Multiwavelength properties of γ-ray loud binary systems.

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Known γ-ray loud binary systems.

Only 3 binary systems regularly observed in TeV:

PSR B1259-63 (young pulsar +Be star, P=3.4 y)

LSI +61 303 (comp. source + Be star, P=26.42 d)

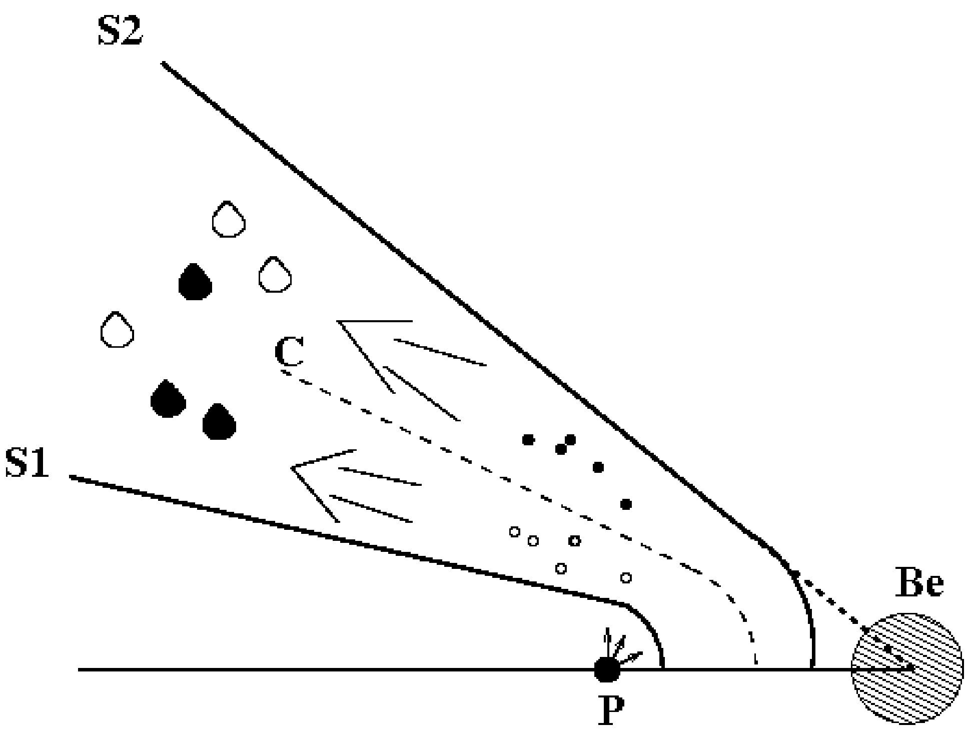
LS 5039 (comp. source + O star, P=3.9 d)

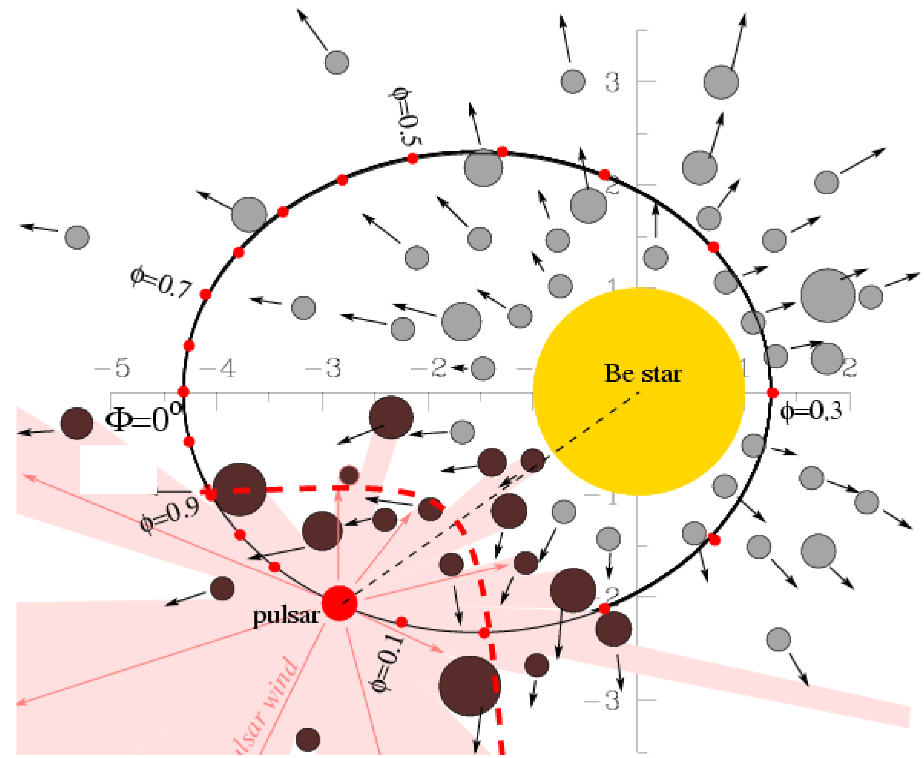
Origin of the high-energy emission?

Difference from other X-ray binaries?

Powered by rotation energy rather than accretion?

Winds collision

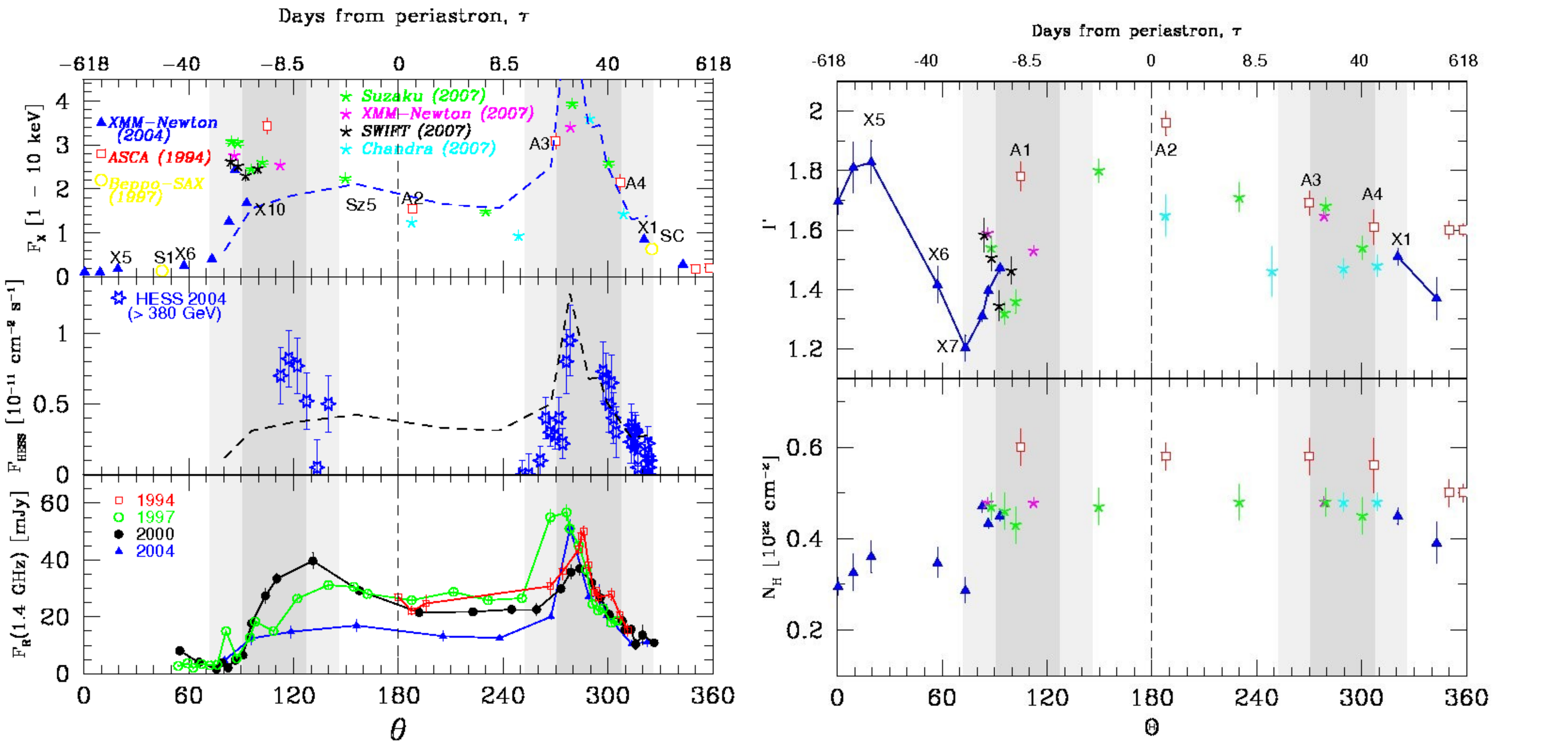




- Due to the intrinsic instabilities in the winds of hot massive stars clumps may form and change the well-ordered structure.
- Emission is due to the synchrotron, IC, bremsstrahlung, and proton-proton interactions.

PSR B1259-63

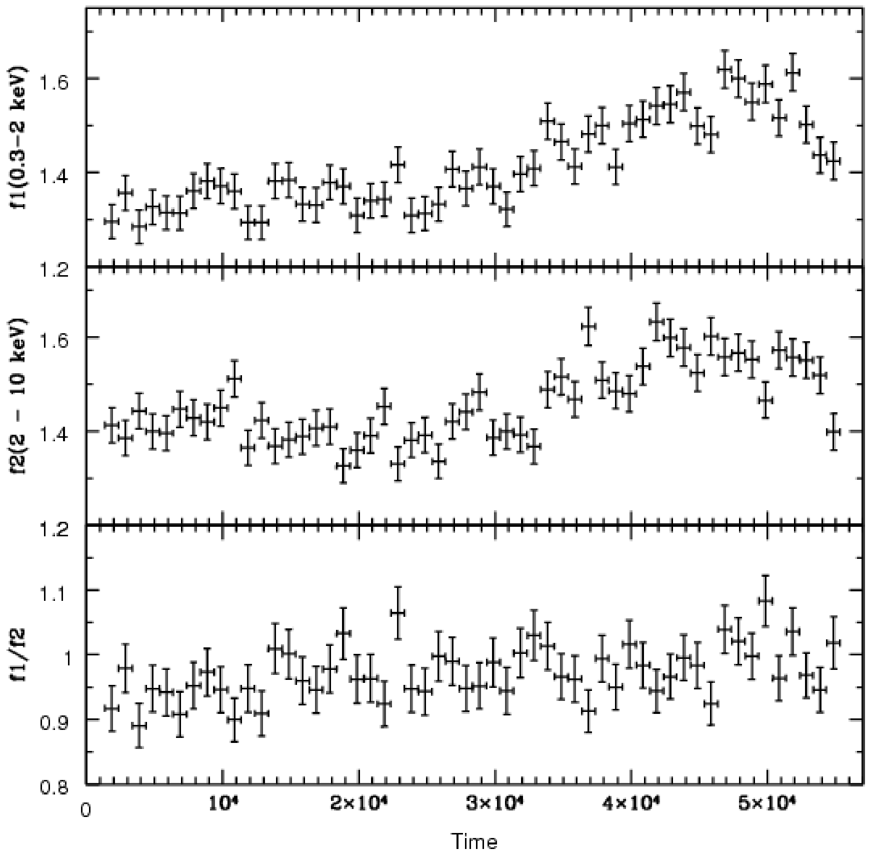
Chernyakova et al., 2006; Neronov &Chernyakova 2007



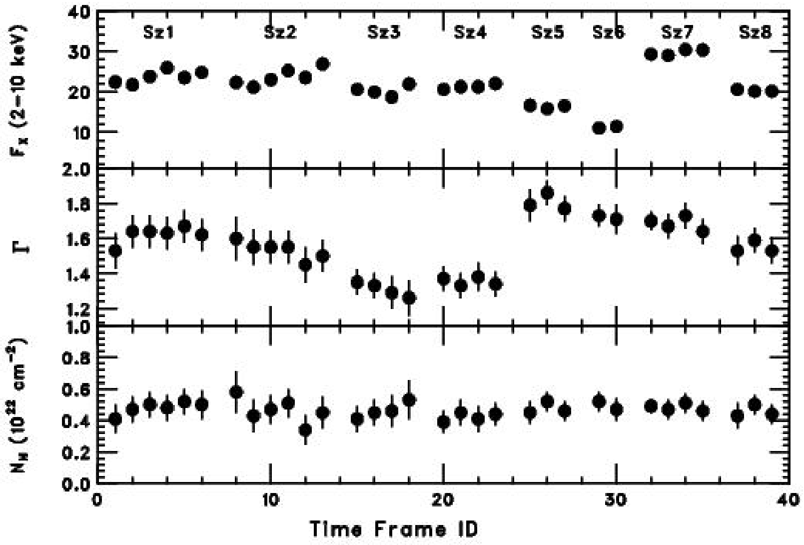
- 3.4 years orbital period.   e~0.87
- Stability of the X-ray orbital lightcurve.
- Correlated variability with a sharp rise ("*two bumps structure*") is seen in radio, X-ray (and TeV?) bands.
- Hardening of the X-ray spectrum on a day scale at the disk entrance.

Short Scale Time Behavior

PN/*XMM* 16.07.2007 (θ=112)

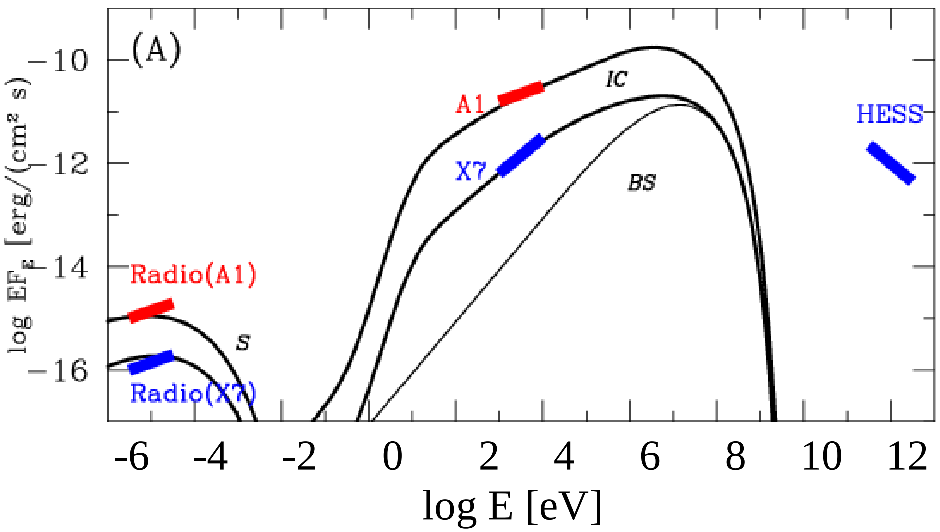


SUZAKU data (3ksec bin)



•Moderate (~20%) variability is seen on an hour time scale. No hour scale spectral variability is found within the statistical errors.

IC X-ray emission

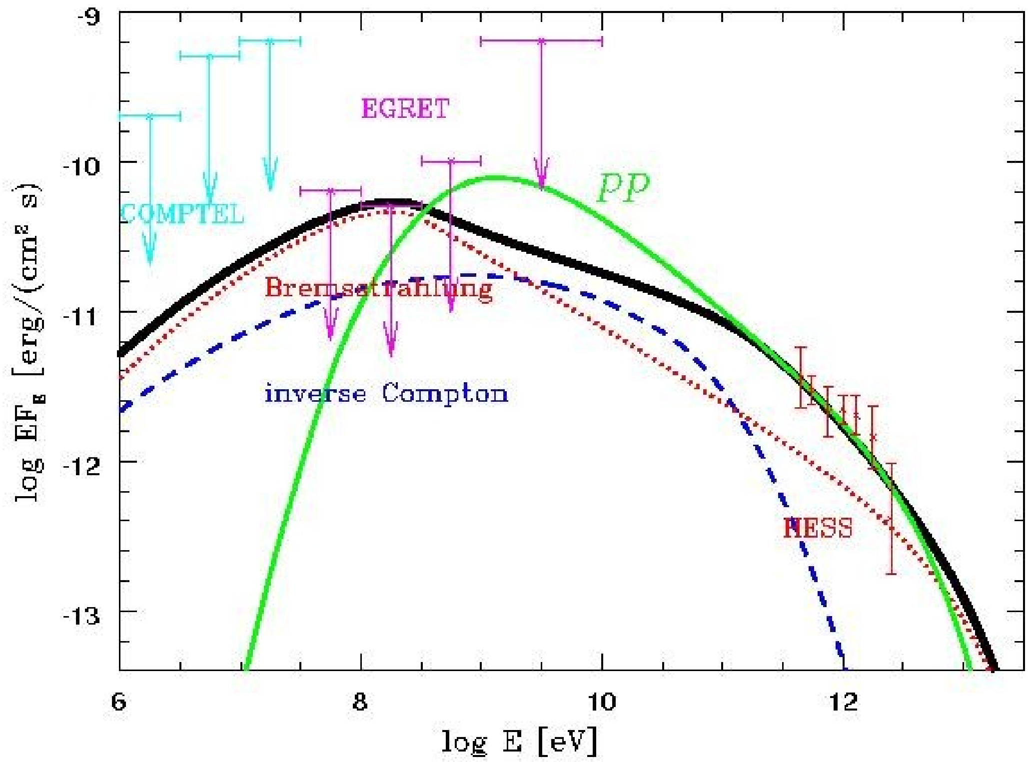


The observed spectral variability is naturally explained in *IC model*

- $E_{ic}=4[E_e/10\text{MeV}]$ keV
- $t_{ic}=10^6[R/10^{13}\text{cm}]^2[10\text{MeV}/E_e]$ s
- $t_s=6\text{x}10^2[B/0.1\text{G}]^{-3/2}[\varepsilon_s/10\text{keV}]^{-1/2}$s

•.... *injection* of electrons with energies above 10 MeV at the moment of disk entrance would result in hardening of the X-ray spectrum on a day scale.

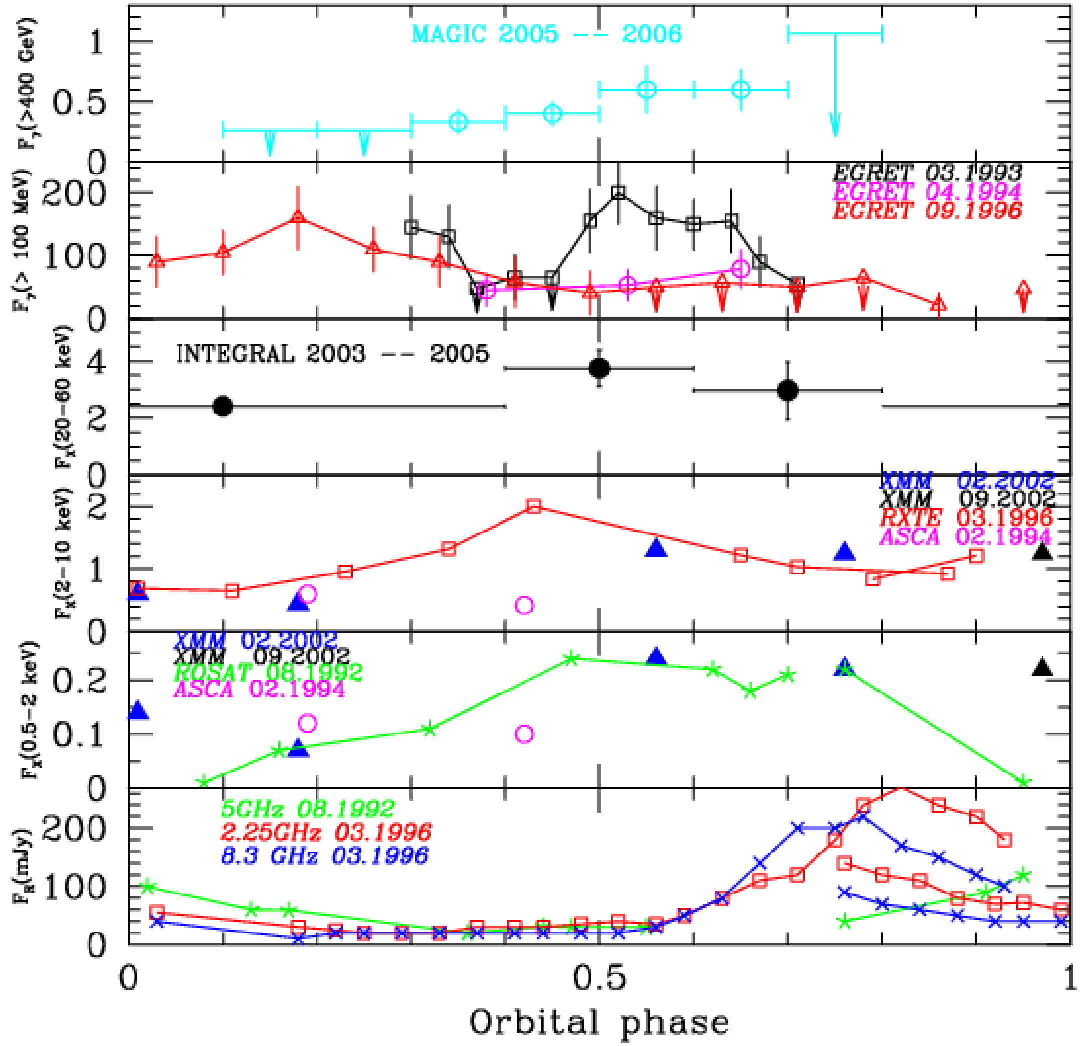
TeV emission: IC, bremsstrahlung or proton-proton interactions?



- The observed TeV lightcurve can be reproduced in the IC model if *adiabatic loss dominates* or the *acceleration efficiency drops* at periastron (Khangulyan et al. 06).
- If the matter density is $n \sim 10^{11} cm^{-3}$, the bremsstrahlung energy loss is comparable to the IC loss (in KN regime) and proton-proton interaction time. TeV emission can be bremsstrahlung from the compact region of interaction of pulsar and stellar winds.

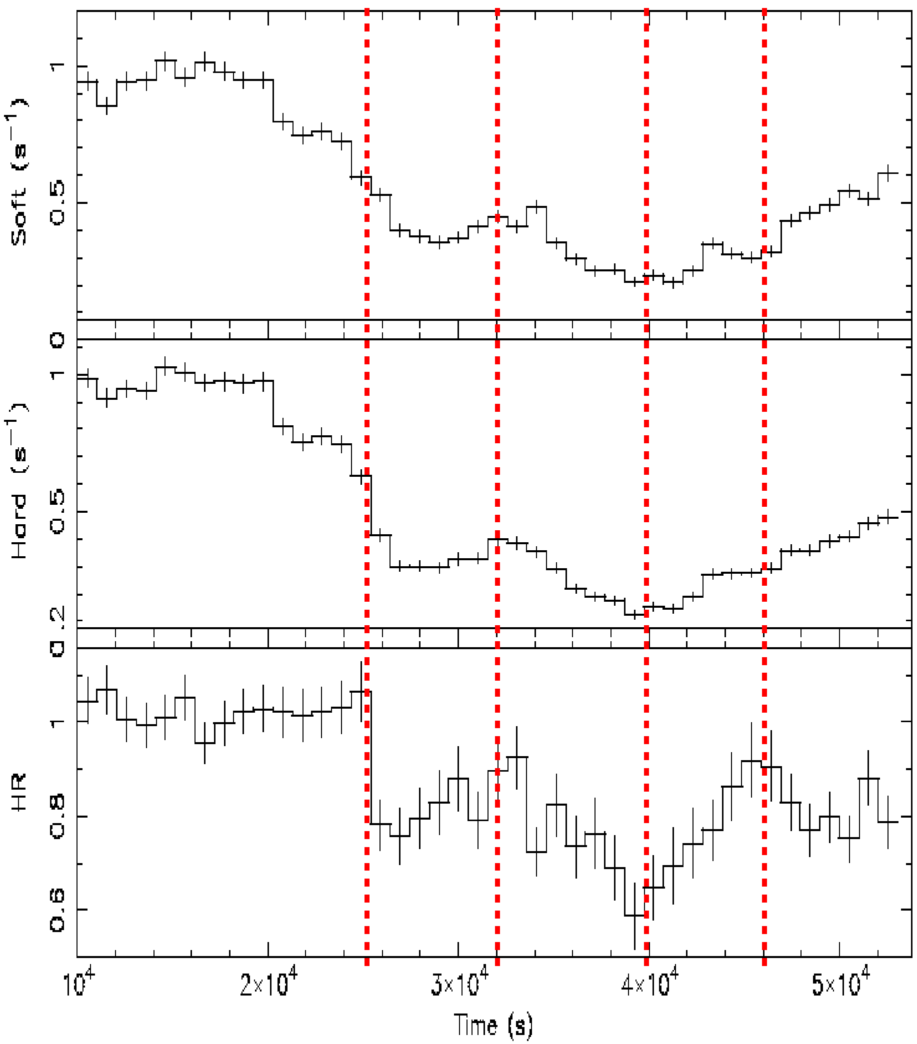
LSI +61 303

Chernyakova, Neronov, Walter 2006



- Compact binary with 26.42 d orbital period. Eccentricity e~0.7
- The X-ray emission peaks almost half an orbit before the radio

Short Scale Variability



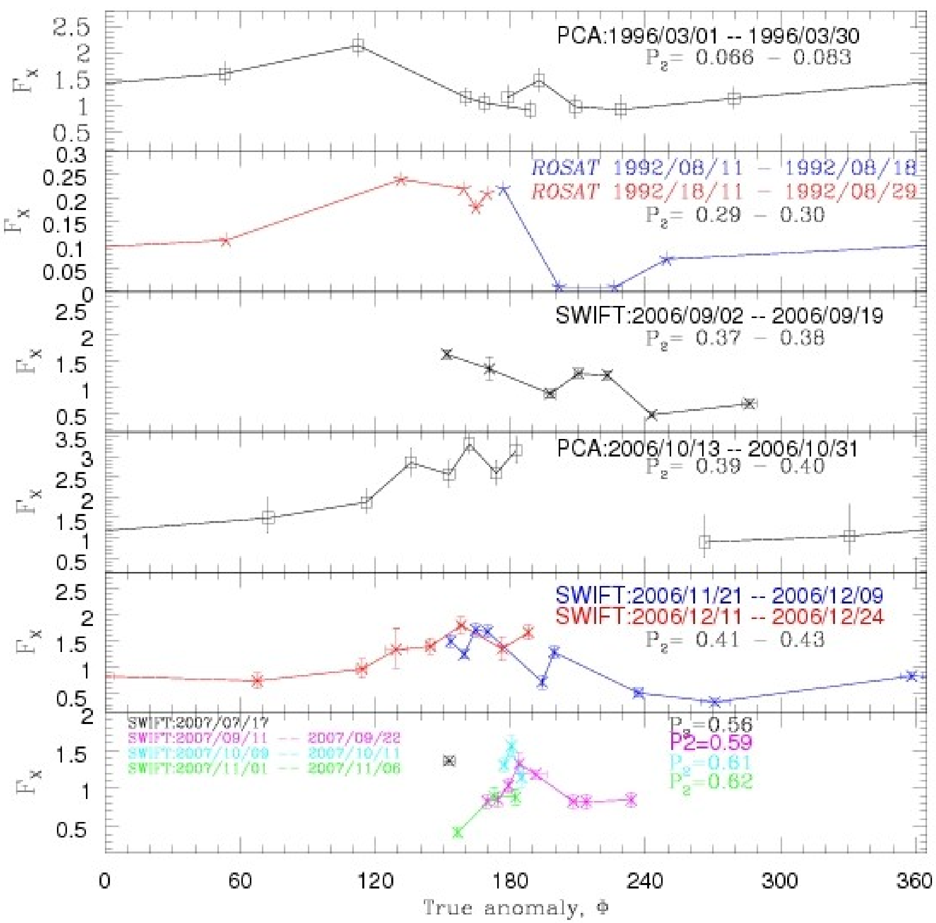
Sidoli et. al 2006

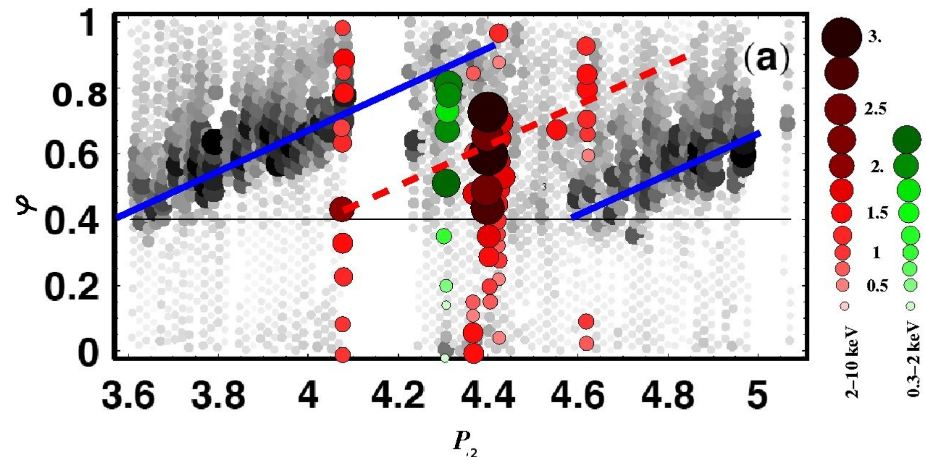
- The typical variability time due to the Compton cooling is

$$t_{IC} \simeq 5 \left[\frac{10^{38}}{L_{star}}\right]\left[\frac{R}{10^{12}}\right]^2\left[\frac{1\,keV}{E_{IC}}\right]^{1/2} ks$$

- The observed short scale variability is an evidence of the clumps in the wind of the Be star. The size of the clump can be estimated as $R \sim v_p \Delta t \sim 10^{11}$cm

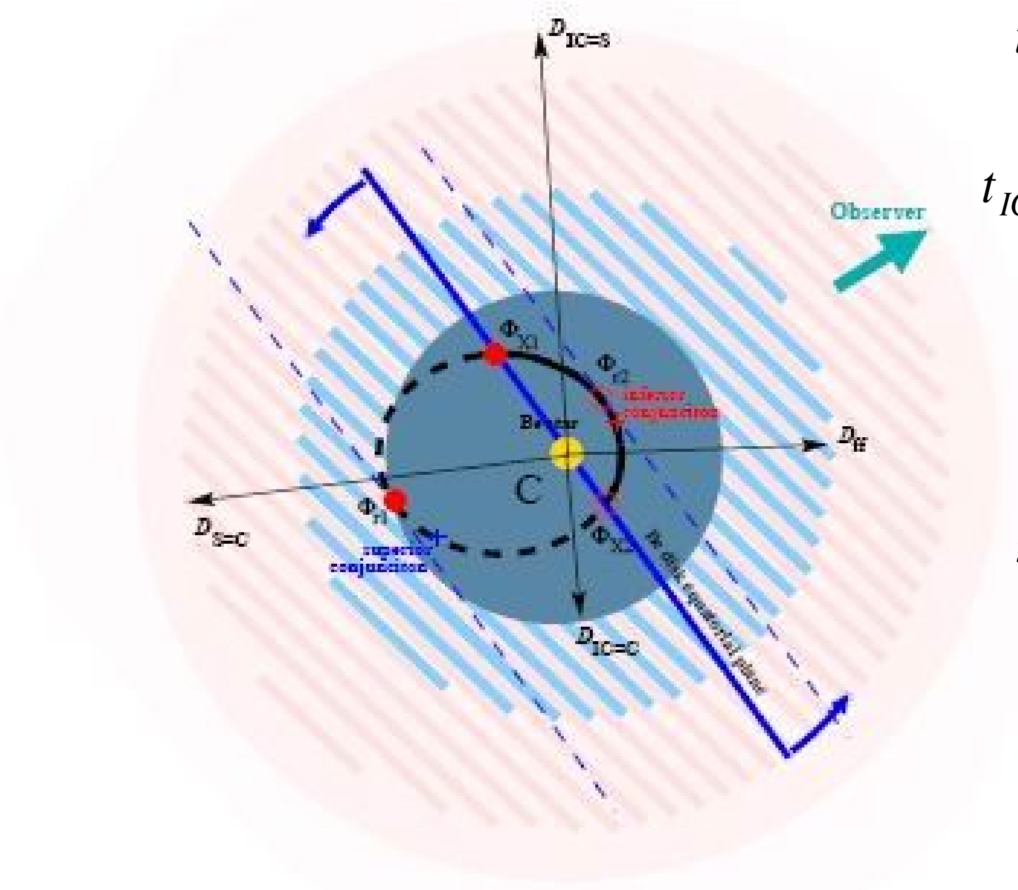
Longterm evolution





- The orbital phases of radio flux maxima “drift” with superorbital period P=4.6 year.
- Evidence for a similar drift in X-rays?

Structure of the Compactified Pulsar Wind Nebula



$$t_{coulomb} \simeq 8\text{x}10^{4}[\frac{3\text{x}10^{8}\,cm^{-3}}{n_e}][\frac{E_e}{10\,MeV}]\,s$$

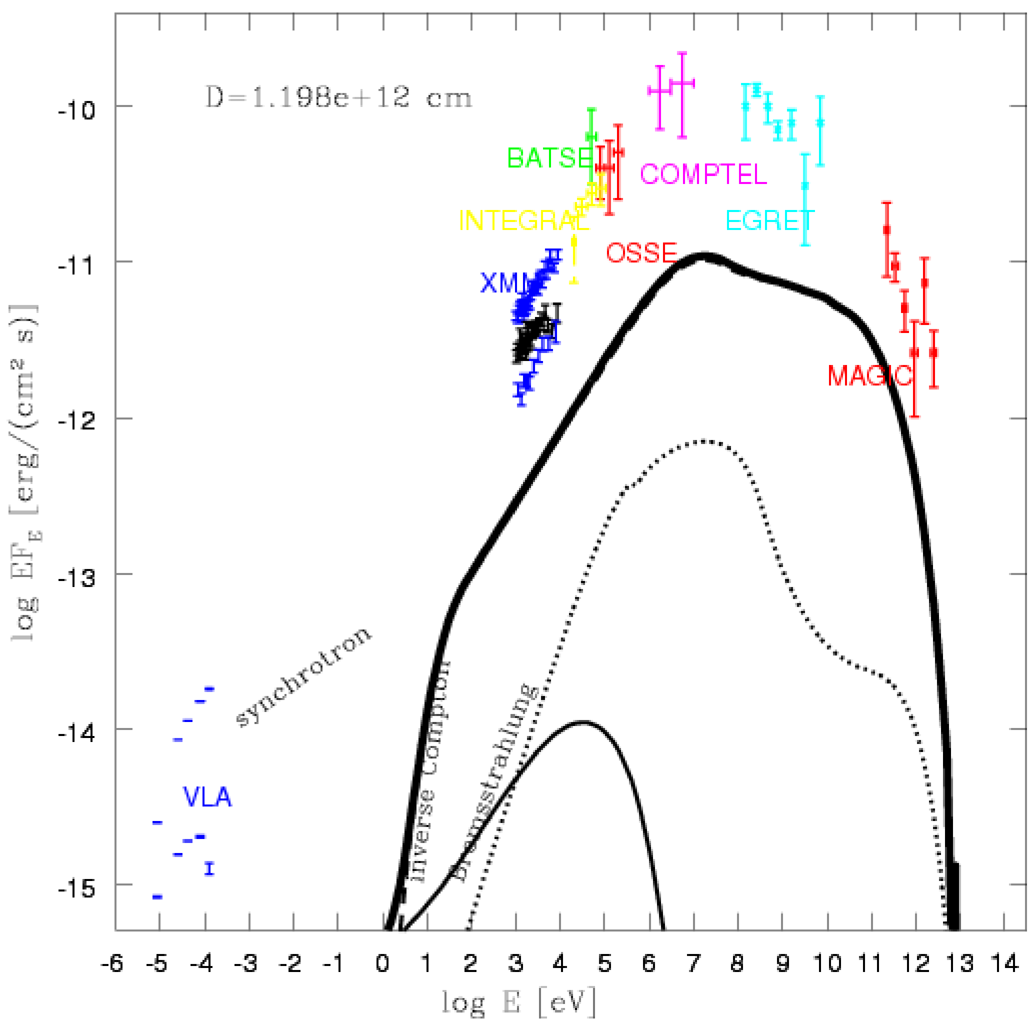
$$t_{IC} \simeq 5\text{x}10^{4}[\frac{10^{38}\,erg/s}{L_{star}}][\frac{D}{3\text{x}10^{12}}cm]^{2}[\frac{10\,MeV}{E_e}]s$$

$$t_s \simeq 4\text{x}10^{7}[\frac{1G}{B}]^{3/2}[\frac{1\,GHZ}{nu}]\,s$$

$$t_{diff} \simeq 1.5\text{x}10^{7}[\frac{R_{clump}}{10^{11}\,cm}]^{2}[\frac{B}{1\text{G}}][10\frac{MeV}{E_e}]\,s$$

$$D_{w,ff} \simeq 5\text{x}10^{13}[\frac{1\,GHZ}{nu}]^{2/3}[\frac{\dot{M}}{10^{-8}\,M_{sun}}]^{2/3}[\frac{v_{inf}}{10^{8}\,cm/s}]^{-2/3}[\frac{T}{10^{5}}K]^{-1/2}[\frac{f}{0.1}]^{-1/3}\,cm$$

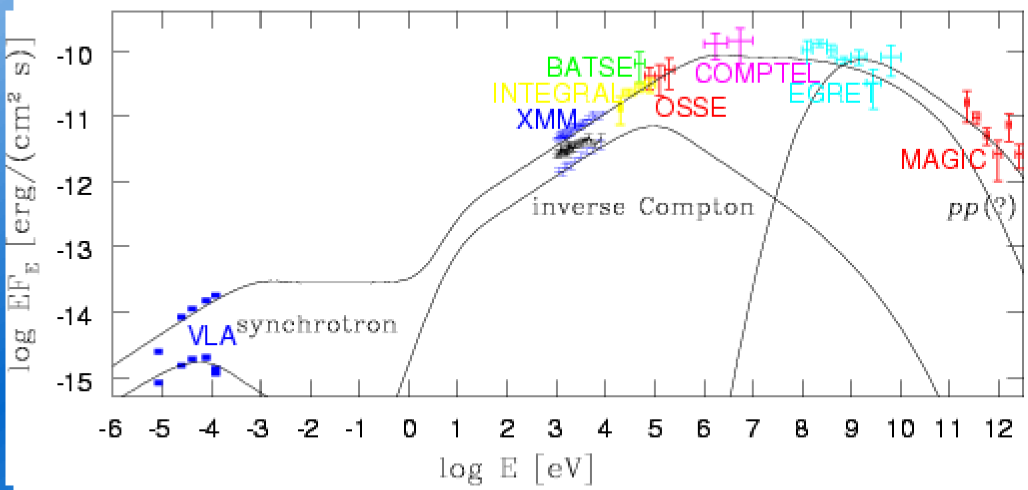
Resulted Spectrum Formation

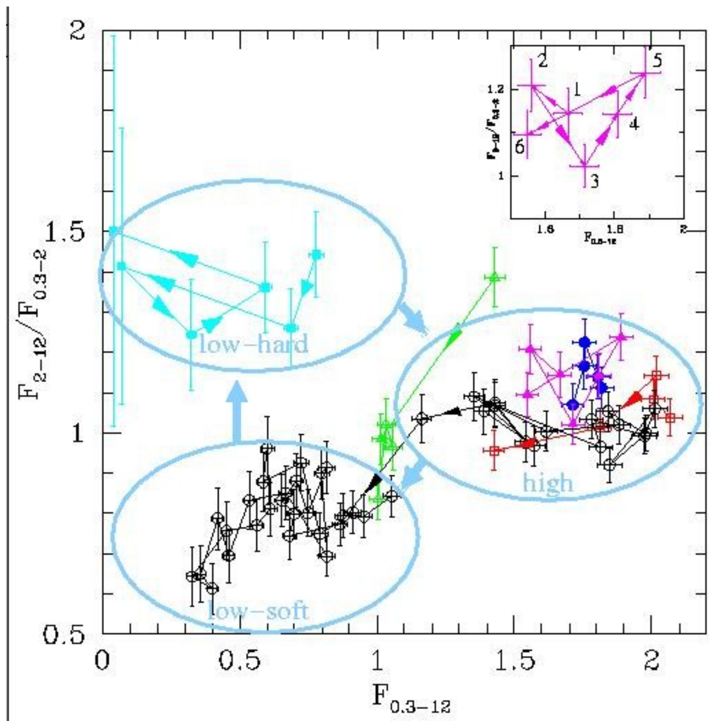


Lightcurves in different energy bands

- Radio:
  - Comes from the region of the size D_{PWN}~2–3x10^{14} cm
  - The maximum is achieved when 10 MeV electrons efficiently escapes from the region close to the Be star
  - Superorbital modulation is due to the Be disc precession.
- X-rays:
  - The maximum close to the moment of the pulsar passage through the equatorial plane of the inclined disc
  - No second maximum due to the Coulomb losses.
- γ–rays (10 GeV): Maximum at periastron
- TeV: Dip at periastron due to pair-pair production.

Arguments for pulsar model

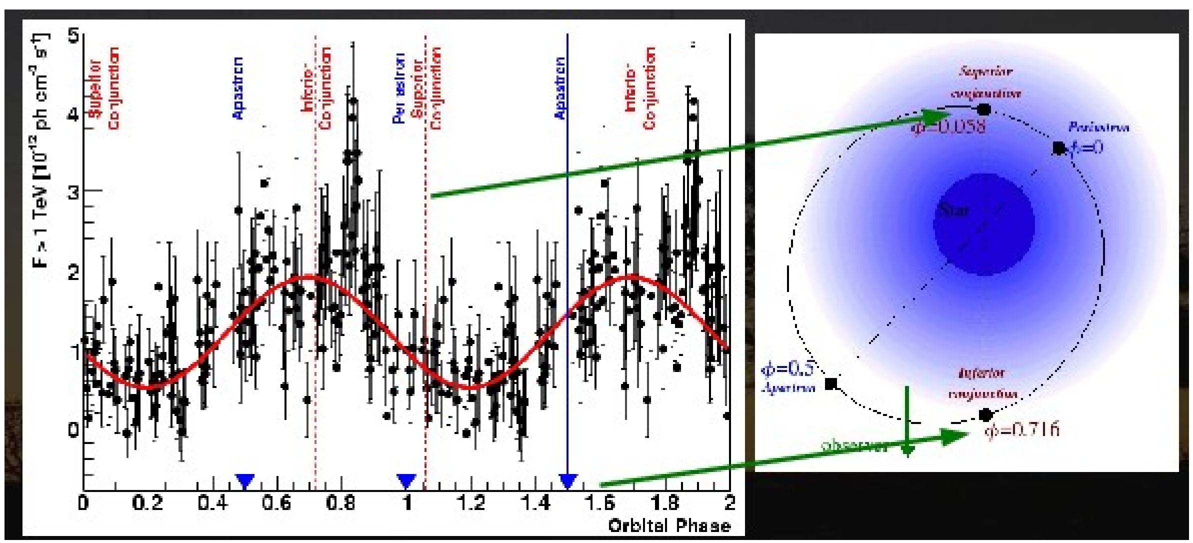




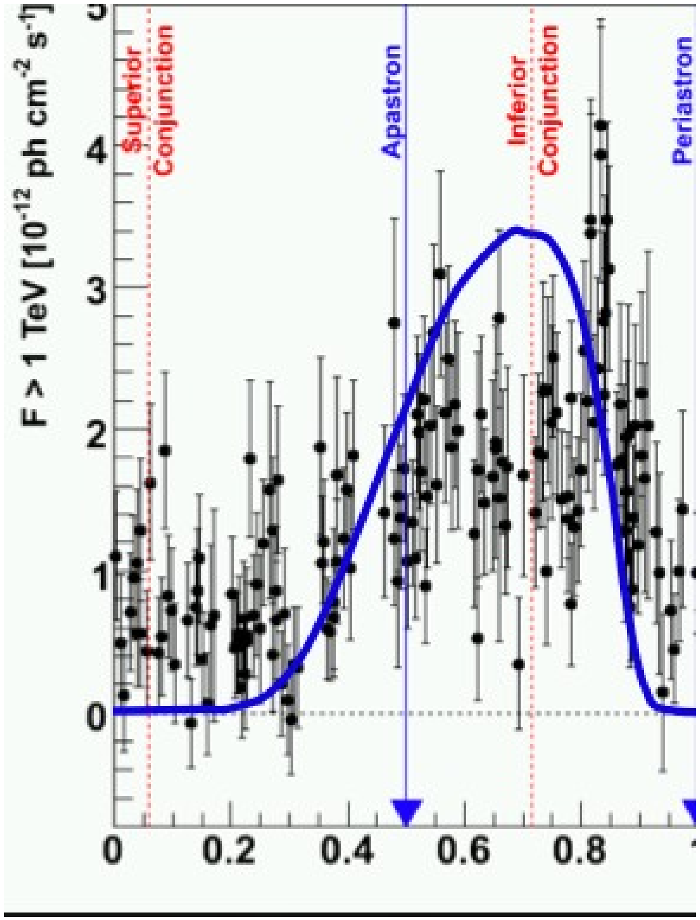
- Similar to PSR B1259-63 radio and X-ray emission can be explained by the synchrotron and IC emission from the same population of the electrons.
- Absence of the break in the X-ray spectrum favors the “hidden pulsar” model.
- Extended radio source has a complicate morphology varying along the orbit (Massi et al. 2004, Dhawan et al. 2006), thus jet emission is unlikely to dominate the spectrum through the whole orbit.
- The pattern of the source variability in the hardness ratio vs. flux diagram is naturally explained in the compact PWN model and is qualitatively different from the pattern in conventional accreting X-ray binaries

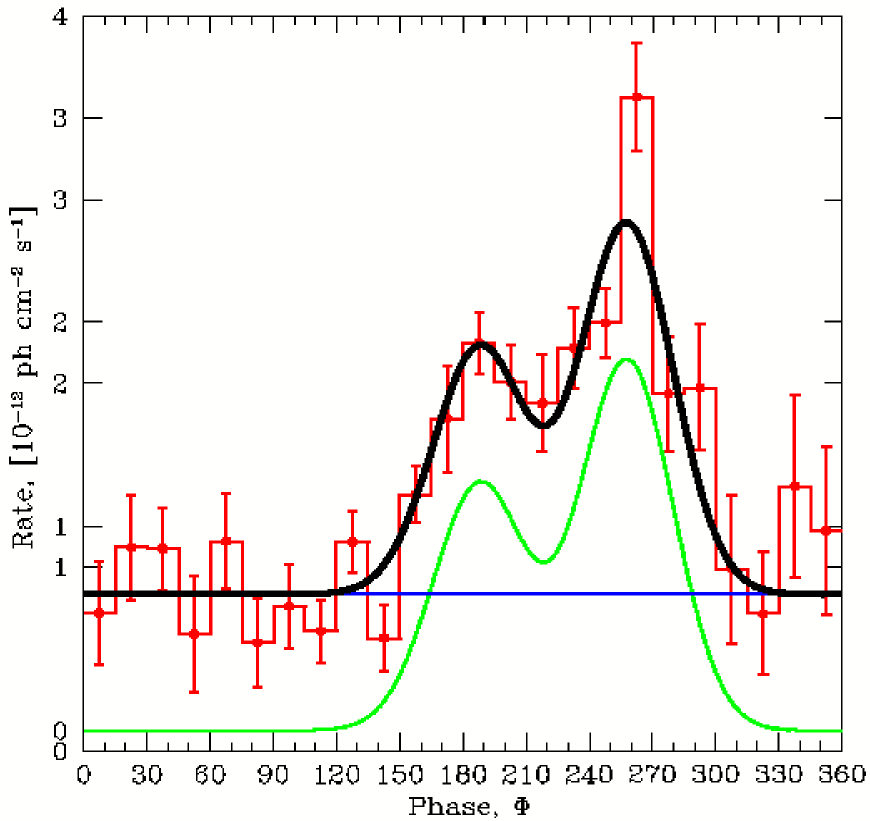
LS 5039

- orbital period is 3.9 d.,
- eccentricity 0.35,
- at periastron $R \sim 2.2 R_*$



LS 5039: TeV lightcurve

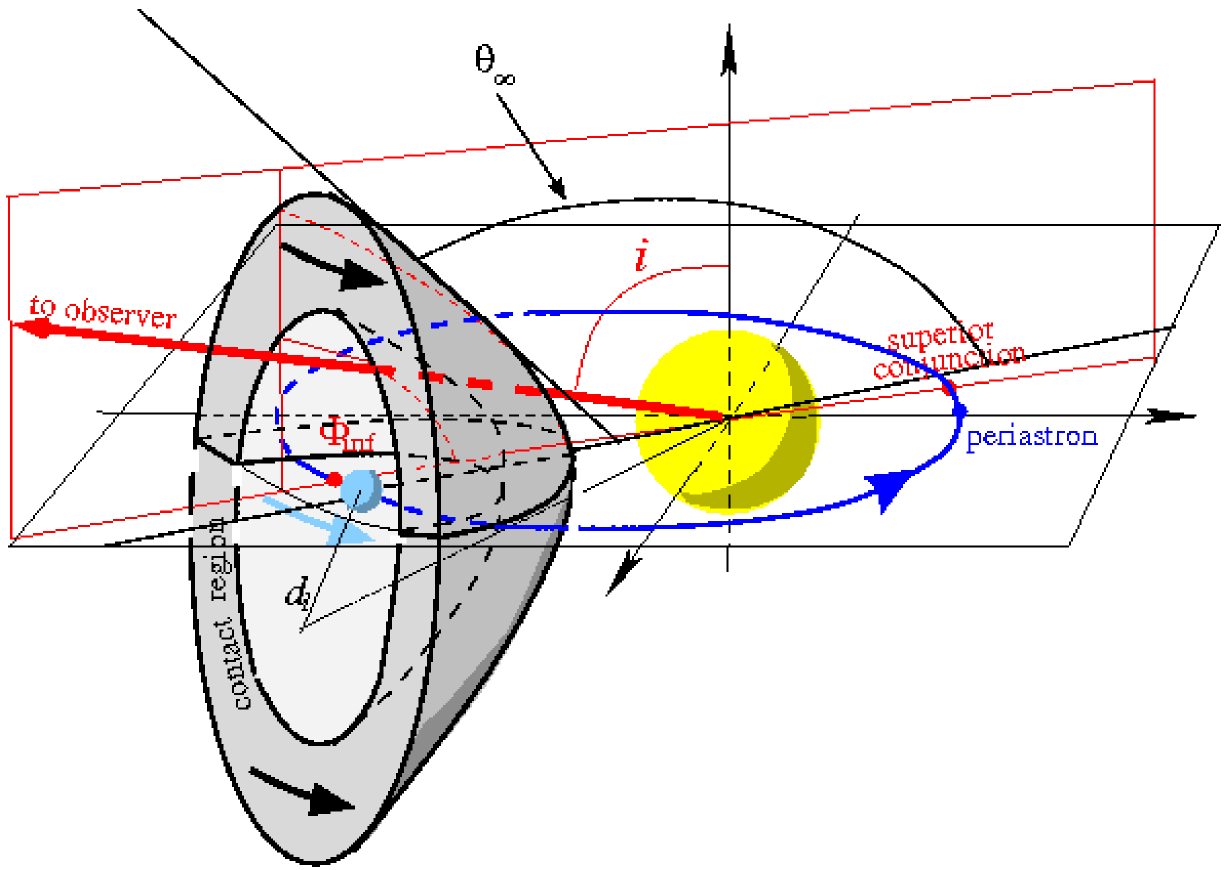




In the lightcurve drawn in terms of the « true anomaly » instead of the « orbital phase »

the two peaks become equidistant from the inferior conjunction!

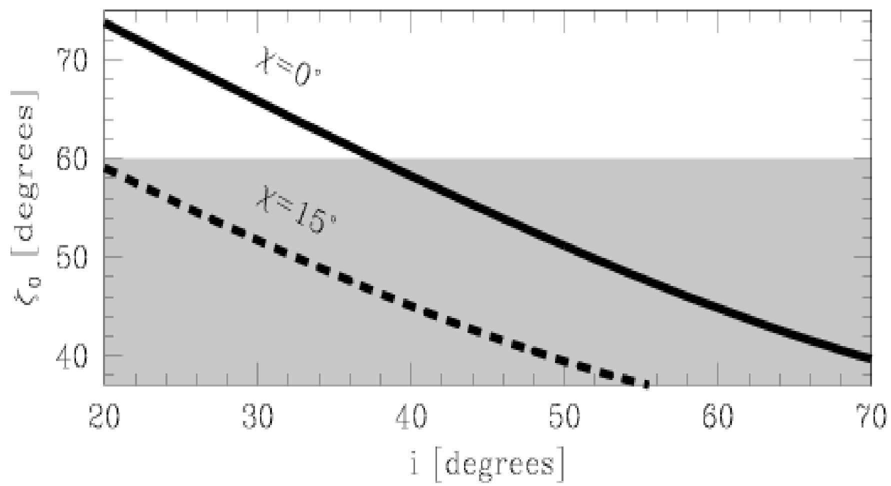
« Rotating hollow cone » model

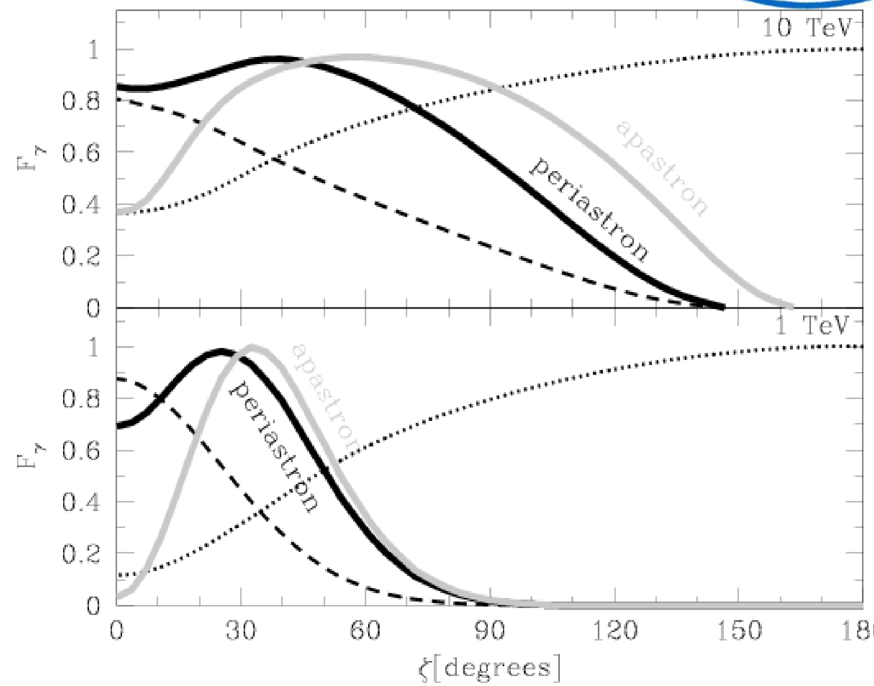


The phases of the maxima coinside with the moment of passage of the contact surface of the relativistic wind with the stellar wind.

The symmetry of the phases of the maxima w.r.t. the the inferior conjunction has a geometrical explanation, similar to the explanation of the two peaks of the folded lightcurves of pulsars.

Constraint on the geometry





- If $i>\pi/2-\zeta_0-\chi$ then the direction of the line of sight passes through the "wall" of the cone twice per orbit ($\chi=\text{atan}(h/D)$)
- Maxima are located at $\Phi_{1,2}=\Phi_{inf} +/- \Delta\Phi$, $\Delta\Phi=\text{acos}\{1-[\sin(i+\chi)-\cos\zeta_0]/\cos\chi \sin(i)\}$
- Thus if the source is located in the orbital plane ($\chi=0$), then the inclination $i>40^0$. If the inclination is small, then source is located above orbital plane, e.g. $i\sim 25^0$, $\chi>15^0$

Conclusions

•γ-ray loud binaries apparently form a separate class of sources powered by interaction of relativistic wind from the compact object with the stellar wind.

- The emission from such a system is
  - variable along the orbit,
  - non-thermal X-ray, γ-ray, and very high-energy γ-ray emission during the periods of pulsar passing through the dense regions of the companion wind.