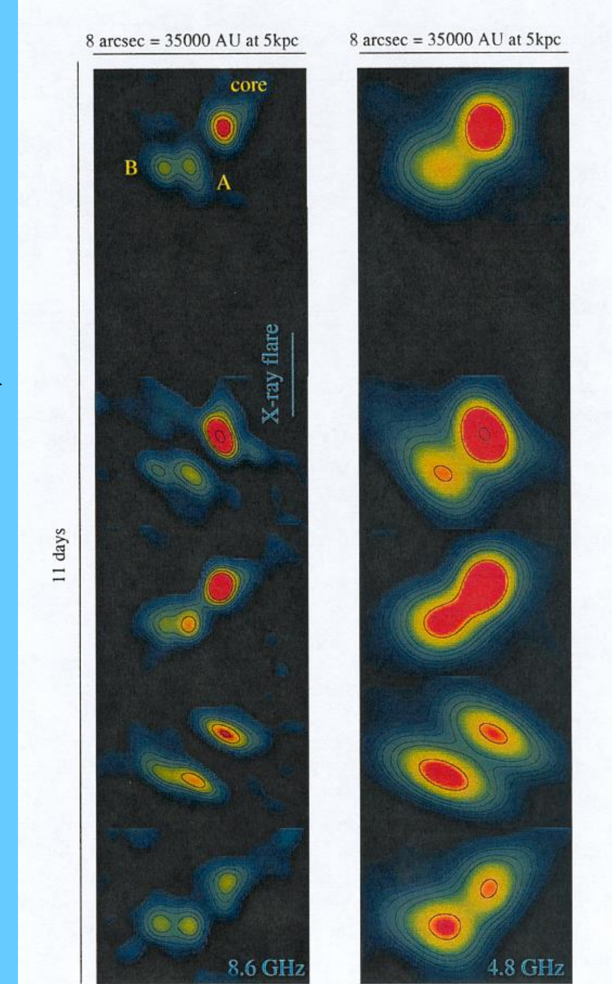
Circ X-1 Nebula, Jets and Compact Radio Source

ATCA Observations 2000-2001



Low resolution image of the nebula at 1.4 GHz, 300x larger than the compact core on the right

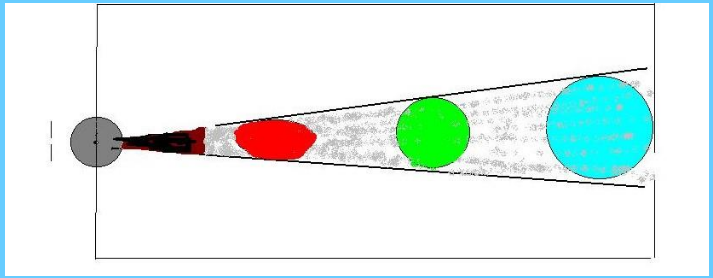
X-ray flare



Radio Observations over 11 days in October 01, Core brightens then within 4 days the extended emission also brightens. Higher resolution observations at 8.4 GHz (L) show that the knots brighten in order of distance from the core. The apparent velocity is >20c

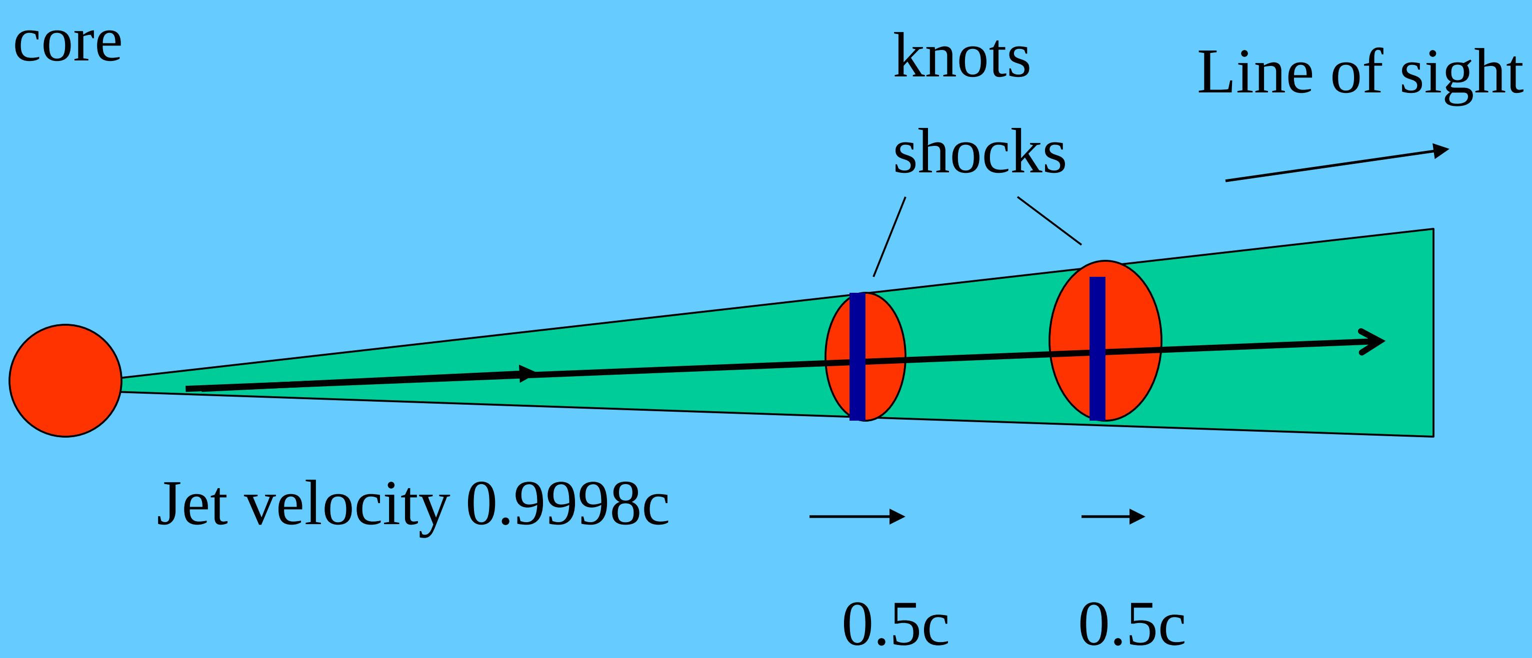
Circ X-1 compact source

- Radio flux decreased since discovery – < 50 mJy in last 10 yrs
- 8 mJy compact source in centre found in 1995 with ATCA, <1 arc sec in size
- Further observations in 1998 showed a slightly extended ~2 arc sec jet on one side of the core, brightness ratio suggested v>0.1c
- Recent observations (2001) show mildly relativistic ejection of radio knots in a jet
- But knots brighten ~day or so after the core – suggesting energy transport from core at a speed close to c – with $\beta\Gamma > 20$, so b>0.9998c



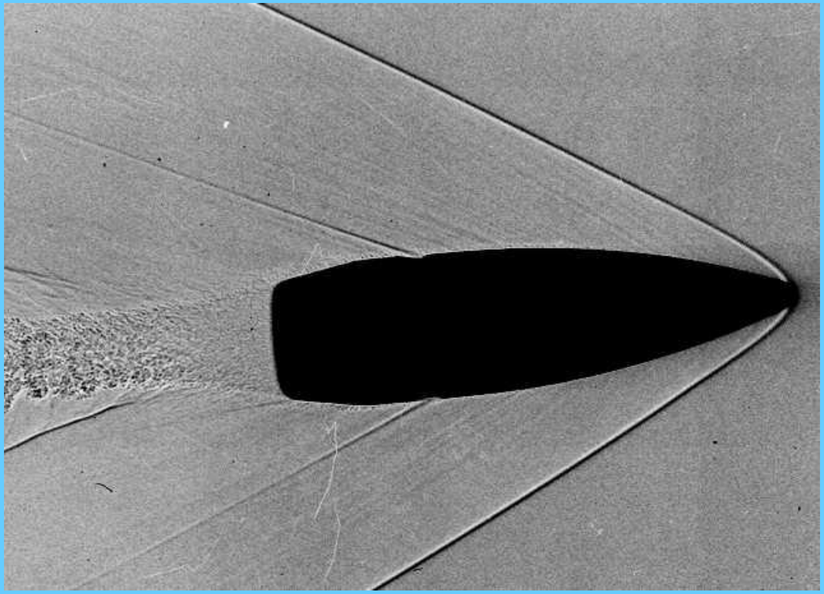
Circ X-1 jet

Simple jet model:-

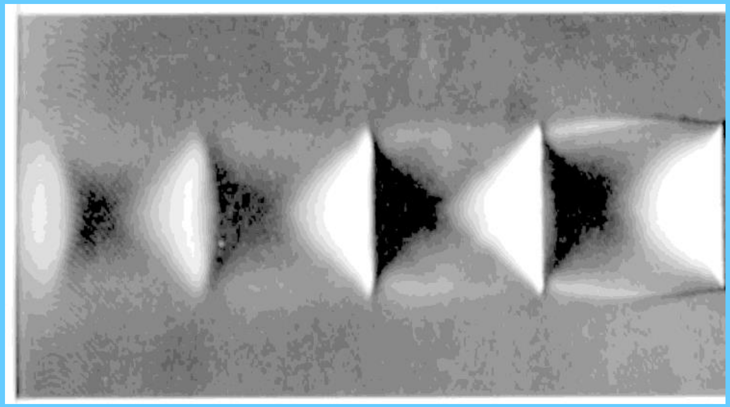


Shocks or Bullets

- Are the radio blobs we see discrete clouds, like bullets, moving through the ISM?



•Or are they shocks in a continuous jet?



Are they triggered by an explosive event in the inner disk?

- Instability in the accretion process?
- Magnetic switch – winding up of magnetic field by the differential rotation of the neutron star or black hole results in an explosive release of energy (Meier et al., 1997, Nature, 388, 350)

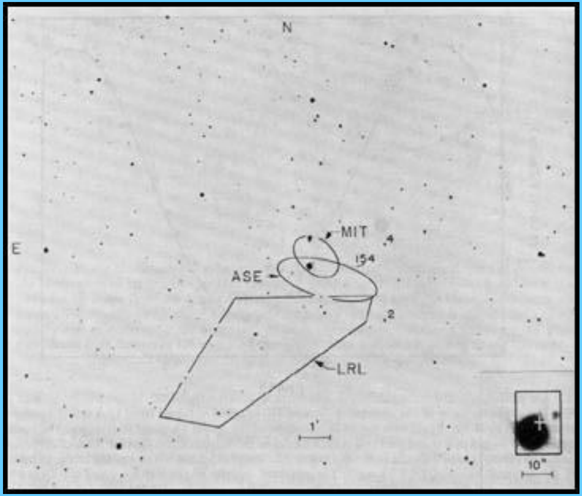
Or do shocks result from a small change in the velocity of a continuous, relativistic jet?

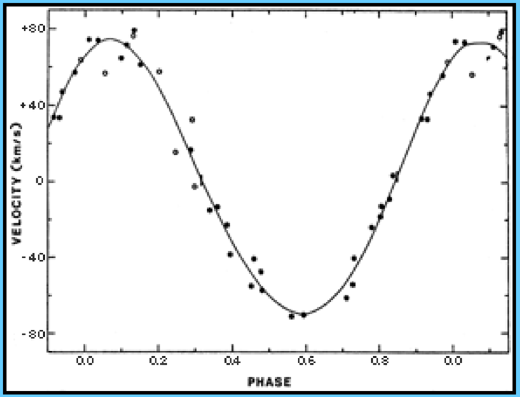
Discrete blobs or Jets?

- Yes!
- We have both.
- Cyg X-1 has a continuous jet
- GRS 1915+105 has a small scale mini-jet ~ same size as that in Cyg X-1 (~30-50 au)
- And has ejection of discrete blobs in flare events.

Cygnus X-1

- First persistent radio emitting X-ray binary to be discovered (Braes ad Miley 1971)
- Primary identified with star HDE226868
- 5.6 d orbit – gives *v* sin(i)
- Inclination i~37^{o}
- 20-33 Ms for primary (O9.7 Iab) and 7-16 Ms for companion. A neutron star above ~3 Ms must collapse to a black hole.





$$\frac{(m_2)^3 \sin^3 i}{(m_1 + m_2)^2} = \frac{(v_1)^3 P}{2\pi G}$$

	Cygnus X1	HDE 226868
Brucato-Kristian	$M_2/M_0 > 5.5$	$M_1/M_0 \sim 22$
Hutchings *et al.*	$10 \le M_2/M_0 \le 18$	$16 \le M_1/M_0 \le 23$
Sunyaev *et al.*	$7.8 \le M_2/M_0 \le 17$	$10 \le M_1/M_0 \le 22$
Bolton	$10 \le M_2/M_0 \le 20$	$25 \le M_1/M_0 \le 35$

Cyg X-1

- Radio emission

vlbi

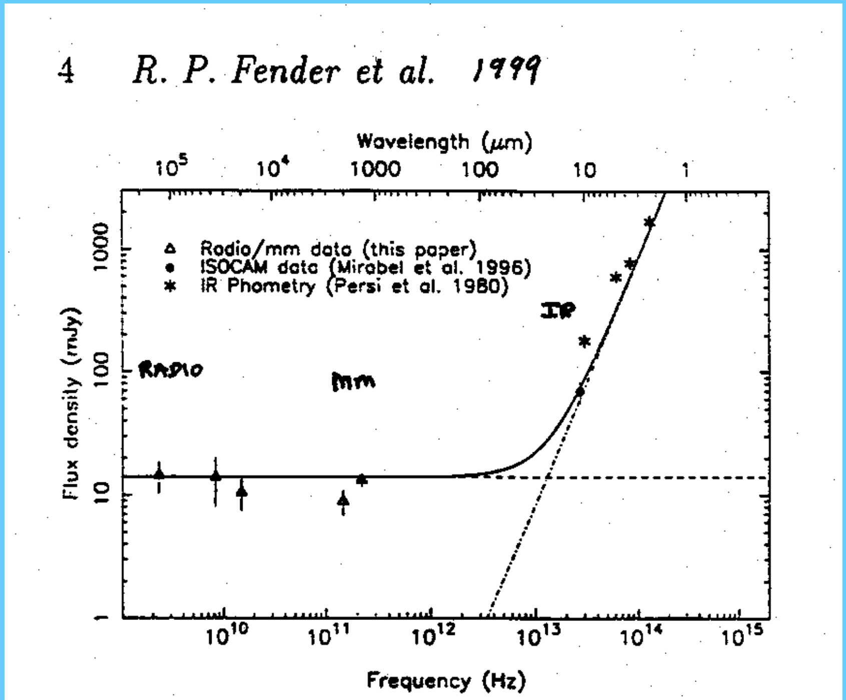


Figure 3. The broadband spectrum of Cyg X-1 from radio to optical wavelengths, combining our radio/mm data with the ISO-CAM observations of Mirabel et al (1996) and ground-based photometry of Persi et al. (1980). It is clear that even without a high-frequency cut-off the flat spectral component will be dominated by the thermal emission from the OB supergiant at wavelengths of 30μm or shorter.

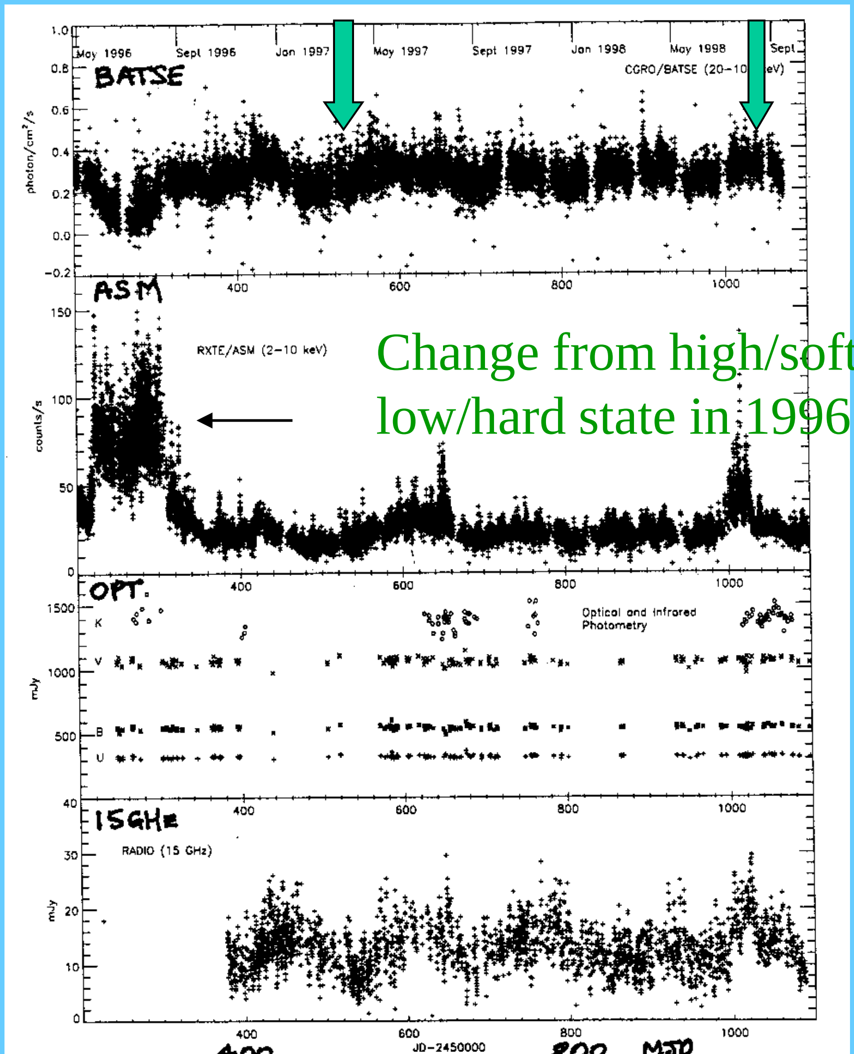


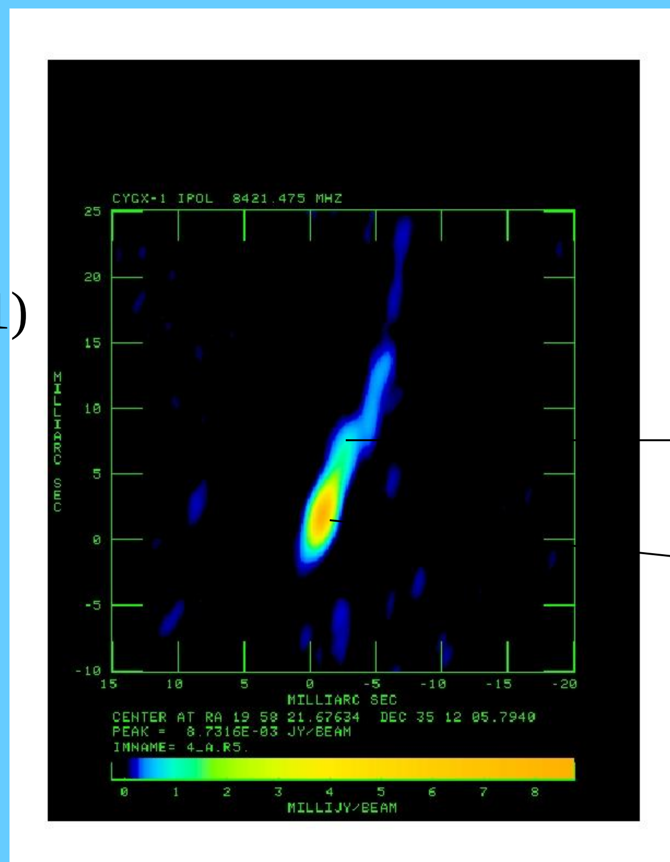
Figure 1. BATSE, ASM, optical, infrared and radio light curves for the full 2.5 years of our observations (MJD 50200–51100).

Change from high/soft to low/hard state in 1996

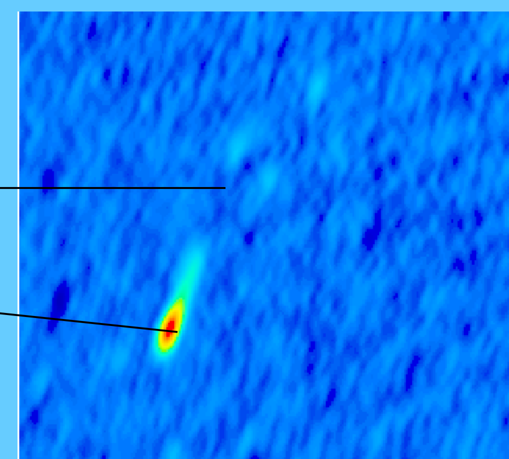
-a very flat radio spectrum out to >300 GHz, 5.6 d binary period seen in 15 GHz radio.

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)

Doppler boosted jet?

- 15 mas = 30 au long jet
- > 64 to 1 brightness ratio for approaching/receding jet.
- If α=0 gives $\beta \, cos(\theta)$=0.6
- Inclination 37^{o} gives β=0.78, γ=1.59, β(apparent) = 1.25.

4 A. M. Stirling et al.

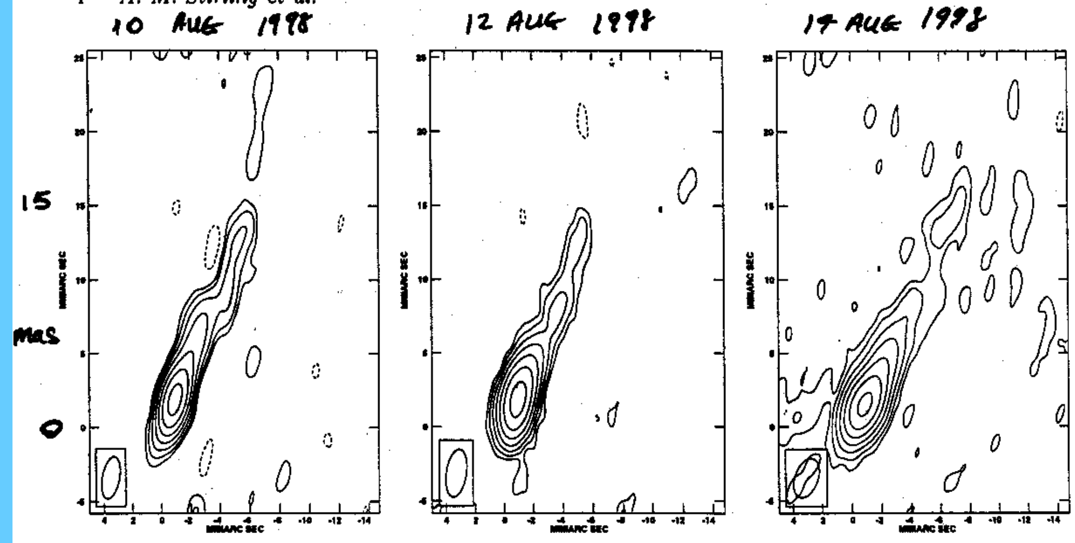


Figure 2. VLBA and phased VLA images of Cygnus X-1 from August, 1998, at 8 GHz; lowest contour 0.1 mJy. Epoch A is on the left with peak flux density 8.7 mJy/beam and convolved with a Gaussian beam 2.88 × 1.19 mas in PA=-10.9, epoch B in the middle with peak flux density 9.0 mJy/beam and convolved with a Gaussian beam 3.24 × 1.37 mas in PA=-20.5 and epoch C on the right with peak flux density 7.7 mJy/beam and convolved with a Gaussian beam 2.76 × 1.56 mas in PA=-20.5.

- At d=2.kpc this gives an expected 110 mas per day proper motion in the jet
- But jet appears smooth – smeared in the ~8 hr long observations, or instrinsically one sided?
- New VLBA observations in 2001 being analysed to try to answer this

GRS 1915+105

40 min state transitions in X-rays

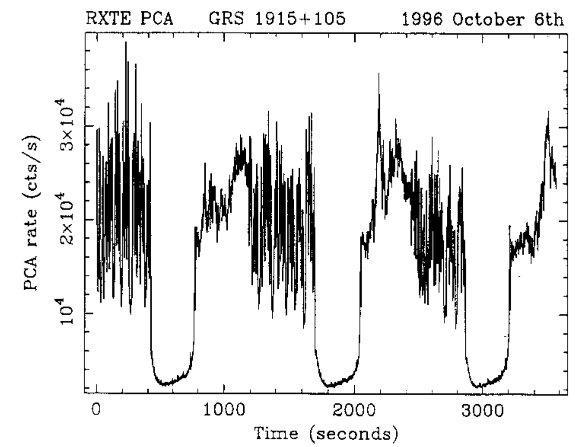
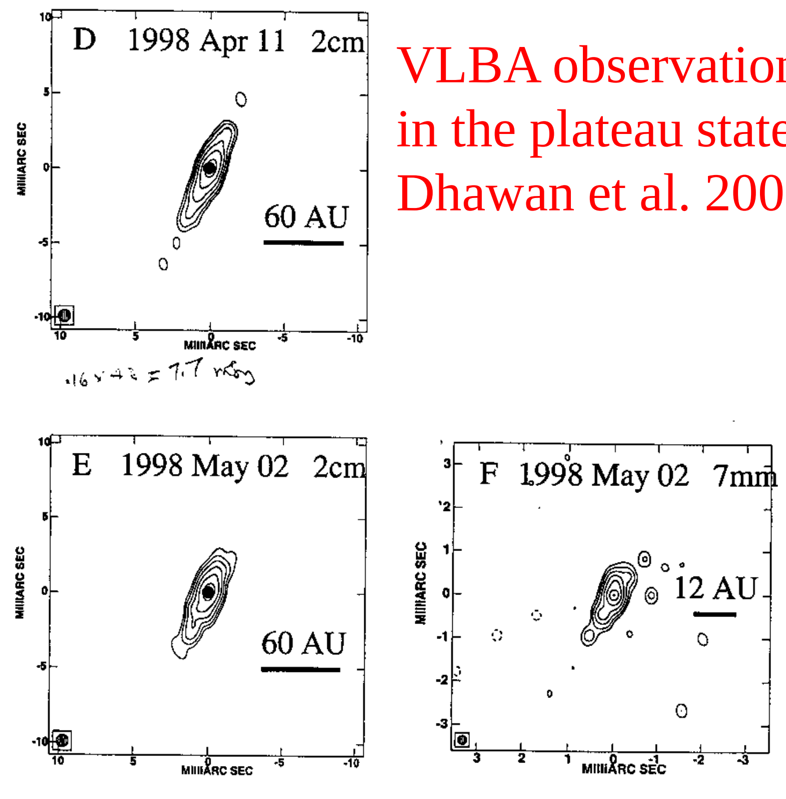


Fig. 6. X-ray light curve of GRS 1915+105 observed with the Rossi XTE on October 6, 1996 (from Belloni et al. 1997).

- Discovered by the WATCH all sky X-ray camera on the GRANAT Russian satellite in 1992
- Bright X-ray flaring up to 10^{32} W, radio and IR flares.
- Complicated X-ray behaviour arising from 3 basic states and relating to radio Persistent radio jet when in low/hard state, radio flaring after plateau state in X-rays/radio



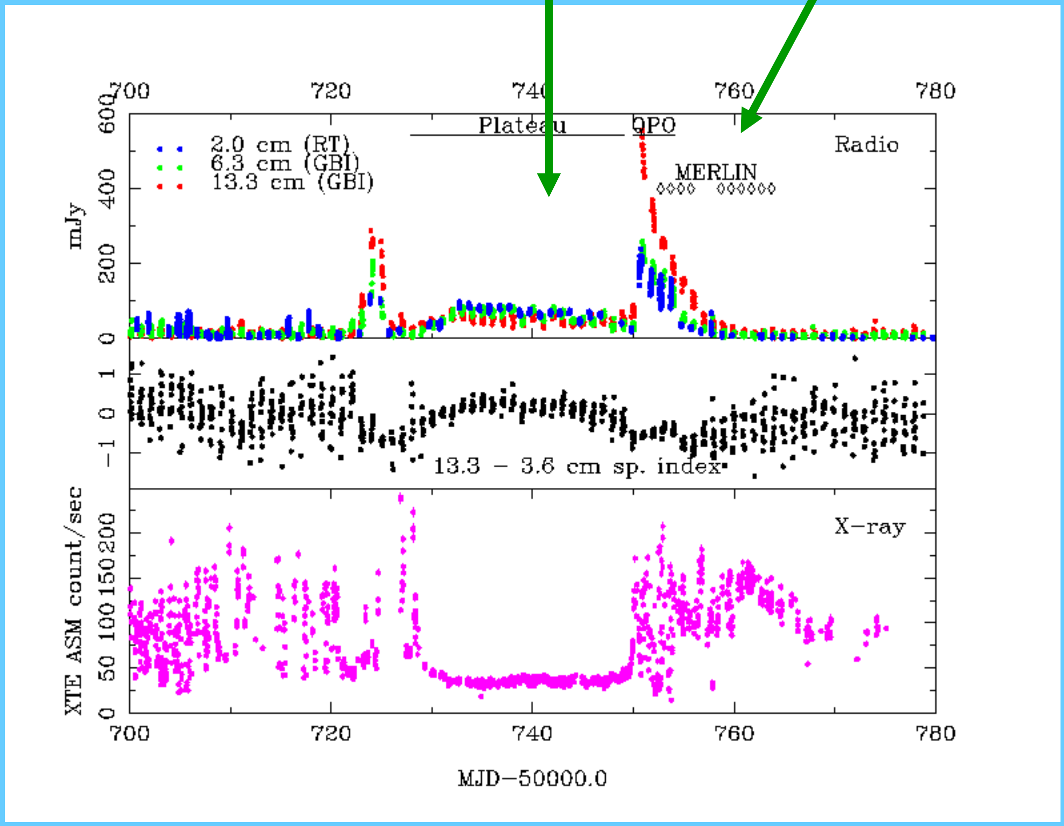
VLBA observations in the plateau state, Dhawan et al. 2000

GRS 1915+105 Radio Flaring

- Monitored at 15 GHz with Ryle telescope and with RXTE
- Outburst in Oct 1997 followed with MERLIN
- VLBI observations also taken during plateau state – mini-jet present

Merlin obs

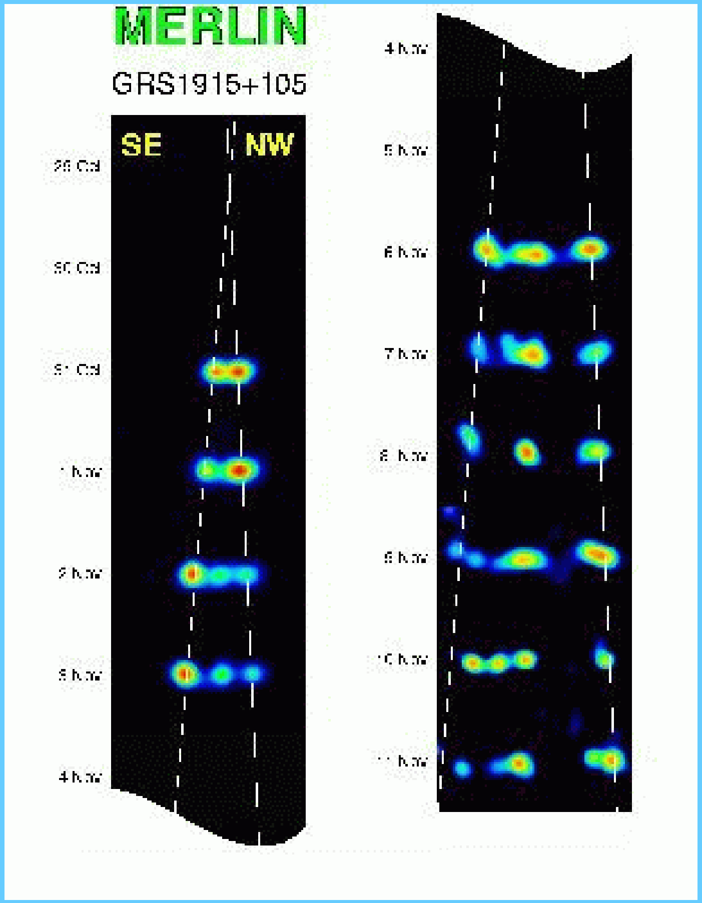
VLBI mini-jet



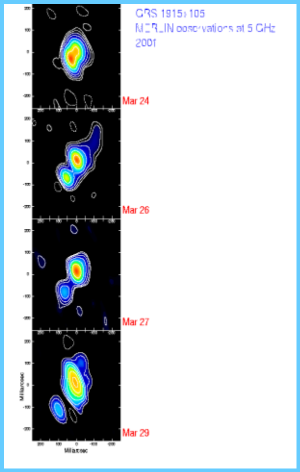
Plateau state

GRS1915+105 – blob ejection!

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

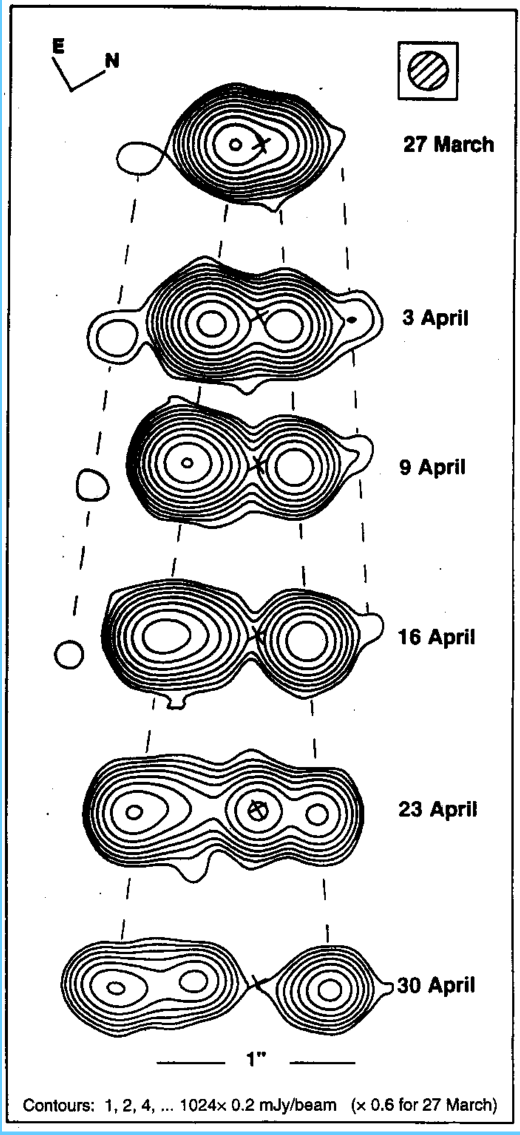


And again
In March
2001
(plus
another 7
Epochs)



NB the images have been rotated in the above

1994 and 1997 results compared

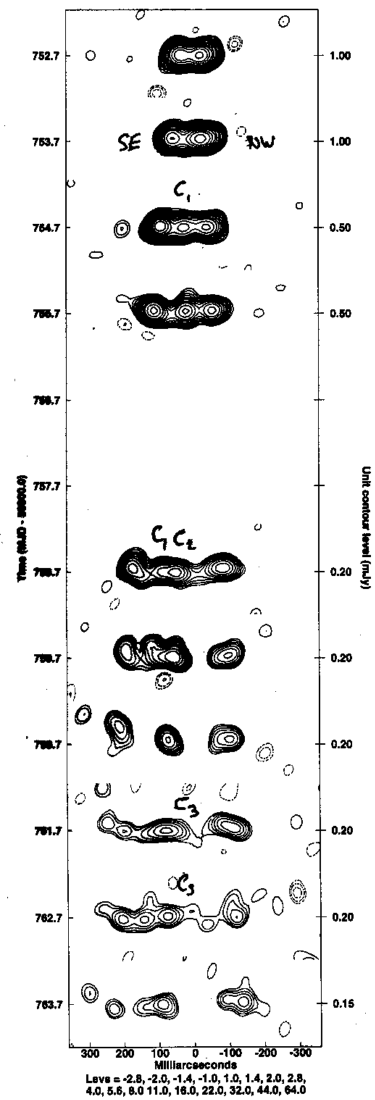


1994

- *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 ± 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

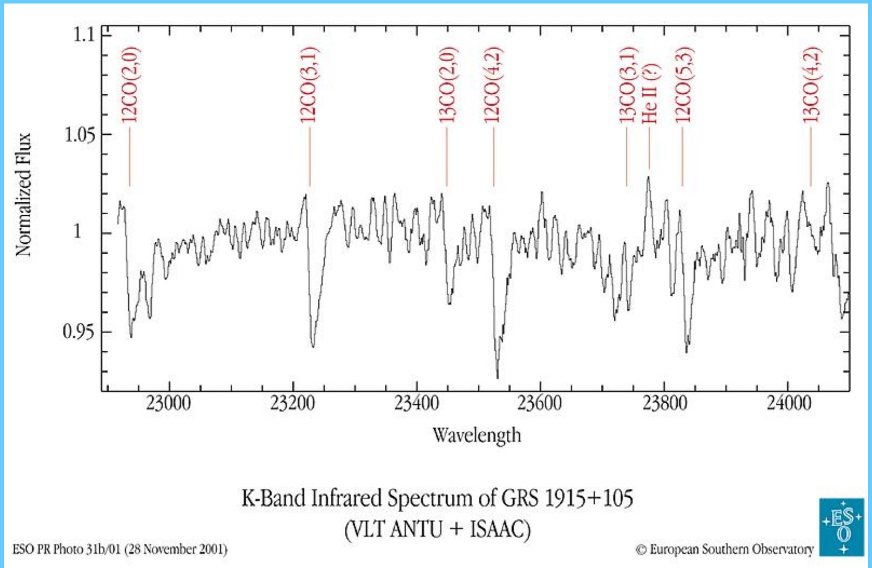
- Component velocities
  (2c) $\mu_{app} = 23.6 \pm 0.5$ mas/d
  (c) $\mu_{rec} = 10.0 \pm 0.5$ mas/d

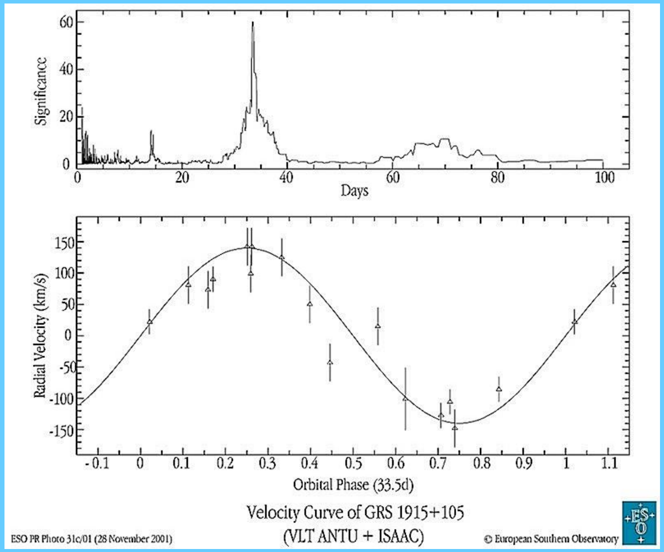
- $\beta\cos\theta > 0.4c$
  $\therefore\ \theta \le 66°$, and
  D < 11.2 kpc
- HII region, G4546+0.06
  $\Rightarrow$ D > 8.8 kpc
  $\therefore\ \theta \ge 62°$, and
  v > 0.84c

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

Optical ID Found!

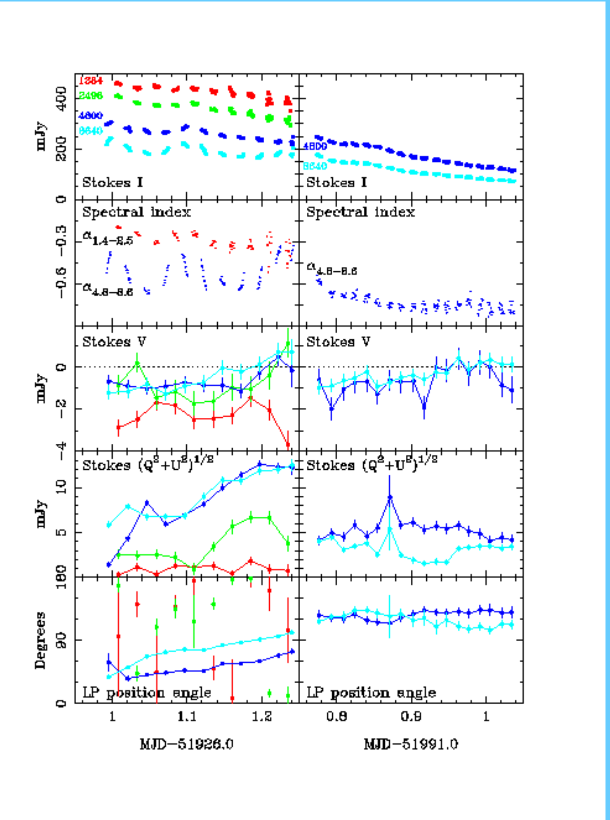
- 25-30 mag extinction!
- Greiner et al 2001 VLT observations find the star!
- Spectroscopy in H and K – CO lines
- K-M III spectral type for companion
- Spectroscopic binary: 33.5 d period
- BH mass 14 M_{sun}
- Nature Oct 29 2001, 414, 522.





Circular Polarization

- New radio observations with ATCA and with the Westerbork array have found circular polarization in SS433, GRO J1655-40 and in GRS 1915+105.



•Rapid variations seen
•Evidence for low energy (10's Mev) electrons
• Linear polarization rotates as the ejection evolves
(Fender et al. MNRAS in press)

X-ray/Radio connection

IR /radio flare follows a change in the X-ray state – perhaps the spike signifies the start of an explosive event, ejecting an expanding plasmon.

IR

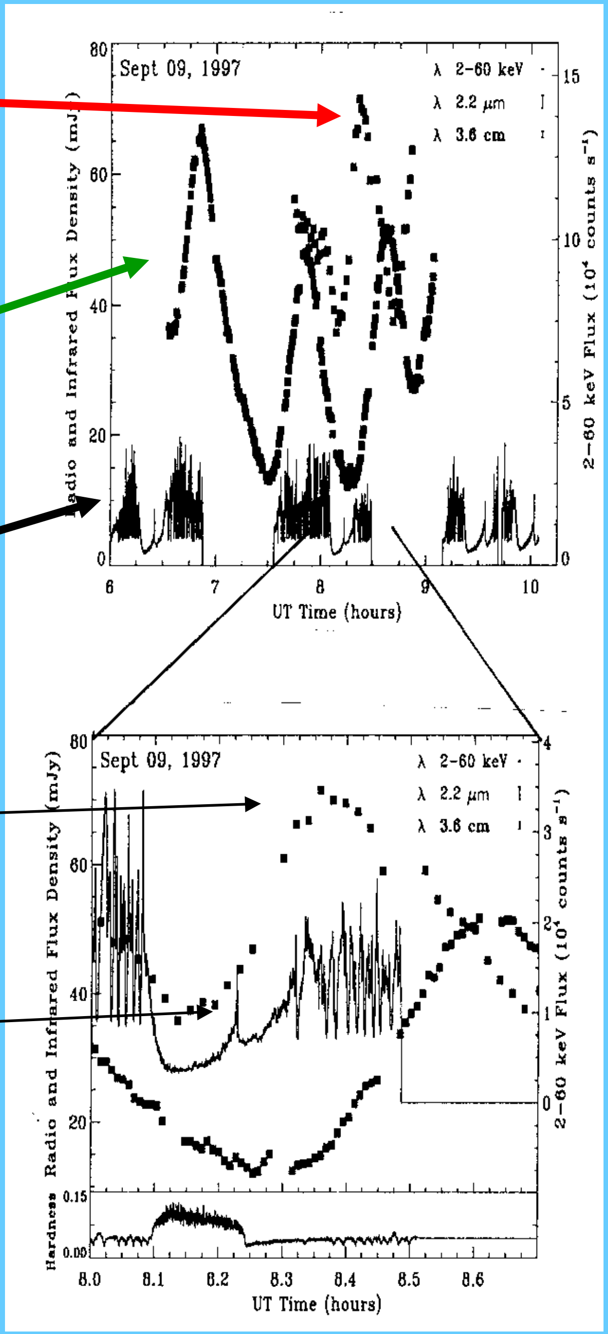
Radio

X-ray

IR Flare

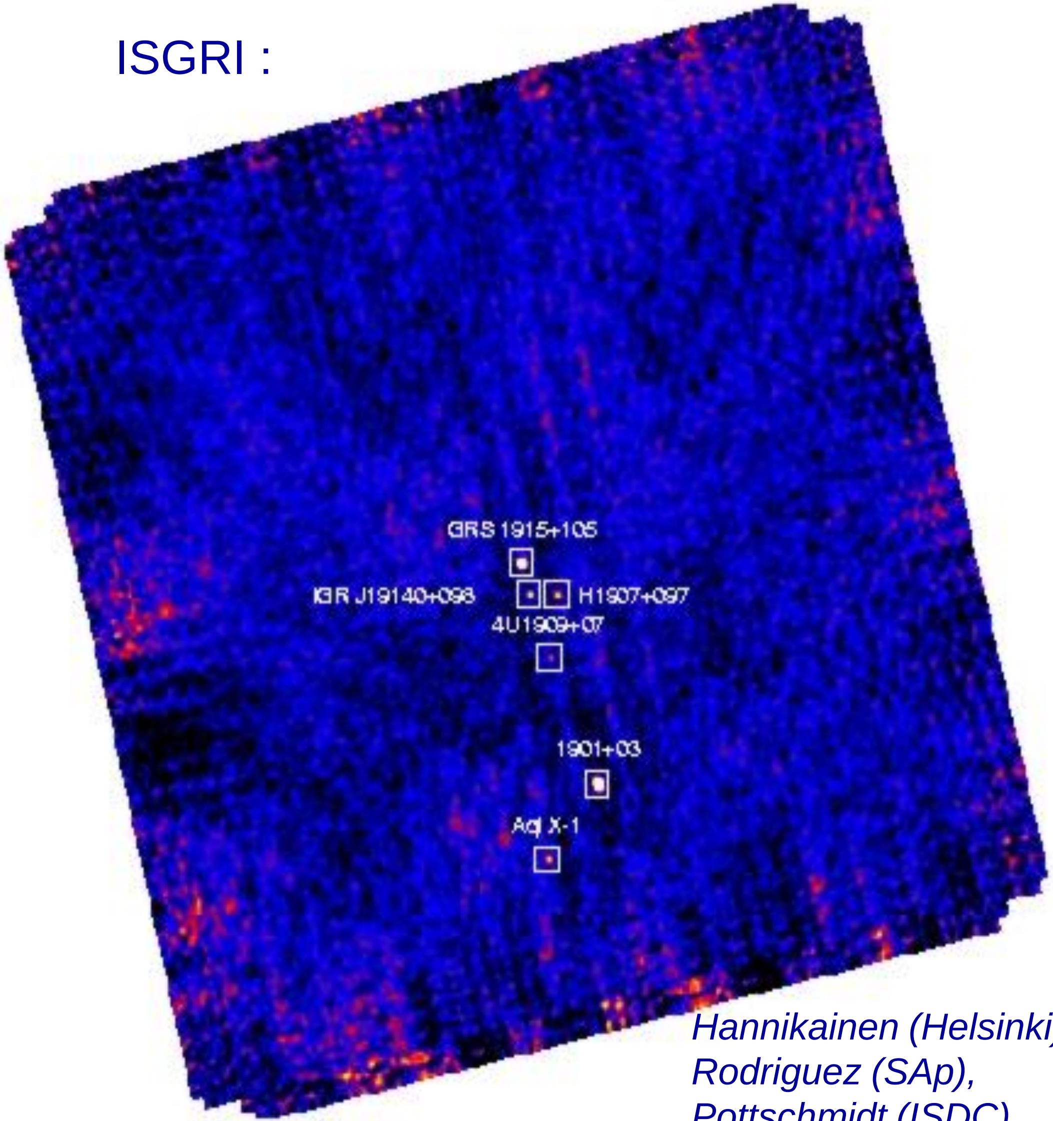
X-ray spike

Hardness



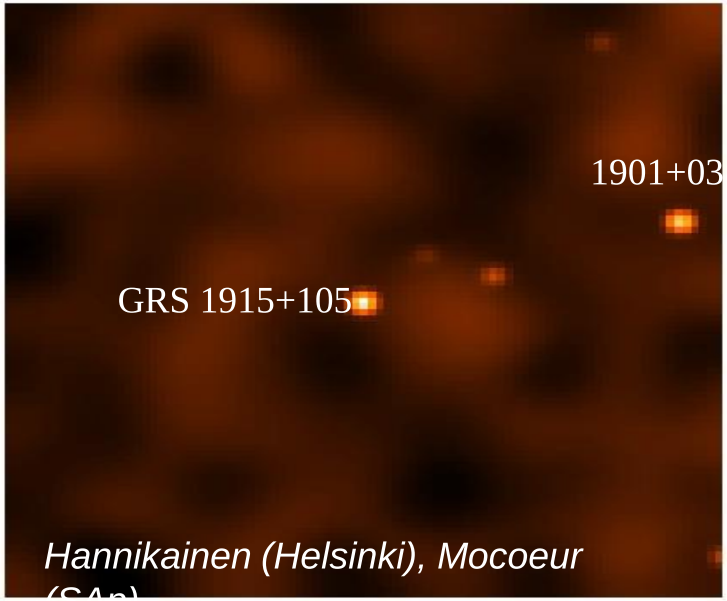
GRS 1915+105: INTEGRAL

ISGRI :



Hannikainen (Helsinki), Rodriguez (SAp), Pottschmidt (ISDC)

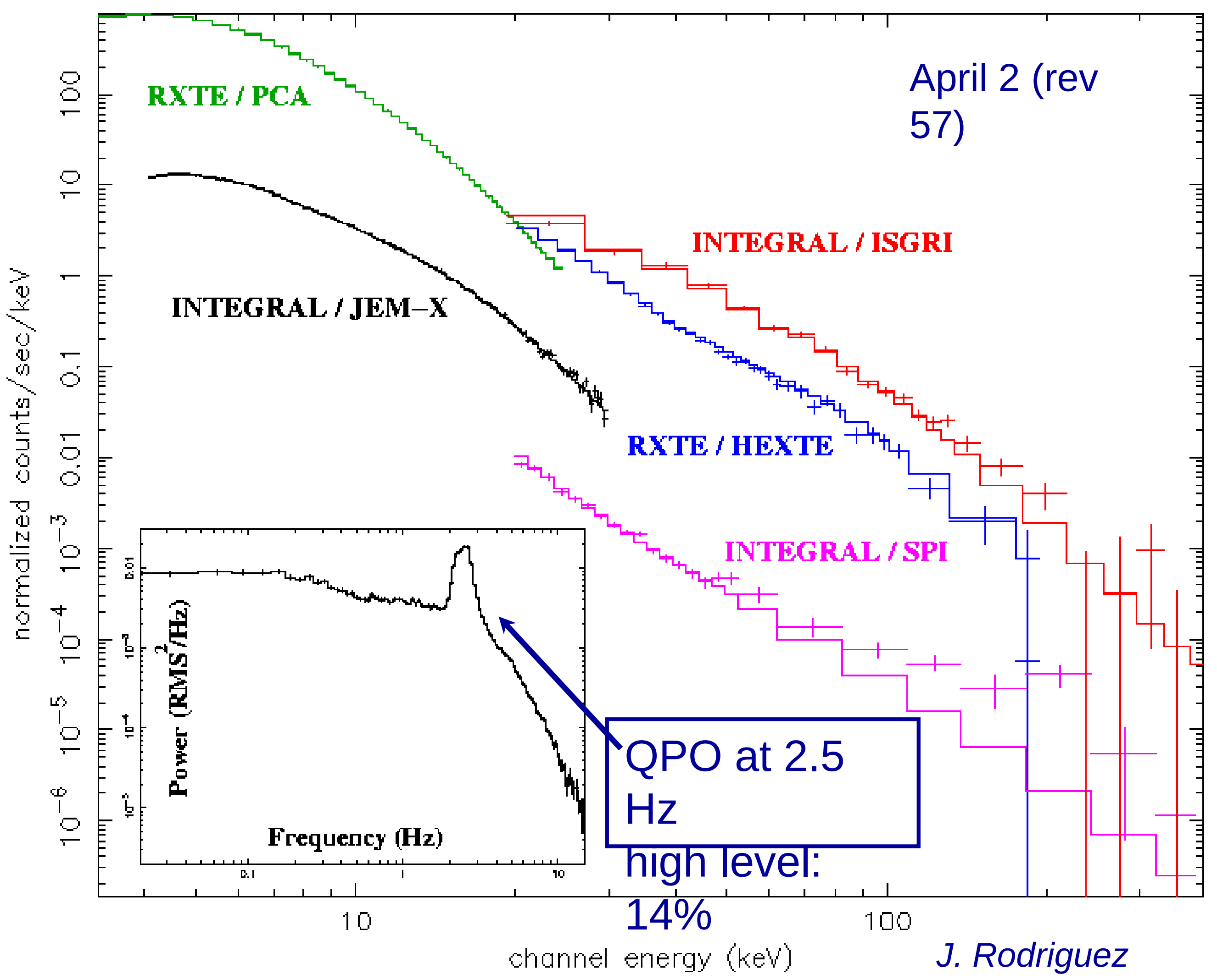
SPI :



Hannikainen (Helsinki), Mocoeur (SAp)

GRS 1915+105: X and gamma-ray spectra
April 2-3 (rev 57)

- **Power law, no cutoff untill 400 keV**
- same photon index for RXTE & INTEGRAL (20-200 keV) $\Gamma \approx 3$



J. Rodriguez (SAp)

- Fit PCA + HEXTE + ISGRI + SPI : $\Gamma = 2.94$
- without PCA : $\Gamma = 3.5$
- L ~40% L_{edd} (overestimation)

PCA (3-25 keV)

JEM-X2 (4-30 keV)

HEXTE (20-200 keV)

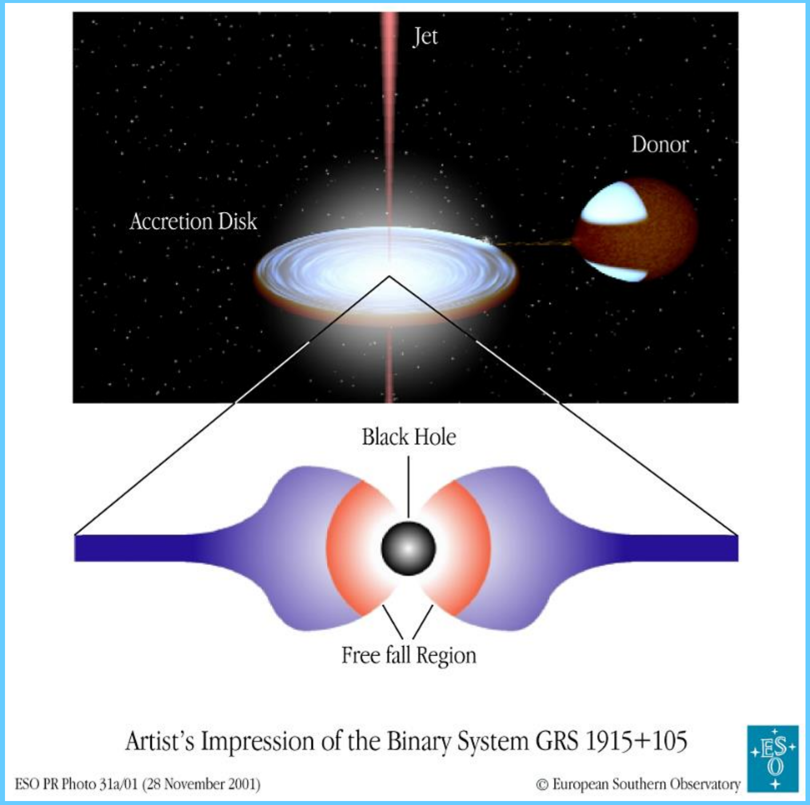
ISGRI (20-200 keV)

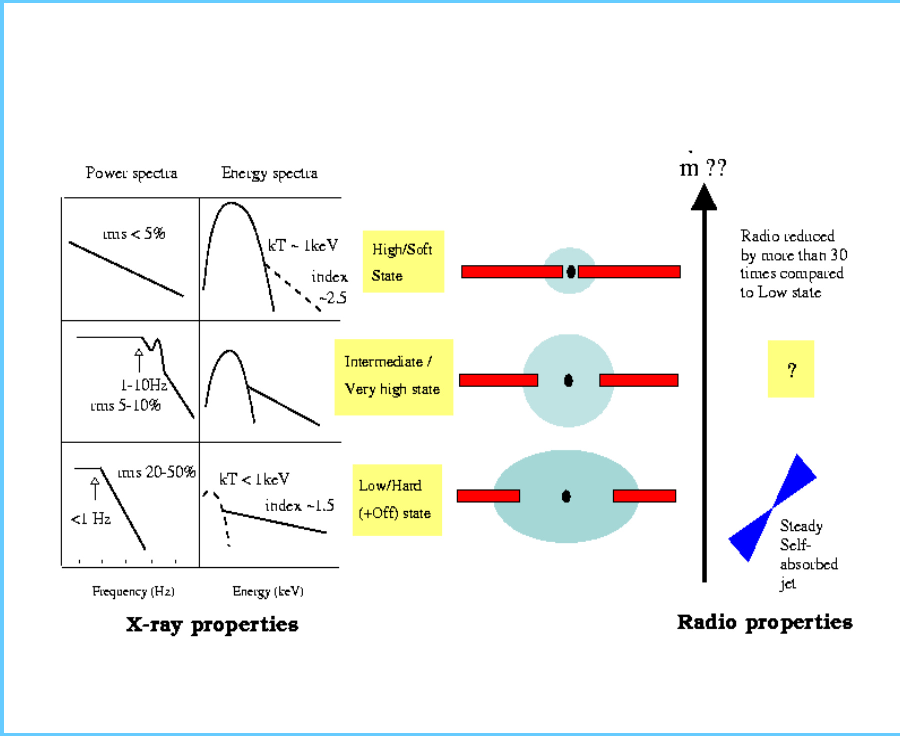
SPI (20-400 keV)

See talk by Jérôme Rodriguez

Fuchs et al. (2003)

Further modelling needed!





Conclusions

- Microquasars have lots of varied properties showing extreme physical conditions
- Origin of the radio jets is largely unknown
- Why is the velocity of the ejections in GRS1915 (0.98c) and SS433 (0.26c) so constant?
- What is the relationship between the persistent mini-jets in Cyg X-1, GRS 1915 etc. and the large scale ejections?
- Are the high energy X-rays really from the jet – Integral will tell us by comparing with radio in multi-wavelength observations.