Exploring the powering source of the TeV X-ray binary LS 5039

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OUTLINE

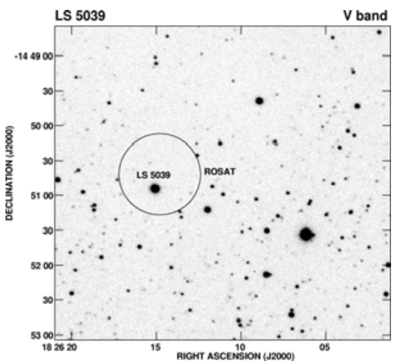
- The binary system LS 5039
- Proposed scenarios for the gamma-ray binary
- Testing the scenarios at milliarcsecond scales
- New VLBA radio observations
- Compendium of VLBA images
- Conclusions

The binary system LS 5039

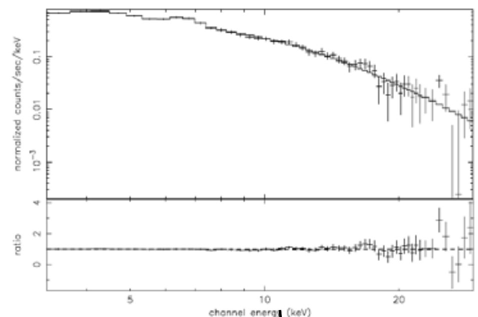
- Distance 2.5 ± 0.5 kpc.
- Compact object 1.5 $M_\odot$ < M < 10 $M_\odot$.
- Orbital period 3.9 days.
- LS 5039 is an O6.5 V((f)) bright star.
- System inclination 11º < i < 65º.
- Eccentricity 0.35 ± 0.04 (0.1-0.2 AU).
- Based on the mass function and inclination, the probability of being a BH is ~20 %.
- If the system is pseudo-synchronized then i ~25º and M ~3.7 $M_\odot$, but age ≥ 1 Myr after SN.

[Casares et al. 2005, MNRAS, 364, 899]

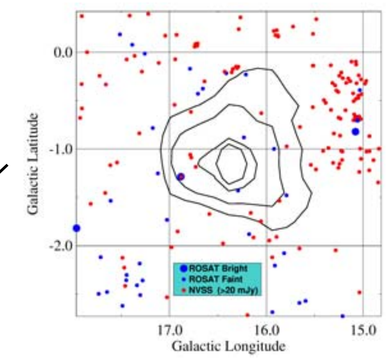
[Martí et al. 1998]

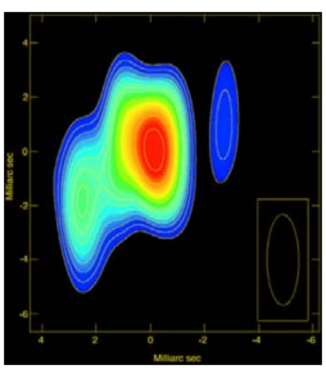


[Bosch-Ramon et al. 2005]

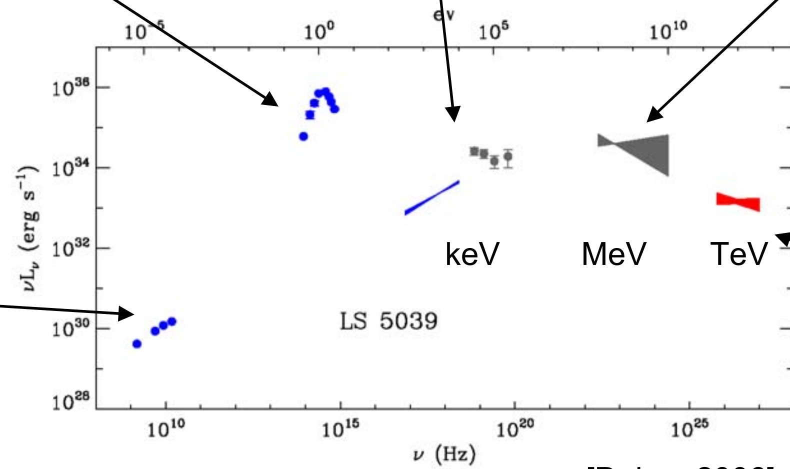


[Paredes et al. 2001]

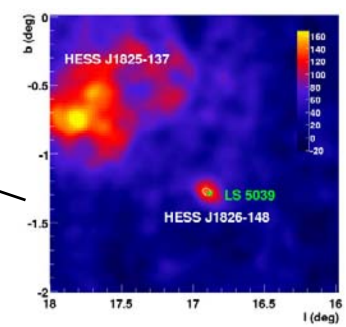




[Paredes et al. 2000]



[Dubus 2006]



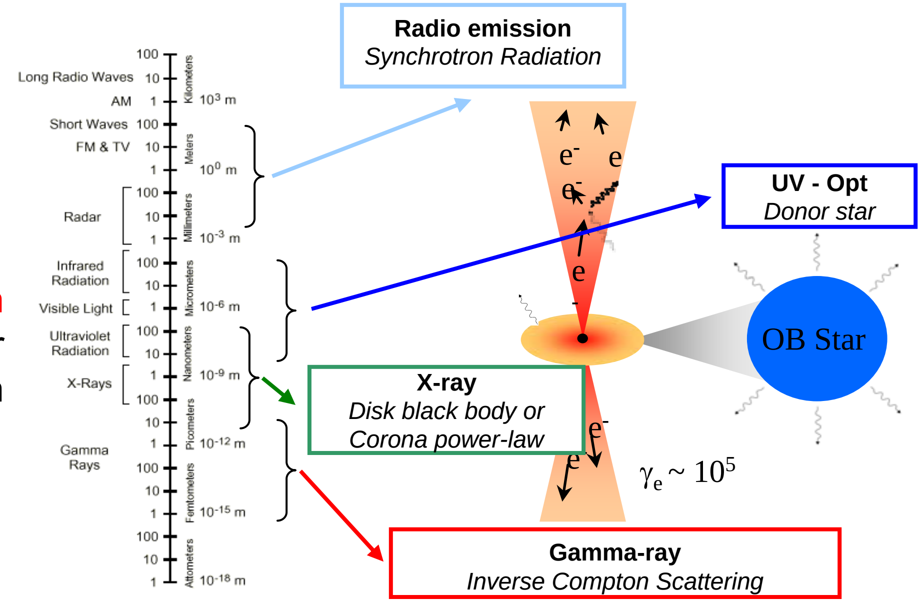
[Aharonian et al. 2005]

Possible scenarios

Microquasar

- An accretion disk is formed by mass transfer.
- Display bipolar jets of relativistic plasma.
- The jet electrons produce radiation by synchrotron emission when interacting with magnetic fields.
- VHE emission is produced by inverse Compton scattering when the jet particles collide with stellar UV photons, or by hadronic processes when accelerated protons collide with stellar wind ions.

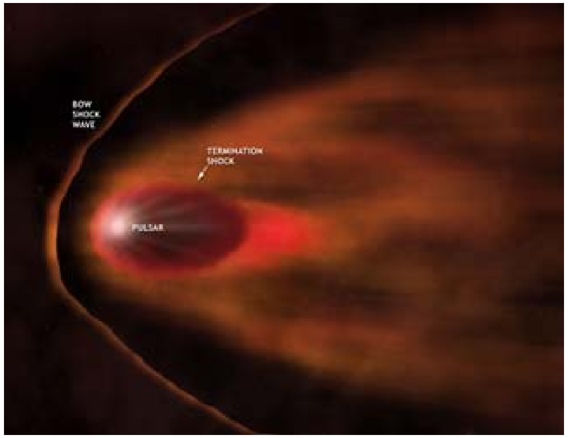
[Bosch-Ramon et al. 2006, A&A, 447, 263; Paredes et al. 2006, A&A, 451, 259; Romero et al. 2003, A&A, 410, L1]



Non-accreting pulsar

- The relativistic wind of a young (ms) pulsar is contained by the stellar wind.
- Particle acceleration at the termination shock leads to synchrotron and inverse Compton emission.
- After the termination shock, a nebula of accelerated particles forms behind the pulsar.
- The cometary nebula is similar to the case of isolated pulsars moving through the ISM.

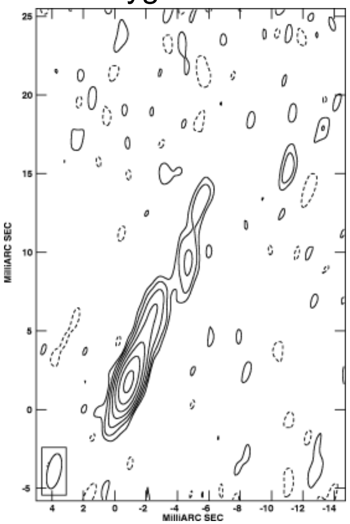
[Maraschi & Treves 1981, MNRAS, 194, P1; Dubus 2006, A&A, 456, 801; Sierpowska-Bartosik & Torres 2007, ApJ, 671, L145]



Testing at mas scales

Microquasar

Cygnus X-1



[Stirling et al. 2001]

Central core with extended jet-like (bipolar) radio emission.

The projection effects and the Doppler boosting produce a flux and distance asymmetry.

The direction of the jet remains constant during an orbital cycle. But it can display long-term precession.

[Mirabel & Rodríguez 1999, ARA&A, 37, 409; Fender 2006, Compact stellar X-ray sources, 381]

Shocks with the stellar wind can disrupt the jets (clumpy wind?).

[Perucho & Bosch-Ramon 2008, A&A, 482, 917]

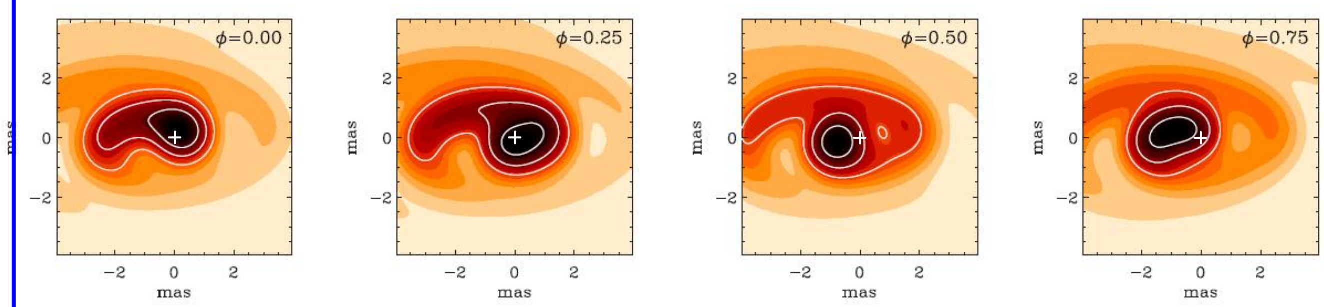
Non-accreting pulsar

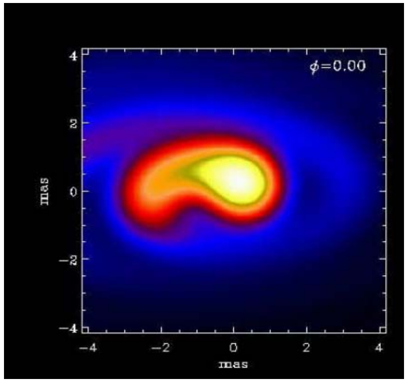
The cometary tail of cooling material displays synchrotron radio emission

+

The peak of the emission follows the path of an elliptic orbit

The direction of the tail changes with the pulsar's orbital motion.





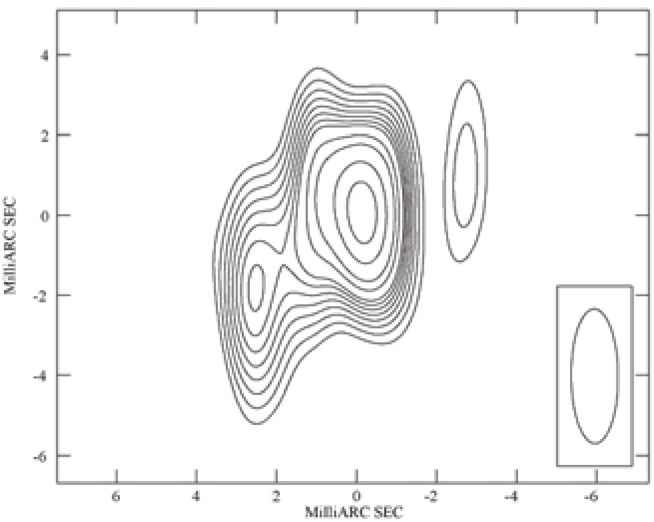
[Dubus 2006, A&A, 456, 801]

Previous radio observations

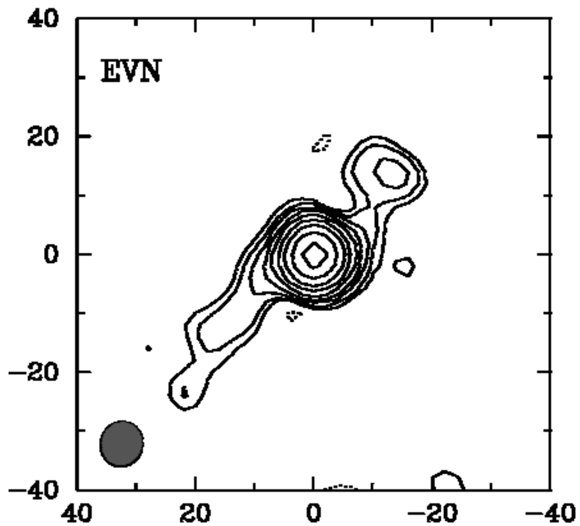
- The radio emission is persistent, non-thermal, and variable. [Ribó et al. 1999, A&A, 347, 518]
- No outburst or periodic variability have been detected. [Clark et al. 2001, A&A, 376, 476]
- No radio pulses have been detected at 1.4 GHz. [Morris et al. 2001, MNRAS, 335, 275]

At all scales it shows elongated bipolar extended emission with P.A. between 125-150º

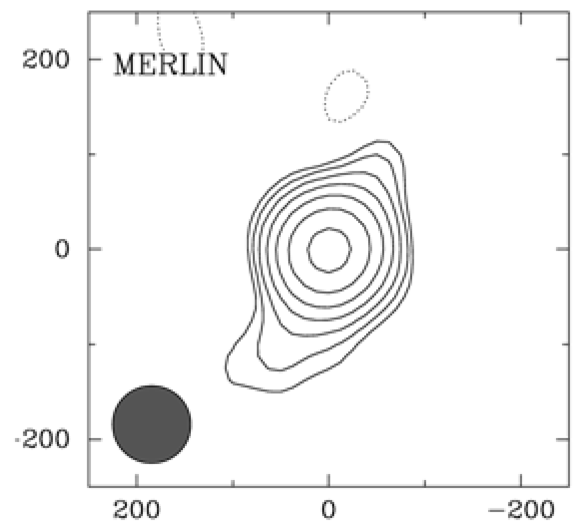
VLBA (5 GHz) BP051



EVN (5 GHz)



MERLIN (5 GHz)



[Paredes et al. 2000, Science, 288, 2340]

[Paredes et al. 2002, A&A, 393, L99]

3 mas (7.5 AU)
Φ = 0.14
P.A. = 125º

20 mas (50 AU)
Φ = 0.37
P.A. = 140º

100 mas (250 AU)
Φ = 0.37
P.A. = 150º

VLBA Observations

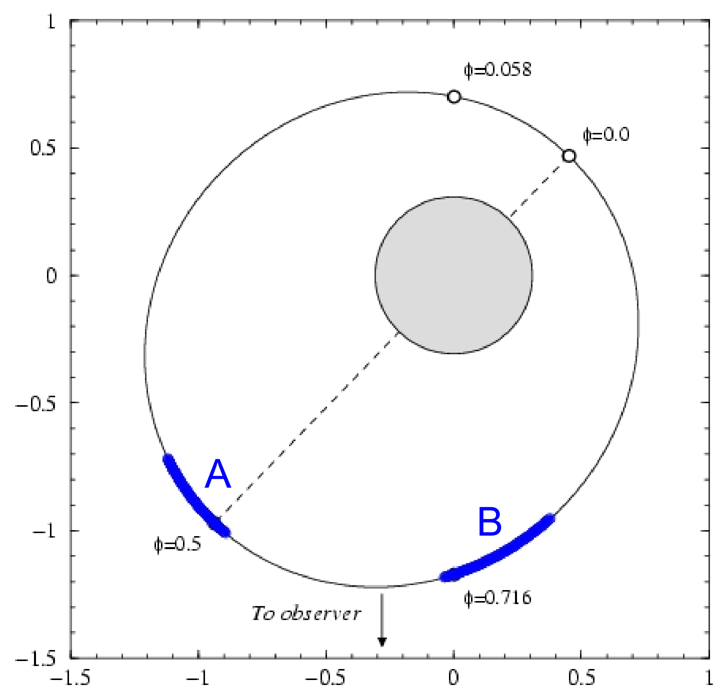
GR021 June 2000 [Ribó et al. 2008, A&A, 481, 17]

VLBA + VLA at 5 GHz. Recorded at 256 Mbps.

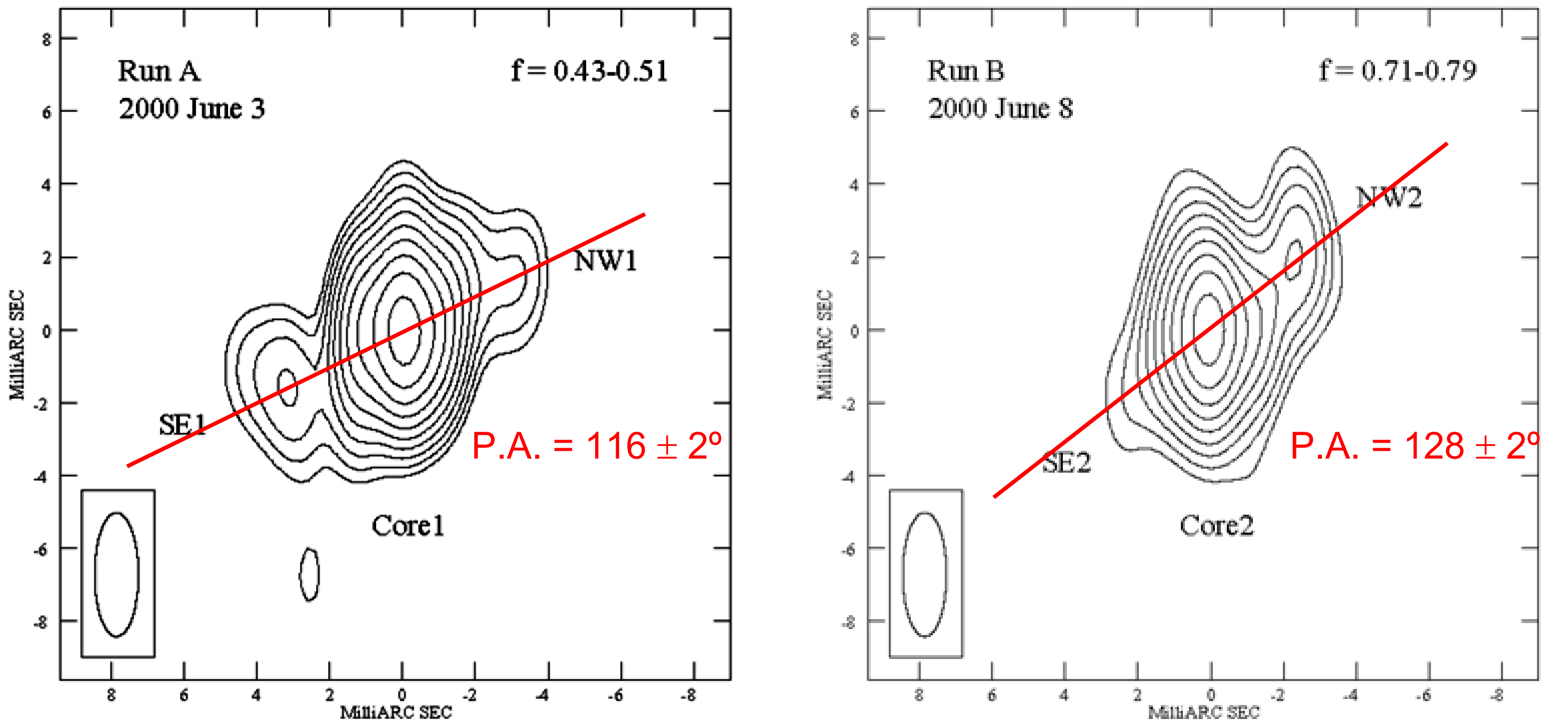
Duration: 8 hr (0.08 of phase).

2 runs separated 5 days (different orbital cycles)

Phases: 0.47 0.75



GR021 (2000) - results

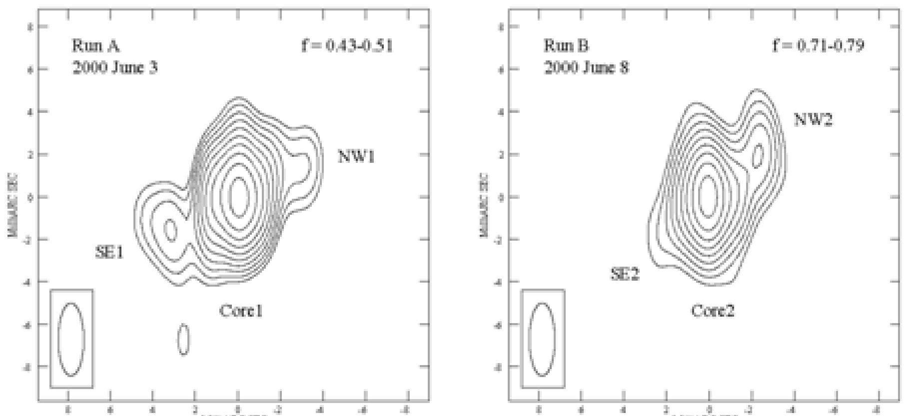


Run	Comp.	Peak $S_{5\ \mathrm{GHz}}$ [mJy beam^{-1}]	$S_{5\ \mathrm{GHz}}$ [mJy]	r [mas]	P.A. [°]	$\Delta\alpha$ [mas]	$\Delta\delta$ [mas]	Maj. Axis [mas]	Min. Axis [mas]	P.A.$_{\mathrm{Axis}}$ [°]
A	Core1	10.54 ± 0.08	20.0 ± 0.2	—	—	—	—	3.69 ± 0.03	2.09 ± 0.02	103 ± 1
	SE1	1.11 ± 0.08	2.6 ± 0.2	3.67 ± 0.08	115.9 ± 1.7	3.30 ± 0.07	−1.60 ± 0.12	4.1 ± 0.3	2.36 ± 0.16	17 ± 5
	NW1	0.88 ± 0.08	1.5 ± 0.2	3.29 ± 0.09	−63 ± 2	−2.92 ± 0.08	1.52 ± 0.14	3.6 ± 0.3	1.99 ± 0.18	3 ± 6
B	Core2	10.45 ± 0.11	17.6 ± 0.3	—	—	—	—	3.71 ± 0.04	1.8 ± 0.2	180 ± 1
	SE2	0.75 ± 0.11	1.8 ± 0.4	2.8 ± 0.2	129 ± 5	2.17 ± 0.13	−1.8 ± 0.3	4.6 ± 0.7	2.1 ± 0.3	1 ± 7
	NW2	2.22 ± 0.11	3.9 ± 0.3	2.94 ± 0.06	−52.2 ± 1.4	−2.32 ± 0.04	1.80 ± 0.09	4.3 ± 0.2	1.68 ± 0.08	174 ± 2

[Ribó et al. 2008, A&A, 481, 17]

GR021 (2000) - results

1. The two VLBA runs separated 5 days, show a changing morphology at mas scales.
2. In both runs there is a core component with a constant flux density, and an elongated emission with a P.A. that changes by 12 ± 3º between both runs.
3. The brightest emission changes its sense from south-east to north-west.
4. There is a symmetry change. The source is nearly symmetric in run A and asymmetric in run B.
5. No significant changes in images from half of the 8 hours of data on each day.
6. No reliable astrometric results obtained with current data.



GR021 (2000) - interpretation

Microquasar

- Assuming ballistic motions of adiabatically expanding plasma clouds without shocks:

	Distance asymmetry		Flux asymmetry			
			continuous (k=2)		discrete (k=3)	
run	$\beta\cos\theta$	θ (°)	$\beta\cos\theta$	θ (°)	$\beta\cos\theta$	θ (°)
A	0.06 ± 0.02	< 87	0.11 ± 0.03	< 84	0.08 ± 0.02	< 85
B	symmetric		0.15 ± 0.05	< 81	0.11 ± 0.03	< 84

Upper limits to the proper motions of the components at 3σ restrict the angle between the approaching jet and the line of sight

$\theta < 48^{o}$ SE

$\theta < 45^{o}$ NW

Fast jet precession?
But strong P.A. variations not seen.

- Alternatively, run B can be a discrete ejection. But X-ray and radio flares are not observed
- The morphology changes can be due to interaction between the jet and a clumpy stellar wind.

Pulsar

- In the young non-accreting pulsar scenario, the inclination of the binary system has to be high (edge on), being very close to the upper limit imposed by the absence of X-ray eclipses (i ~ 75º).