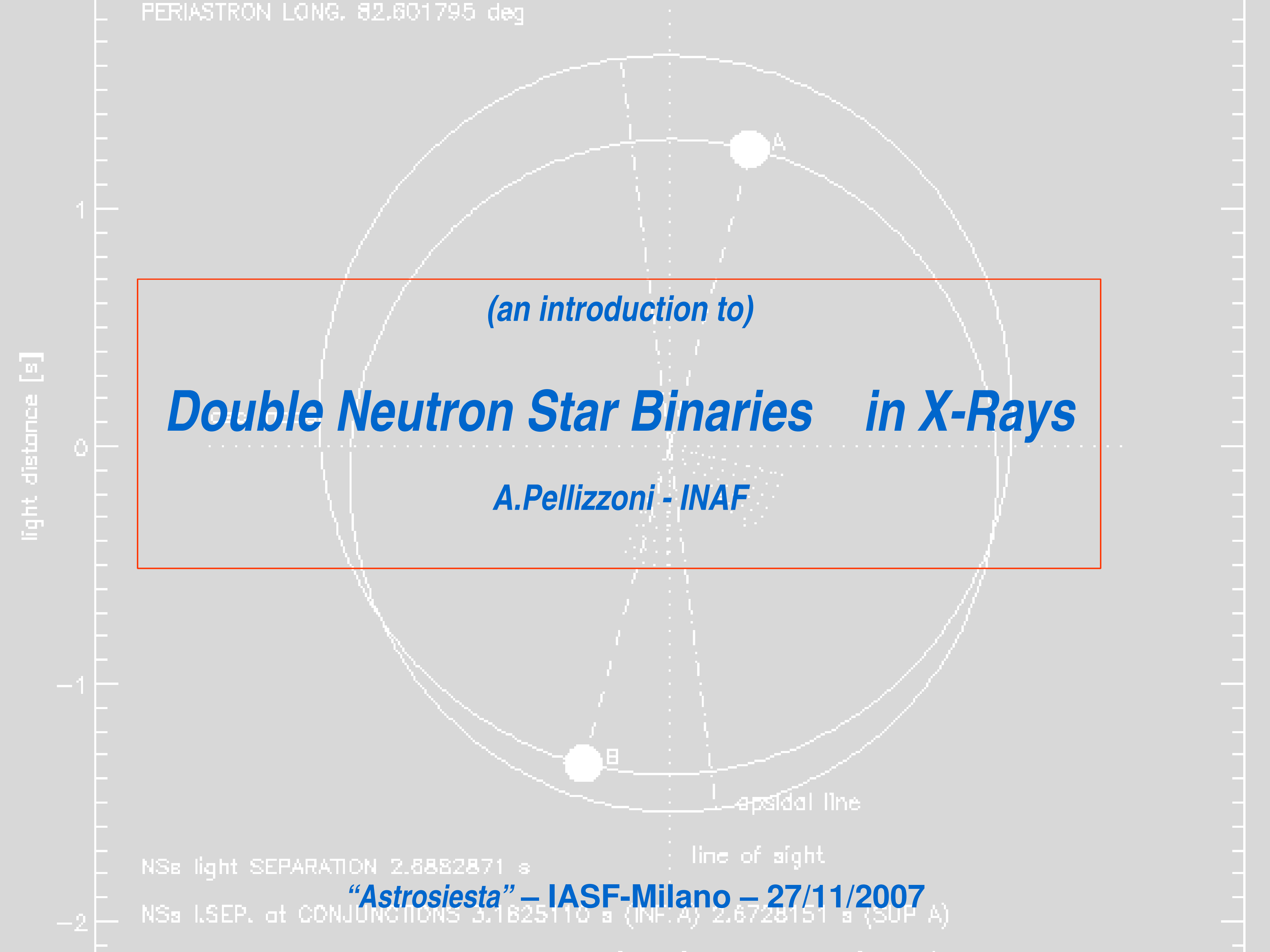
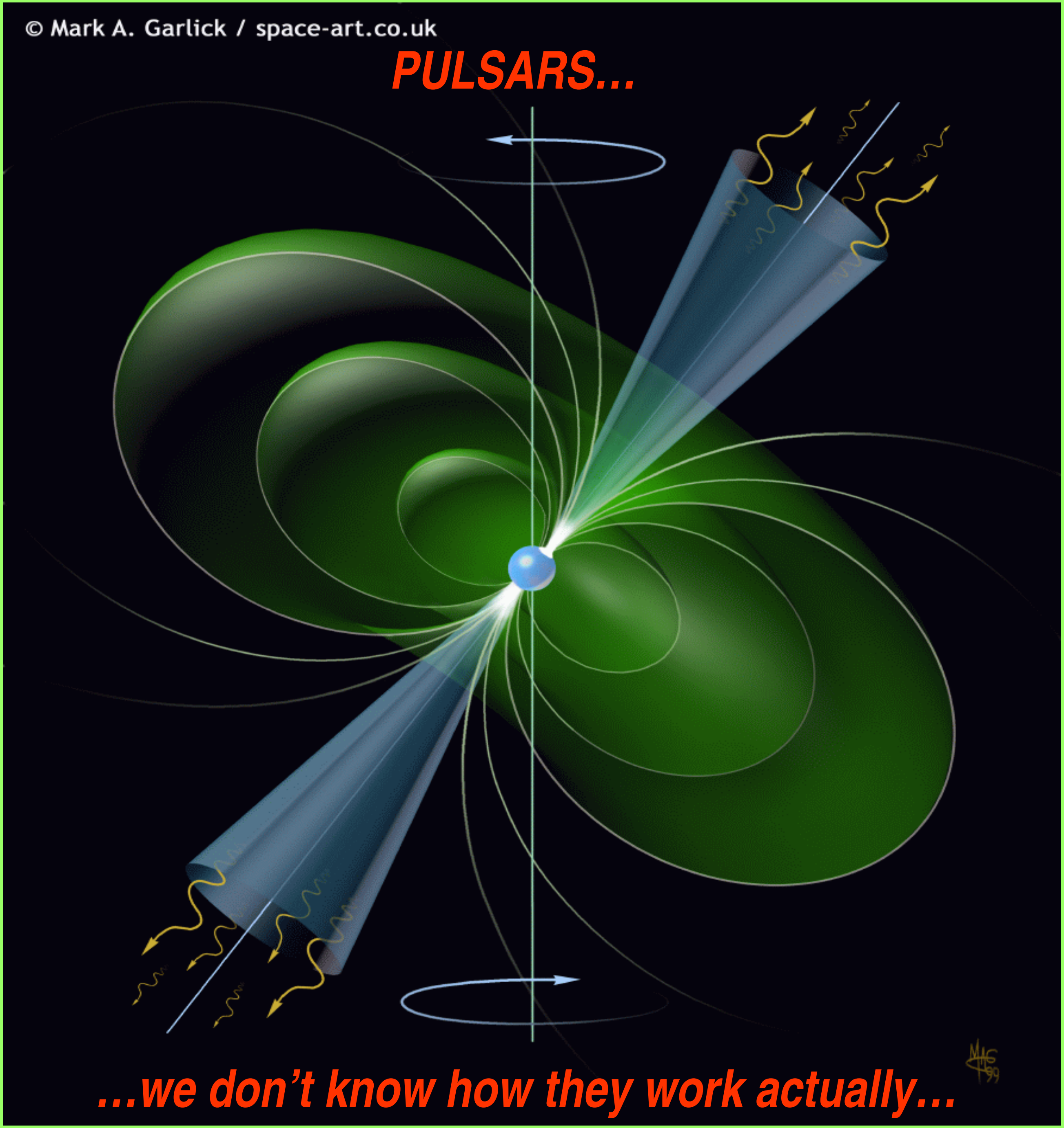
(an introduction to)

Double Neutron Star Binaries in X-Rays

A.Pellizzoni - INAF



“Astrosiesta” – IASF-Milano – 27/11/2007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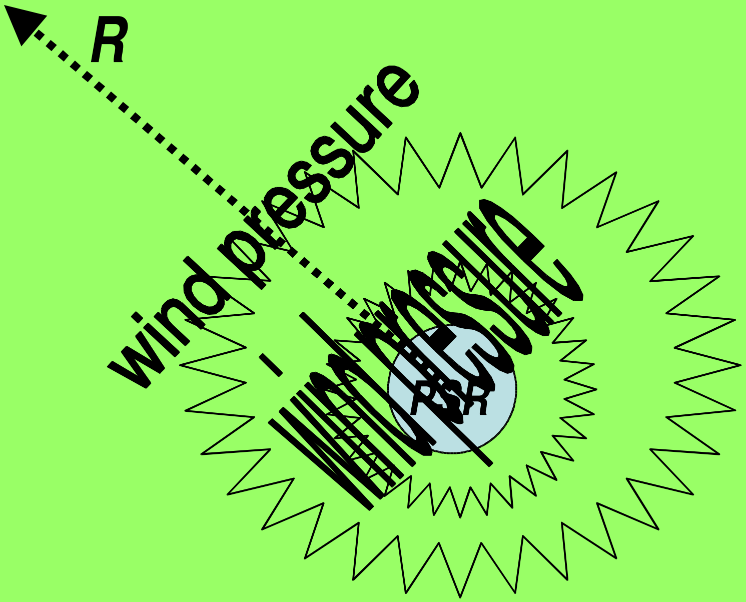
PULSARS...
...we don't know how they work actually...

PULSAR WIND PRESSURE

Most of PSR spin-down energy $\dot{E}_{rot}$ (10^{35}-10^{39} erg/s) in pulsar wind ($\gamma=10^{6}$)

$$P_{wind}(R)=\frac{\dot{E}_{rot}}{4\pi R^{2}c}$$

$R=$ Distance from PSR surface



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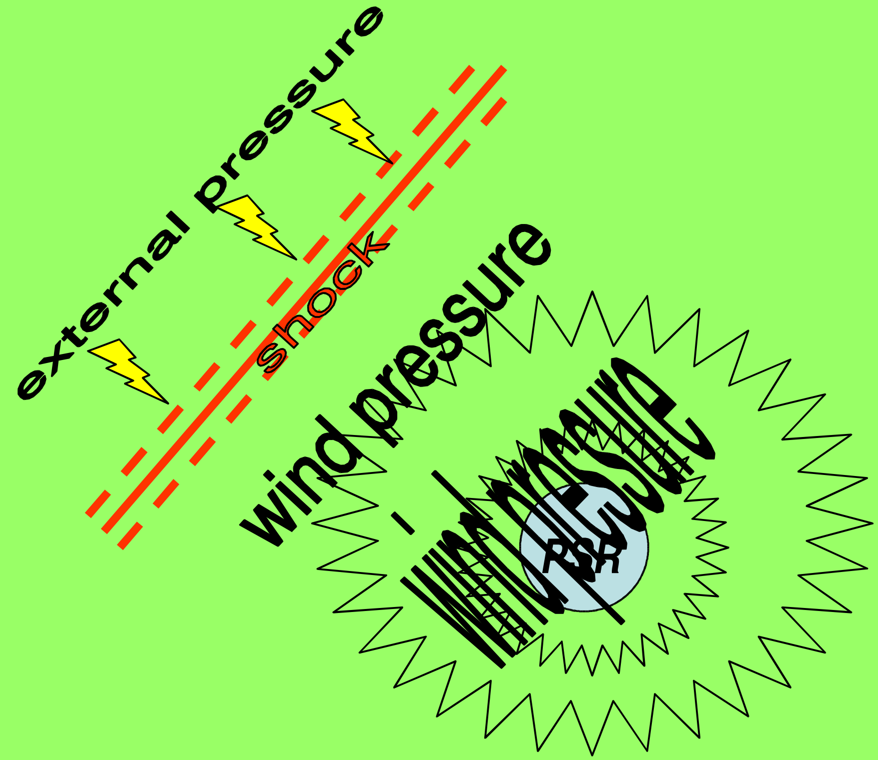


$R=$ Distance from PSR surface

$$P_{wind}(R_{EQ})=P_{external}(R_{EQ})$$

$R_{EQ}=$ Equilibrium distance

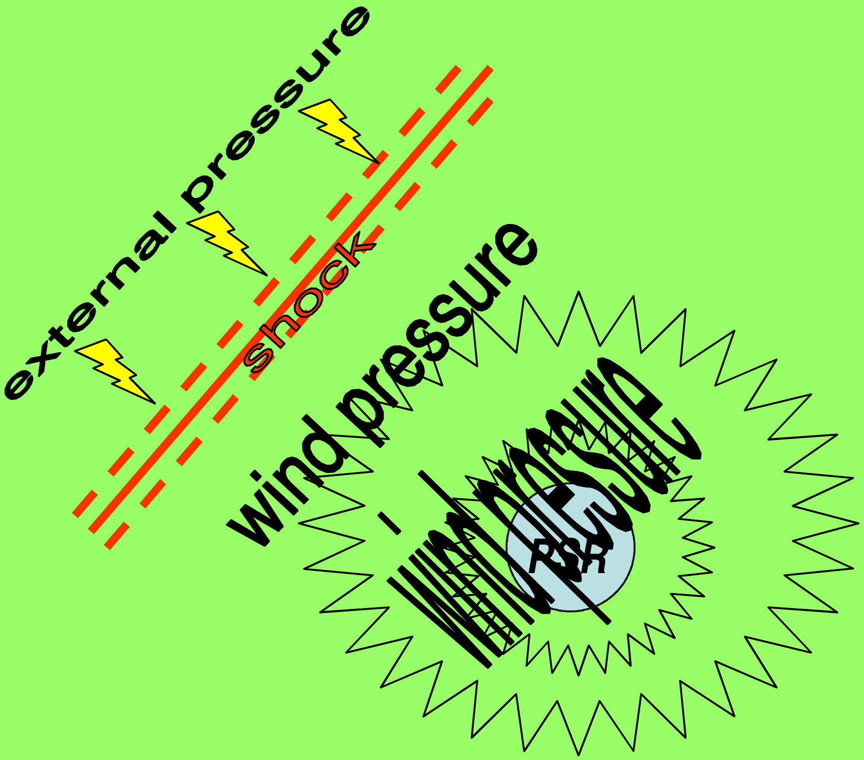
At R_{EQ}: shock → synchrotron emission (+ IC emission)

Nature/strength of $P_{EXTERNAL}$?

Typical R_{EQ} ?

$$P_{wind}(R)=\frac{\dot{E}_{rot}}{4\pi R^2 c}$$

$R =$ Distance from PSR surface



$$P_{wind}(R_{EQ})=P_{external}(R_{EQ})$$

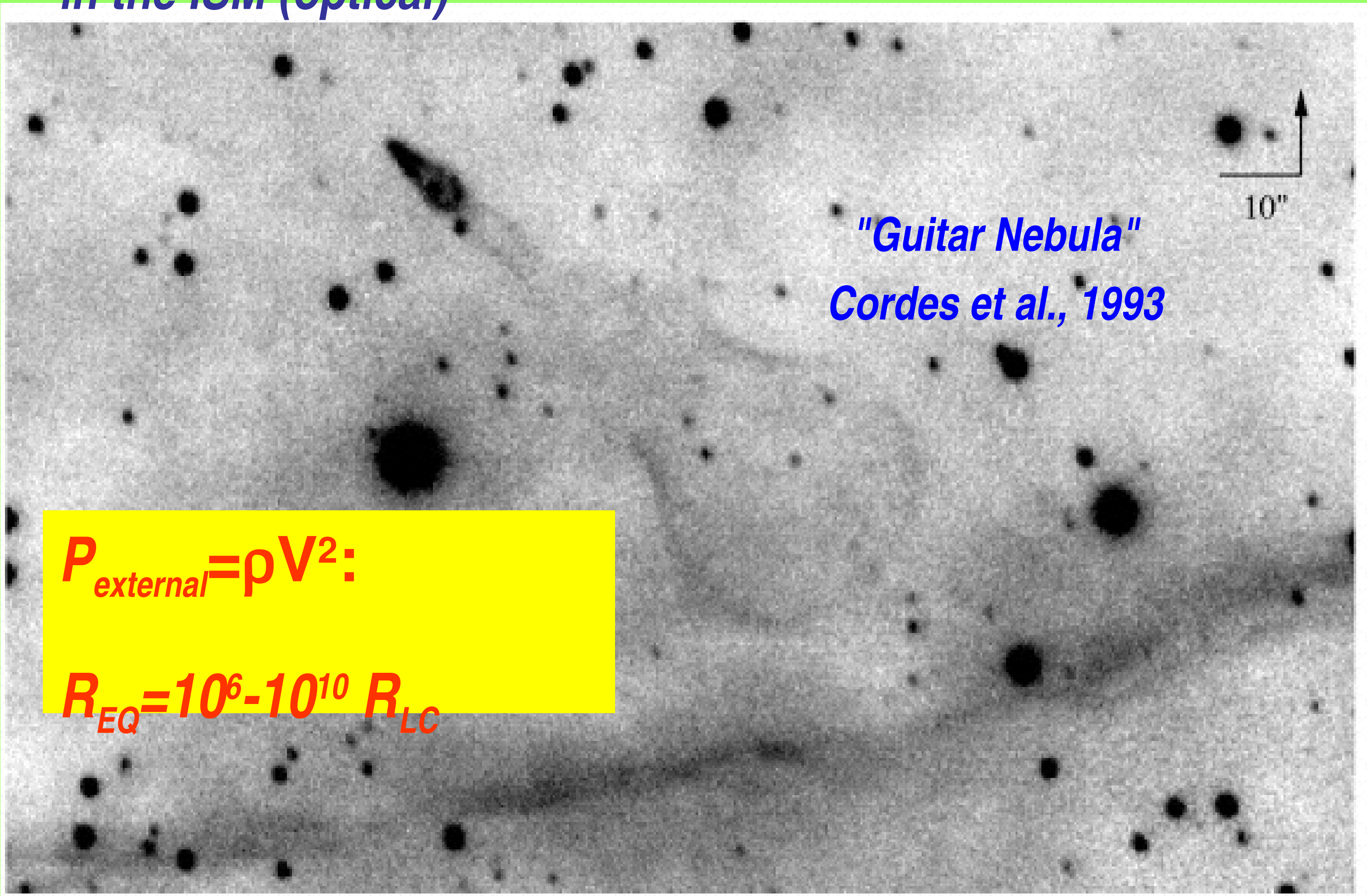
$R_{EQ} =$ Equilibrium distance

At R_{EQ}: shock → synchrotron emission (+ IC emission)

$P_{EXTERNAL}$ possible origins:

- **Ram pressure** *due to supersonic motion (>10 km/s) of the NS in the ISM*
- **Supernova Remnant cold ejecta**: *static Pulsar Wind Nebulae/plerions (e.g. Crab)*
- **Outflow from a stellar companion** *(e.g. PSRB1259-63 + Be star, PSRB1957+20 + white dwarf)*
- **Wind/magnetosphere pressure** *of a companion NS (DNSB)*

Ram pressure due to supersonic motion of the NS (>10 km/s) in the ISM (optical)



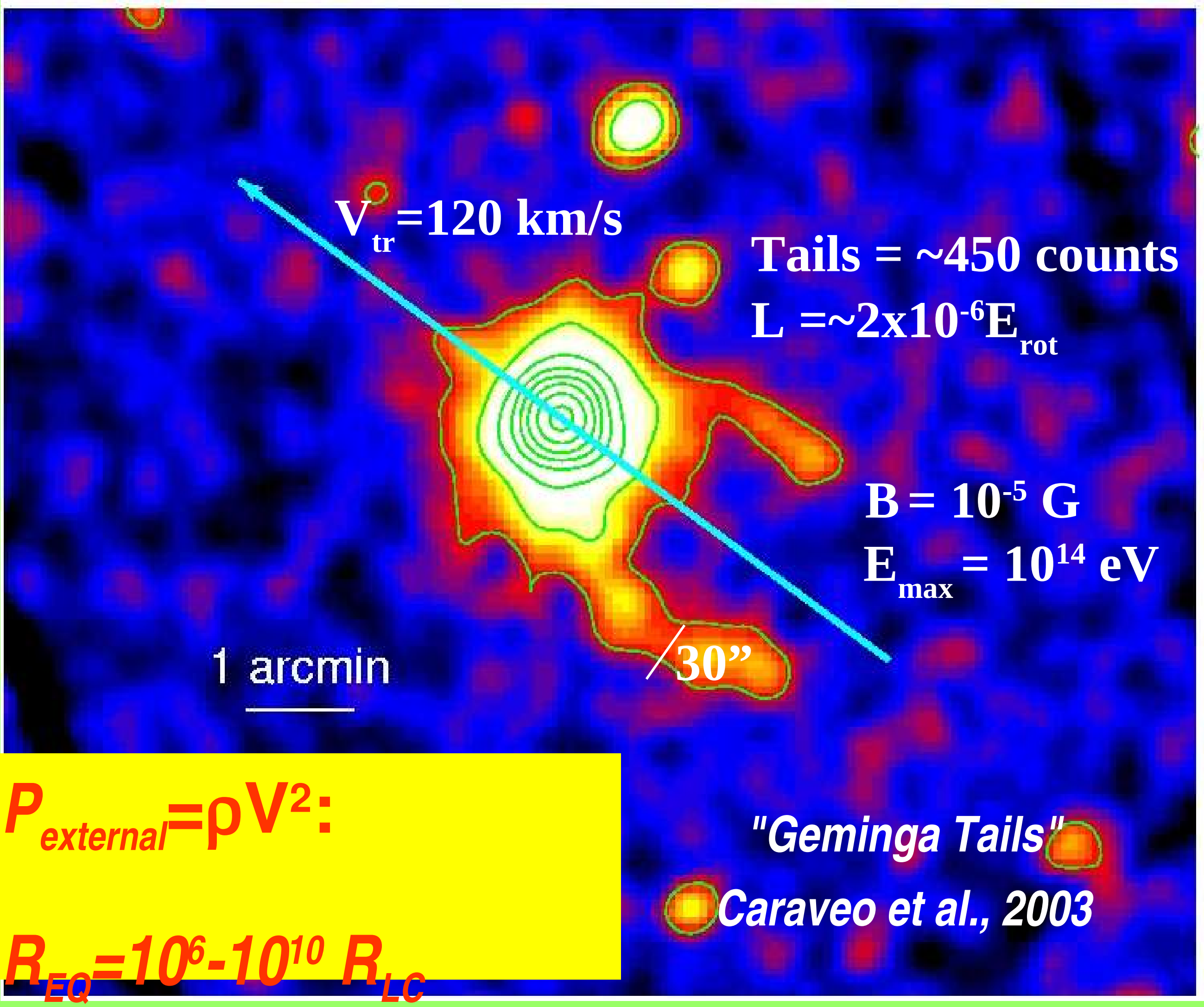
$P_{external} = \rho V^2$:

$R_{EQ} = 10^6 - 10^{10}\ R_{LC}$

"Comet-shaped" bow-shocks:

High pulsar velocity in the Interstellar Medium

Ram pressure due to supersonic motion of the NS (>10 km/s) in the ISM (X-rays)



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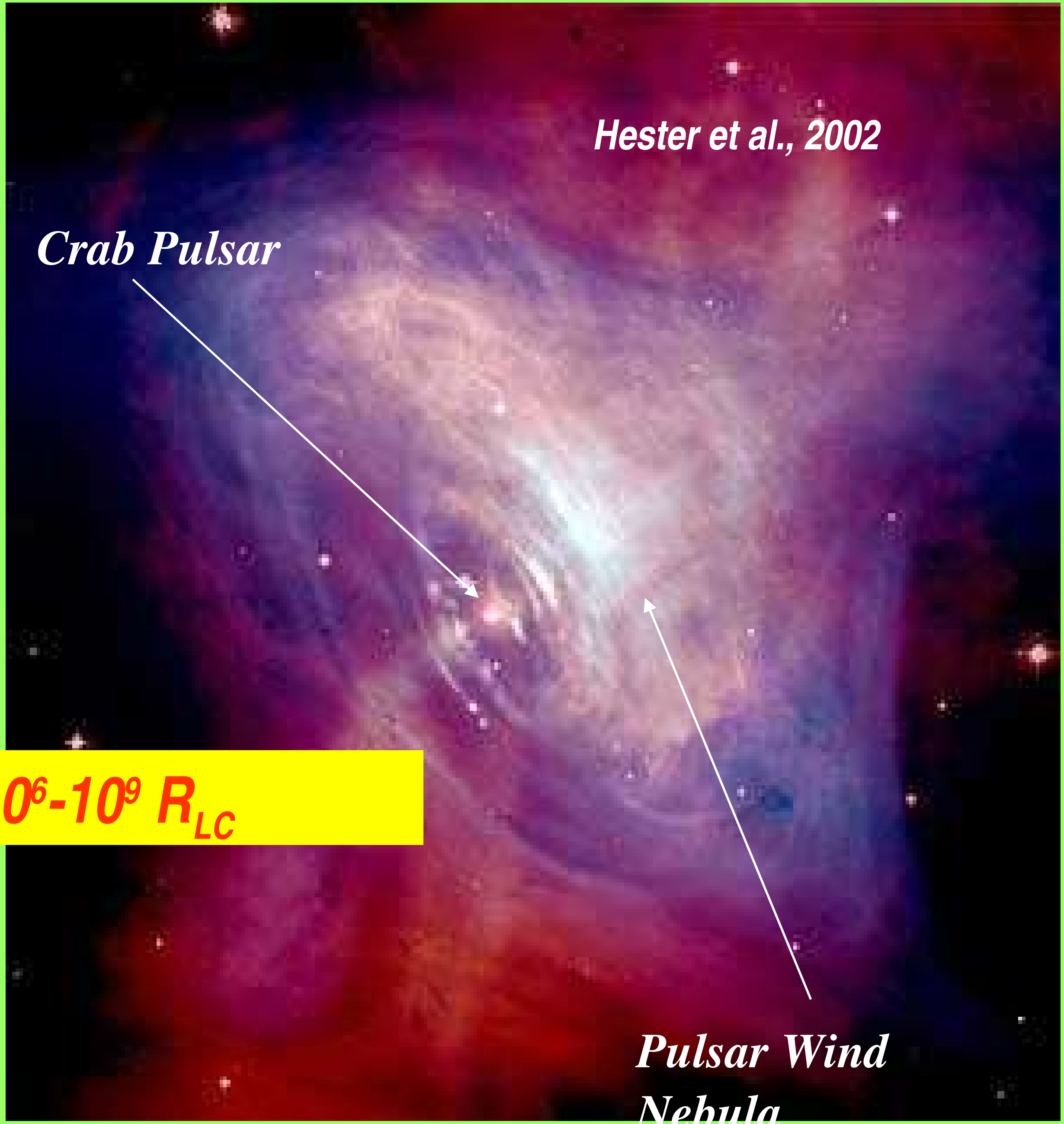
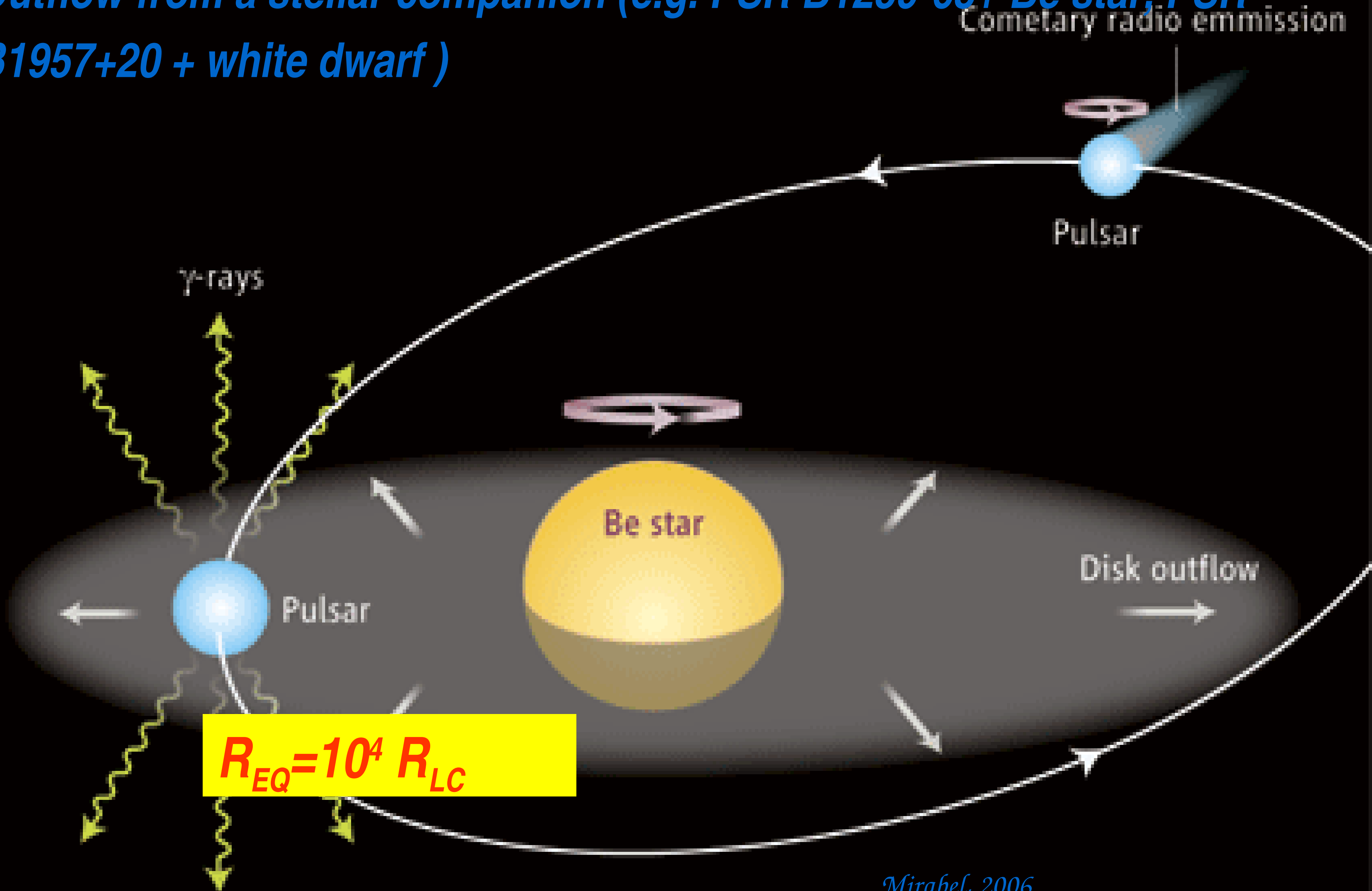
SNR cold ejecta pressure: static Pulsar Wind Nebulae/plerions



$R_{EQ}=10^6-10^9\ R_{LC}$

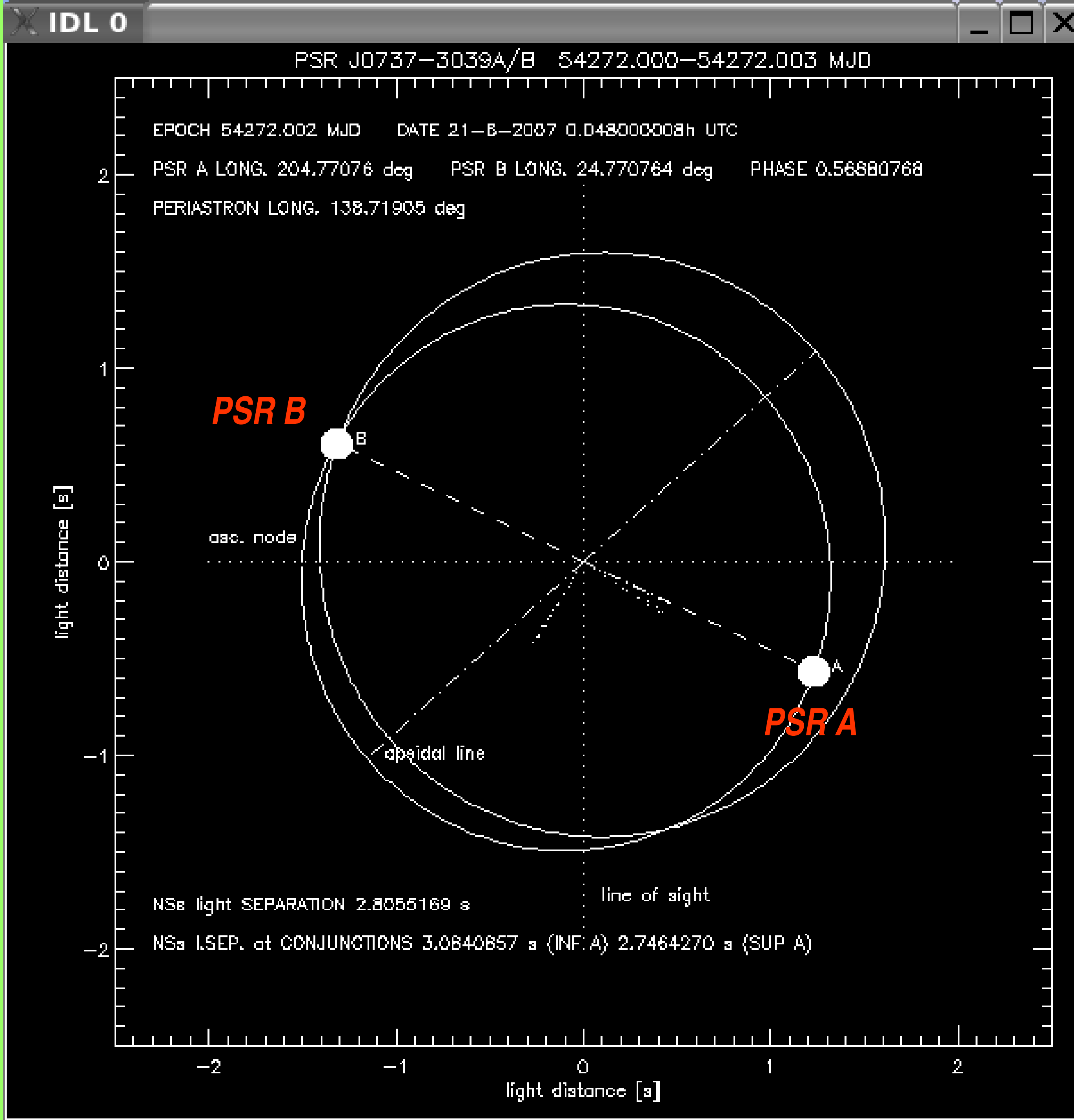
Outflow from a stellar companion (e.g. PSR B1259-63+ Be star, PSR B1957+20 + white dwarf)



$R_{EQ}=10^4\ R_{LC}$

Mirabel, 2006

Wind/magnetosp.pressure of a companion NS:



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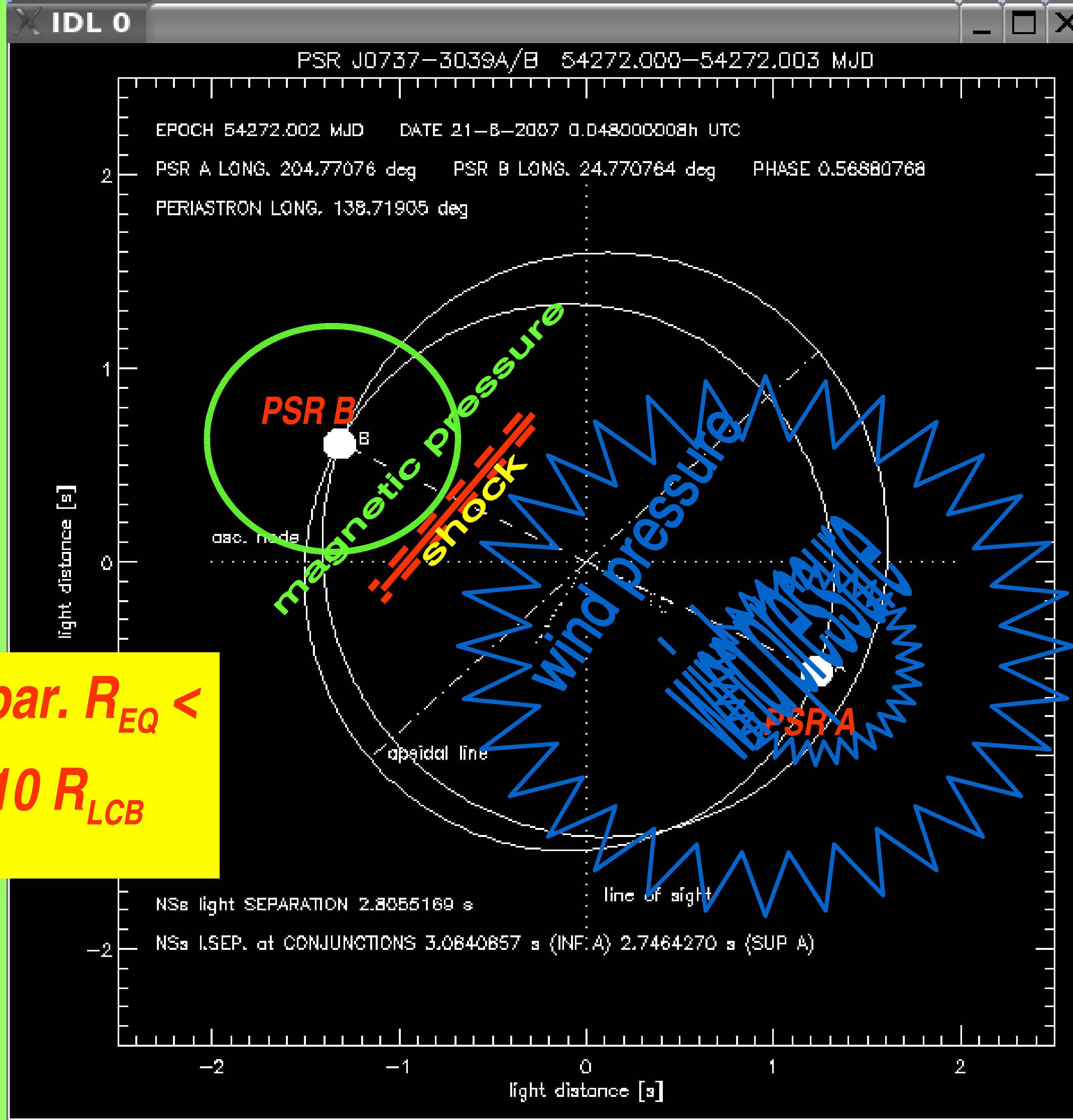

R_{EQ} < system separ. $R_{EQ} < 10^3 R_{LCA}$ $R_{EQ} < 10\, R_{LCB}$

$P_{EXTERNAL}$ possible origins and typical R_{EQ}:

- **Ram pressure** *due to supersonic motion (>10 km/s) of the NS in the ISM*

  → $R_{EQ}=10^6\text{-}10^{10}\ R_{LC}$

- **Supernova Remnant cold ejecta***: static Pulsar Wind Nebulae/plerions (e.g. Crab)*

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PSR wind magnetization parameter:

σ=Poynting flux/kinetic energy

σ *(R) dependences on pulsar distance*

σ *<<1 for $R_{EQ}=10^8$ Rlc as in Crab-like PWN*

σ *>>1?? for $R_{EQ} < 10^3$ Rlc as for DNSB as 0737*

Shock efficiency prop to 1/sqrt(σ), Kennel & Coroniti (1984)

Double Neutron Star Binaries (DNSB), a unique laboratory for studies in several fields:

Pulsar wind structure and magnetosphere close to PSR surface:

- *PSRs wind/magnetosphere shock → synchrotron emission (+ IC emission) → X-rays/γ-rays*

- *PSRs mutual interactions/absorption*

Double Neutron Star Binaries (DNSB)

Table 1: Firmly identified double neutron star binaries. Listed are the spin-down energy E_{rot}, distance d, pulsar period P and period derivative $\dot{P}$, E_{rot}/d^2, observed or estimated X–ray fluxes F, orbital period P_{orb} and eccentricity e.

	J0737-3039	**J1537+1155**	J1756-2251	J1915+1606	J2130+1210C
$E_{rot}(10^{33} ergs\ s^{-1})$	5.8	1.8	1.7	1.6	6.8
d (kpc)	0.5	1.0	2.5	7.0	10
P (ms)	22.7(PSR A)	37.9	28.5	59.0	30.5
$\dot{P}$ (10^{-18})	1.74	2.42	1.01	8.60	4.99
E_{rot}/d^2 $(10^{-10}$ erg cm^{-2} s$^{-1})$	24	1.9	0.28	0.03	0.07
$F^{(a)}_{0.2-3keV}$ $(10^{-15}$ erg cm^{-2} s$^{-1})$	35	2.4	0.7 7$^{(b)}$	0.08 7$^{(b)}$	0.2 7$^{(b)}$
P_{orb} (days)	0.102	0.421	0.32	0.3	0.3
e	0.0877	0.274	0.18	0.62	0.68

[a] X–ray flux in the 0.2-3 keV range.

[b] Extimated X–ray flux assuming $L_X = 3 \times 10^{-4} E_{rot}$.

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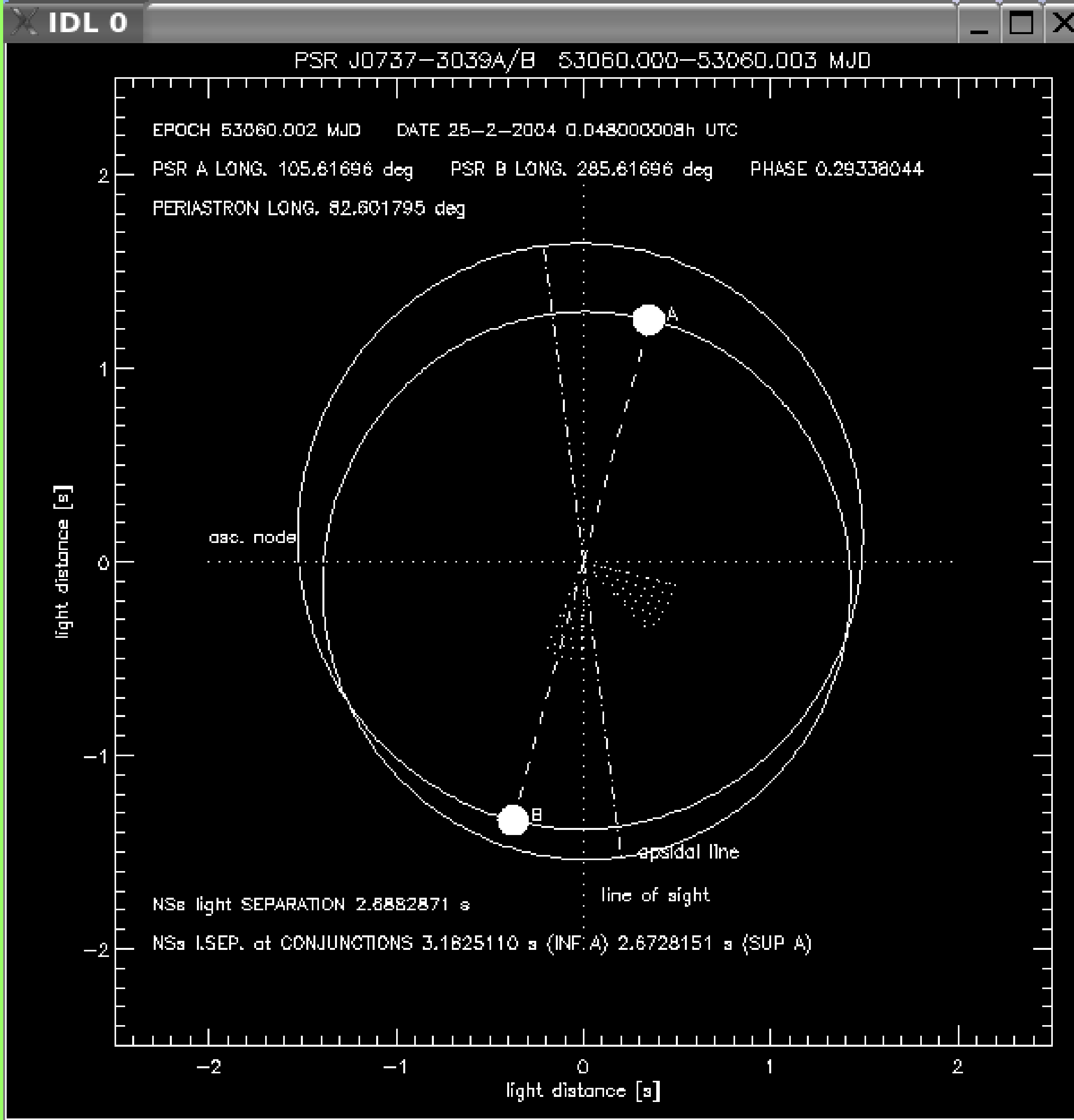
PSR J0737-3039: highest E_{ROT}/d^2 and shortest orbital period

Double neutron star system 0737-3039

Orbital period: 2.4 h

eccentricity=0.09

(Burgay et al., 2003)



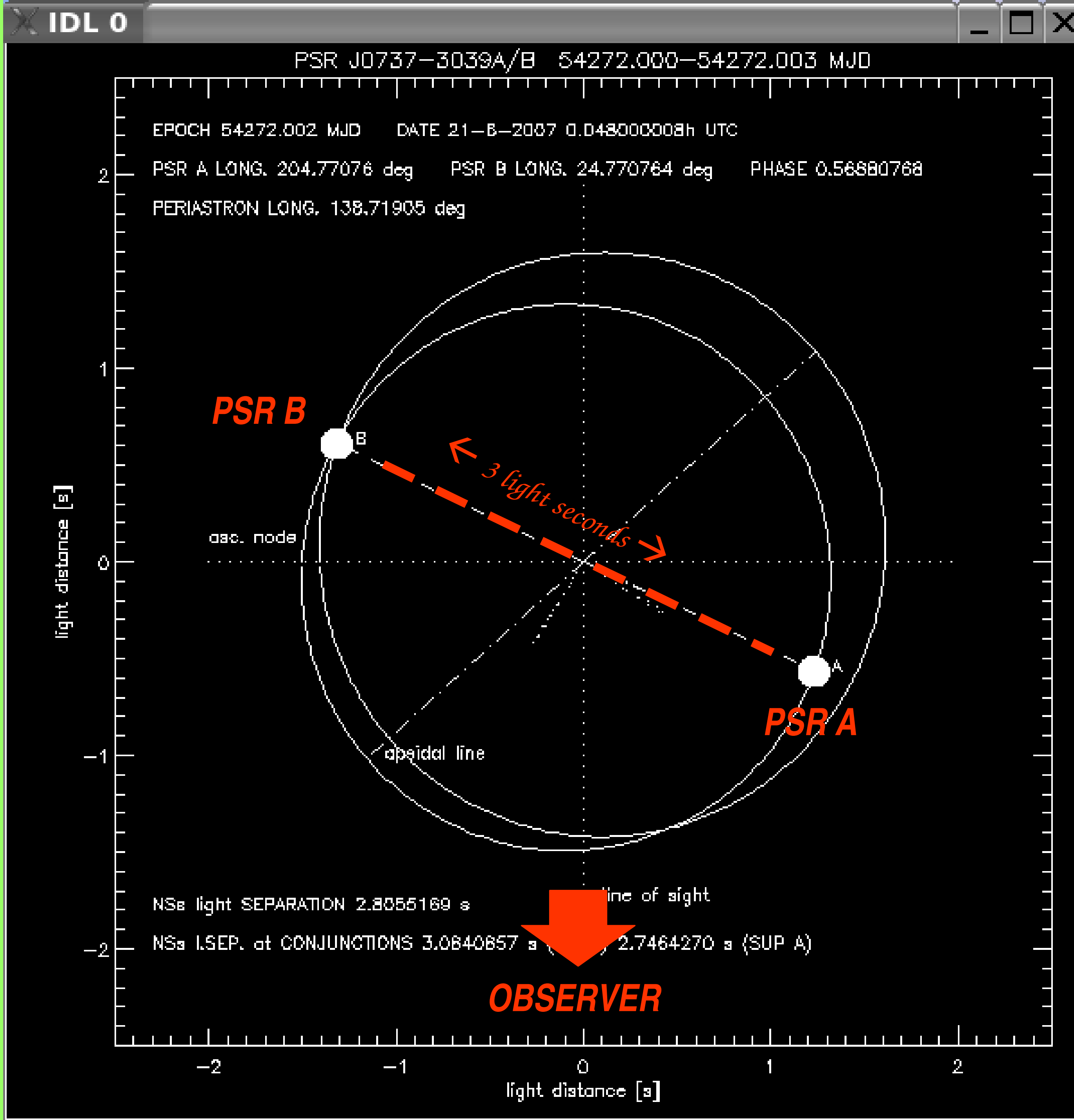
Double neutron star system
0737-3039

Orbital period: 2.4 h

eccentricity=0.09

System observed nearly edge-on

PSRs separation 3 light seconds



PSR A: P=22.7 ms $E_{ROT}=6x10^{33}$ erg/s, τ=210 Myr

$B=6.3x10^{9}$ G

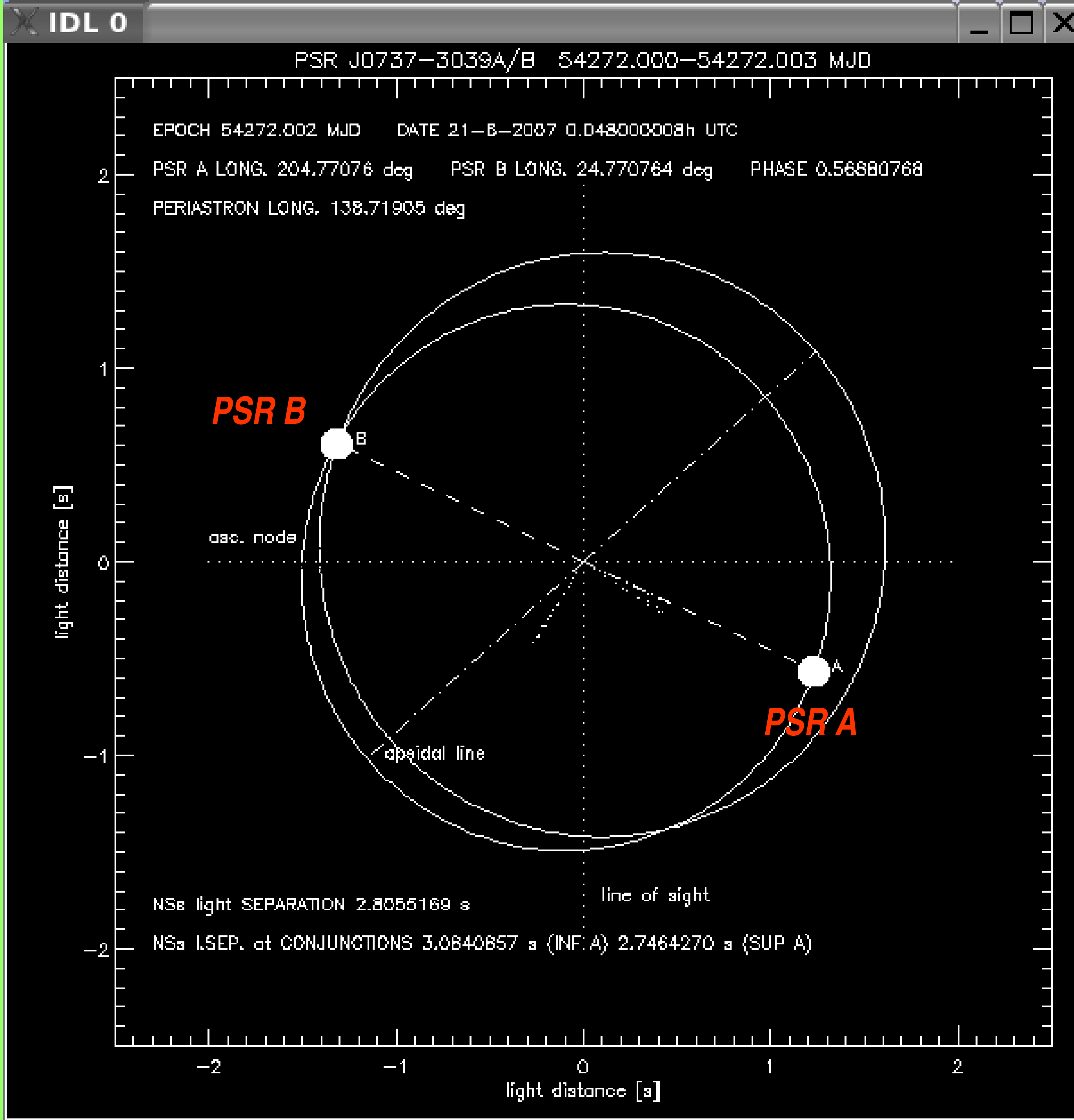
1.337 M_{SOL}

PSR B: P=2.7 s $E_{ROT}=2x10^{30}$ erg/s τ=50 Myr

$B=1.2x10^{12}$ G

1.25 M_{SOL}

Lyne et al., 2004



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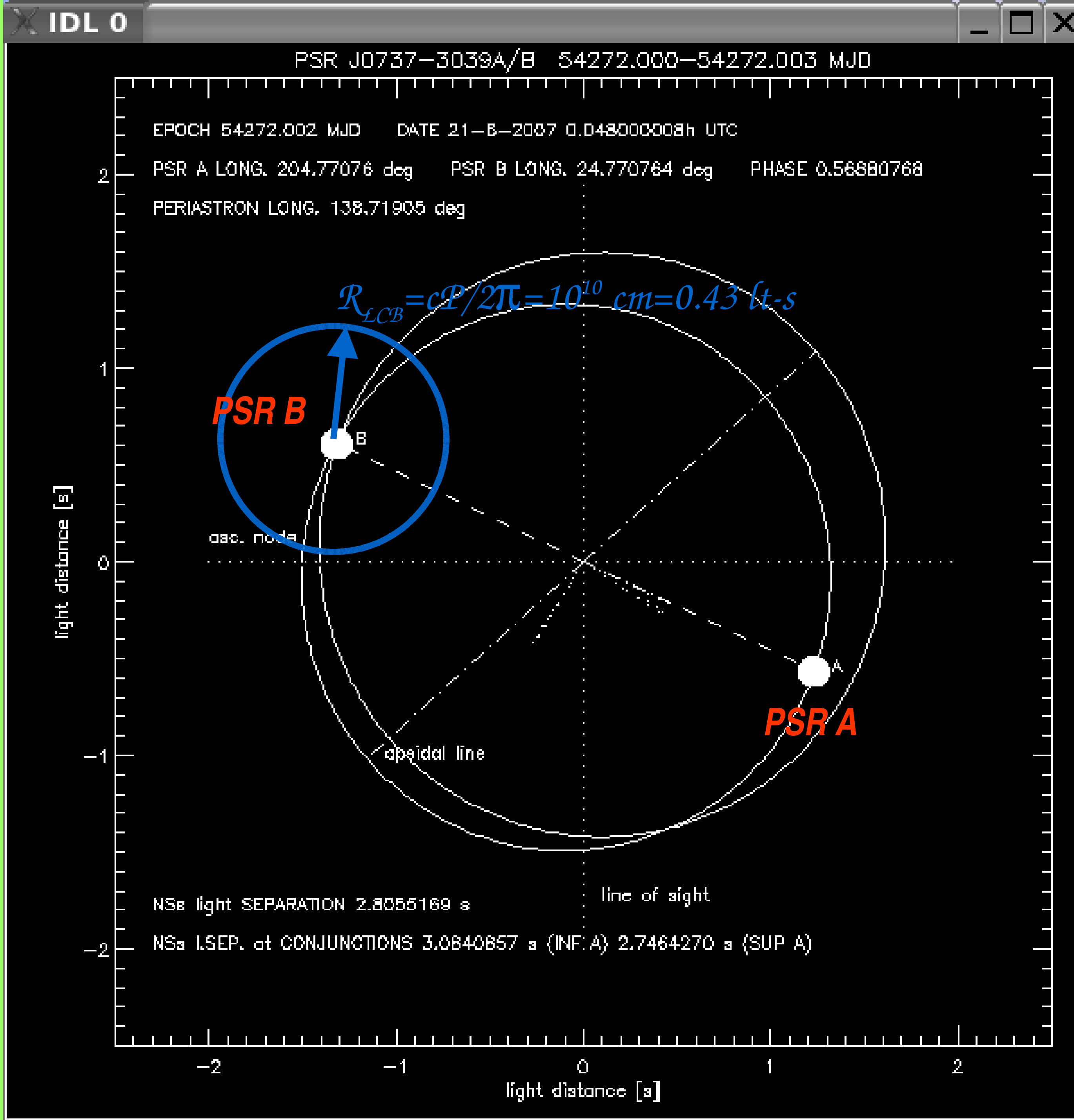


Double neutron star system 0737-3039

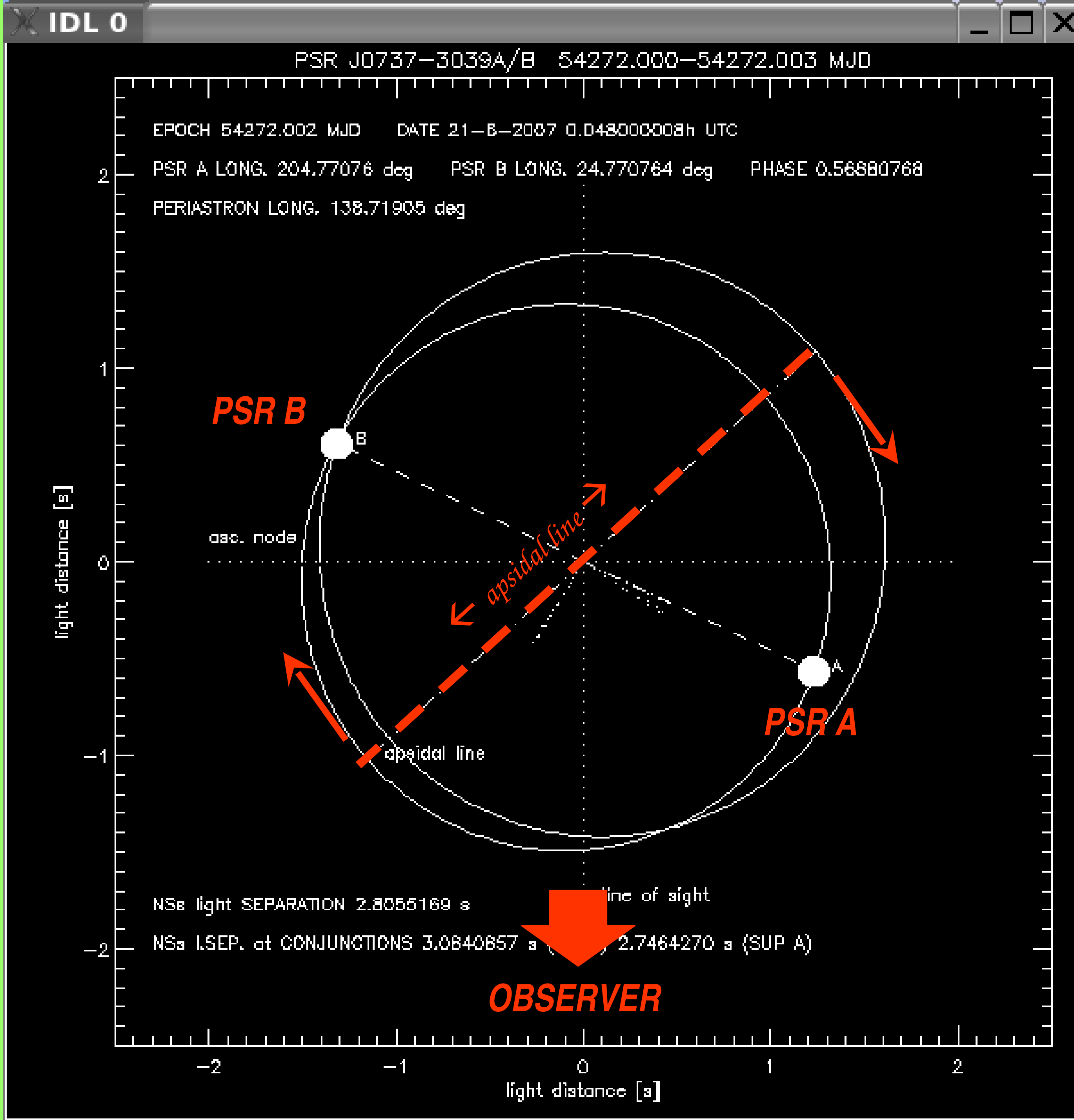
Advance of Periastron:

16.9 degrees/year!

PSR separation shrinkage: 7mm/day

Future: moment of inertia of NS…

(Kramer et al., 2006)



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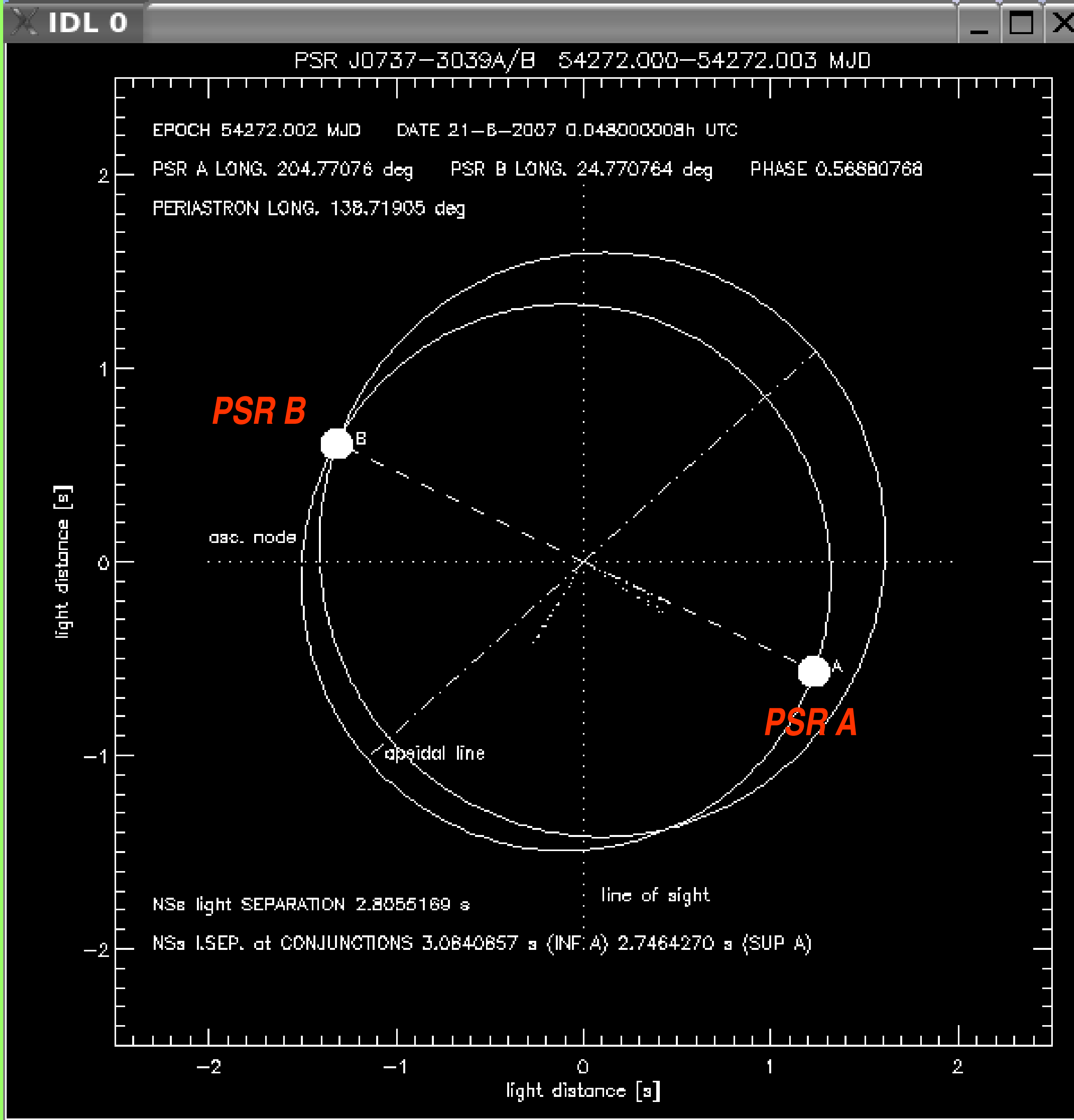
PSRs similar to PSR A are well known as X-ray emitters.



WHERE DO X-RAYS COME FROM?

The engine providing power via spin-down is PSR A's E_{ROT}

(PSR B is too slow to contribute)

No other comparable power plants in the system

WHERE DO X-RAYS COME FROM?

- *Emission originating from magnetosphere and surface of PSR A* **(“Normal” ms PSR model**)

- *Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM* (**PWN model**)

- *Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A’s relativistic wind and B’s magnetosphere* (**magnetosheath model**)

- *Thermal emission from PSR B heated by A through magnetospheric absorption* (**PSR B “illumination model”**)

- …

WHERE DO X-RAYS COME FROM?

- ***Emission originating from magnetosphere and surface of PSR A ("Normal" ms PSR model)***

- *Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM*

- *Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A's relativistic wind and B's magnetosphere*

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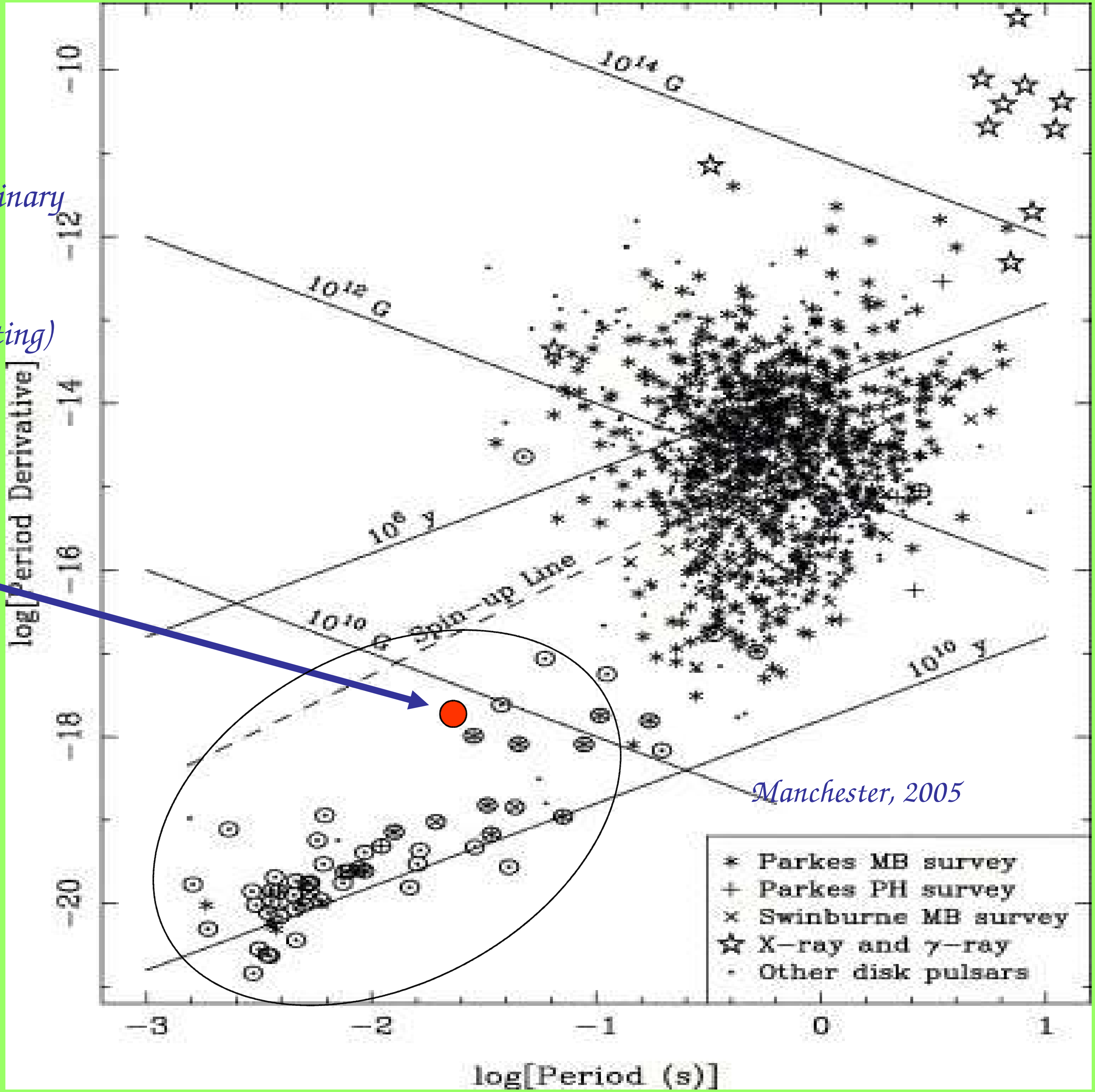
- *…*

Emission originating from magnetosphere and surface of PSR A:

>170 ms PSRs known (most in binary systems)

→ *40 in X-ray (non accreting)*

PSR A



$P_{dot} \le 10^{-18}$

$B \le 10^{10}$ G

τ = 0.1-10 Gyr

Emission originating from magnetosphere and surface of PSR A:

ms PSRs classification (e.g. Zavlin, 2006):

High-luminosity (E_{ROT}>10^{35} erg/s) fast (P<3 ms) ms PSRs:

non-thermal emission ($2<\gamma<2.5$), pulsed fraction (65%-100%), narrow pulses

Low-luminosity ($10^{32}<E_{ROT}<10^{33}$ erg/s) ms PSRs:

thermal BBs from PCs, pulsed fraction (35%-50%), broad pulses

Both classes: $L_X=10^{-4}-10^{-3}\ E_{ROT}$

WHERE DO X-RAYS COME FROM?

- *Emission originating from magnetosphere and surface of PSR A*
- ***Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM (PWN model)***
- *Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A's relativistic wind and B's magnetosphere*
- *Thermal emission from PSR B heated by A through magnetospheric absorption*
- …

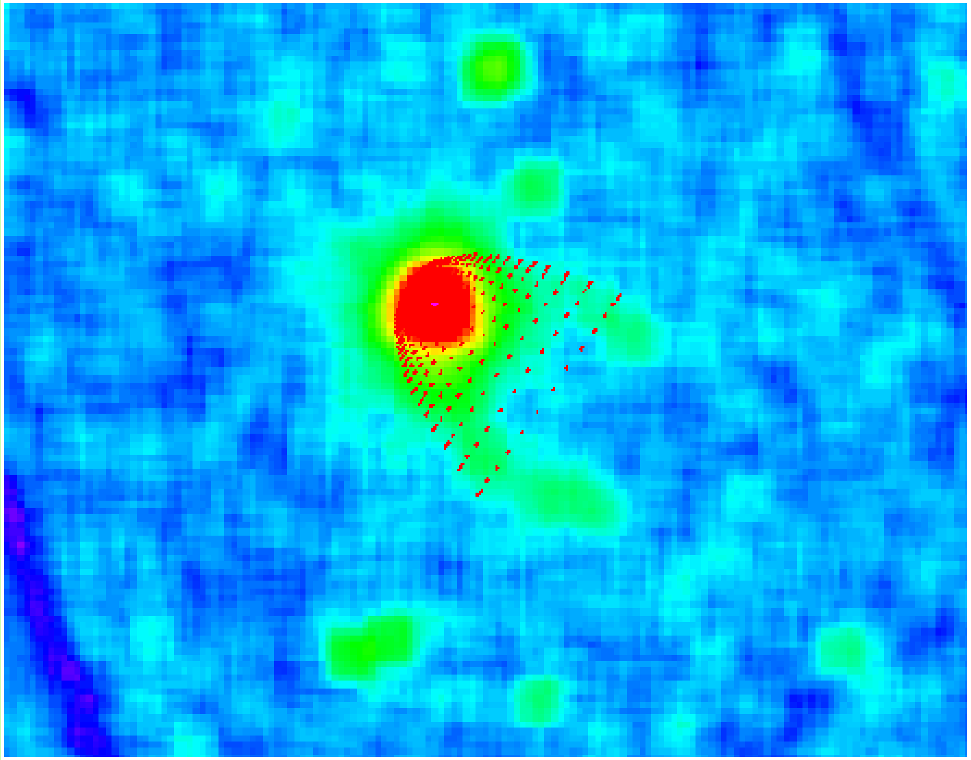
Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM (Granot & Meszaros, 2004)

Emission from the interaction of the two pulsars is lower ($<10^{29}$ erg/s) than that expected from the interaction of pulsar A's wind alone with the ISM:

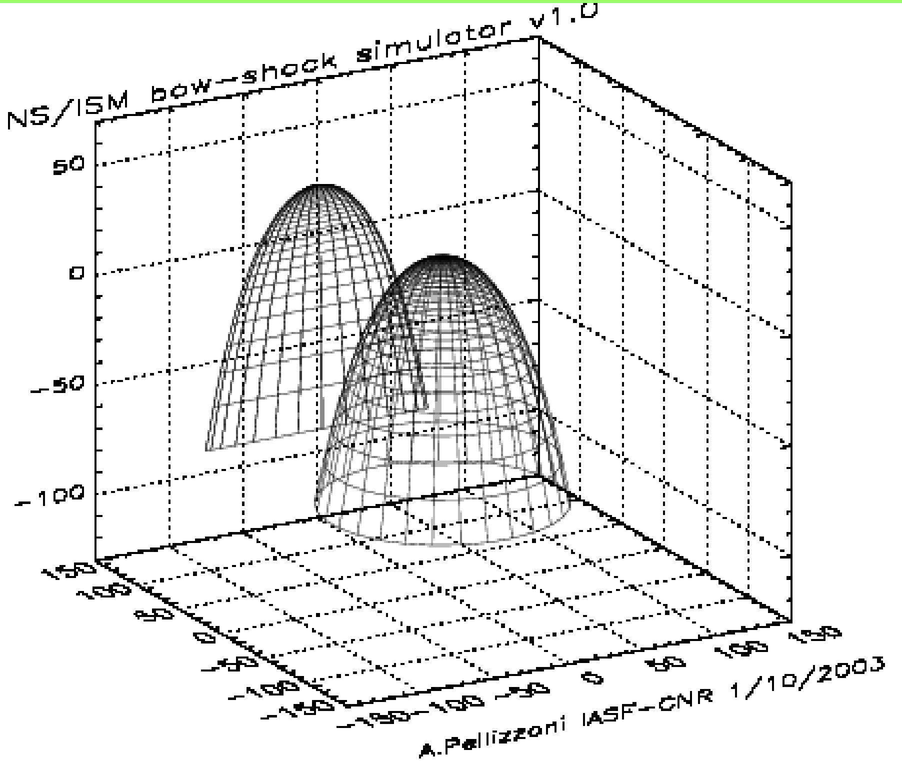
Power-law spectrum up to 60 keV: **$L_X = 7 \times 10^{29}$ erg/s $= 10^{-4}$ E_{ROT} erg/s**

Shock at $R_{EQ} = 5 \times 10^{15}$ cm, very far from PSR A

PSR/bow-shock angular separation < 1 arcsec



3D pulsar/ISM bow-shock model



proper motion inclination angle and bow-shock stand-off angle can be obtained from the fit of the 3d model

WHERE DO X-RAYS COME FROM?

- *Emission originating from magnetosphere and surface of PSR A*

- *Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM*

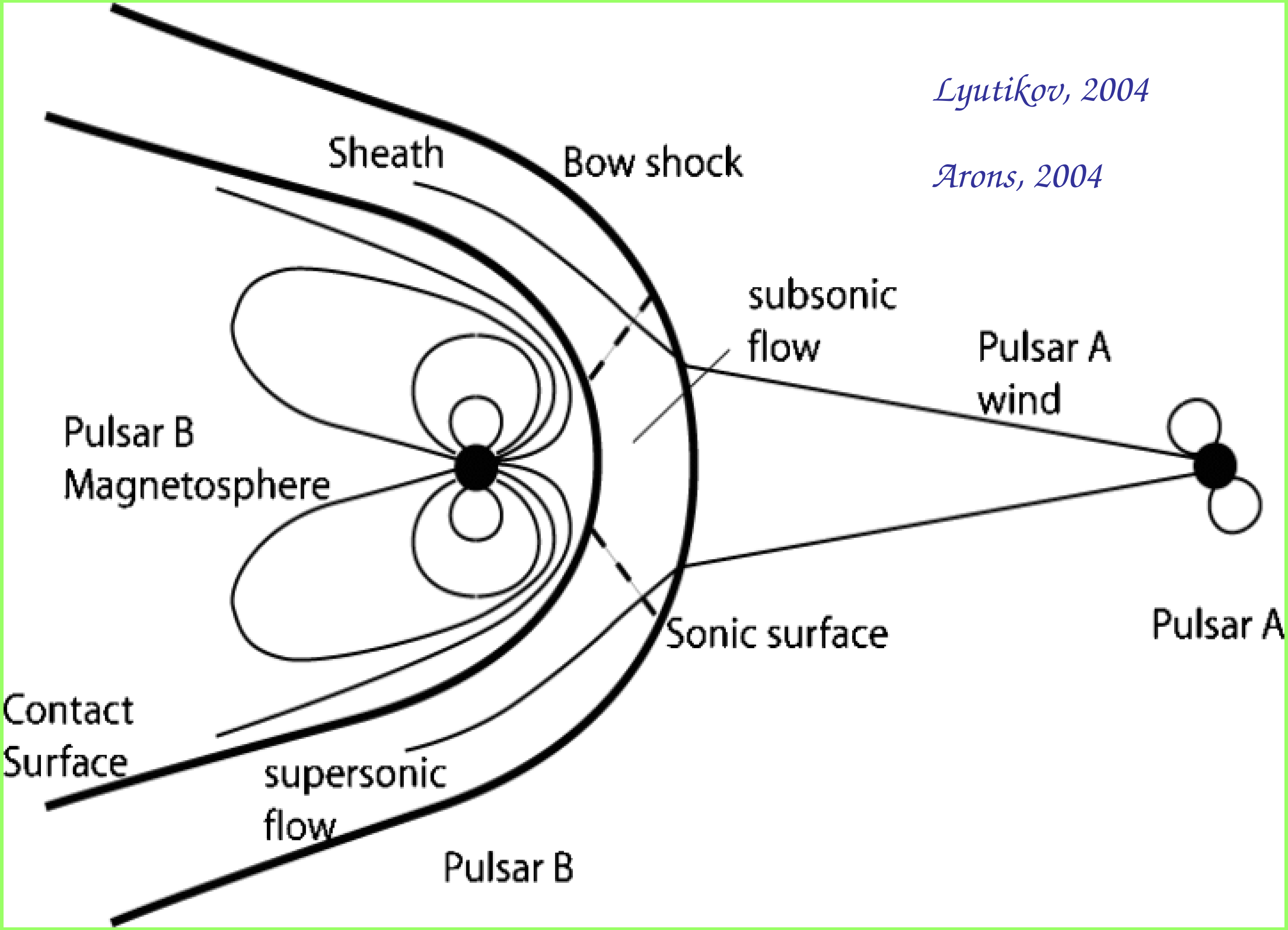
- ***Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A's relativistic wind and B's magnetosphere** (**magnetosheath model**)*

- *Thermal emission from PSR B heated by A through magnetospheric absorption*

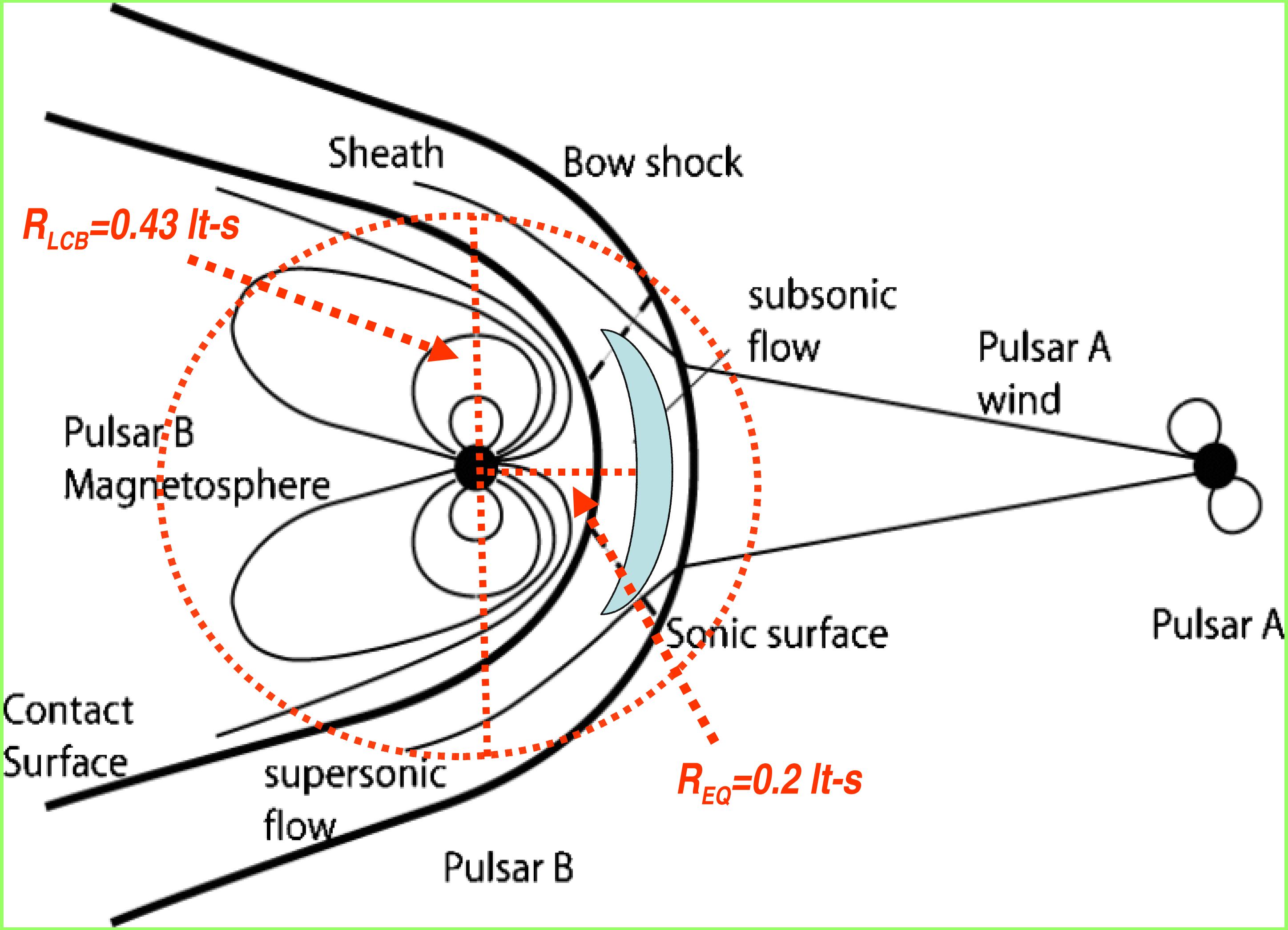
- …

$P_{EXTERNAL}(R)$? PSR B wind or PSR B magnetosphere pressure?

Similar to the interaction between the Earth and the solar wind

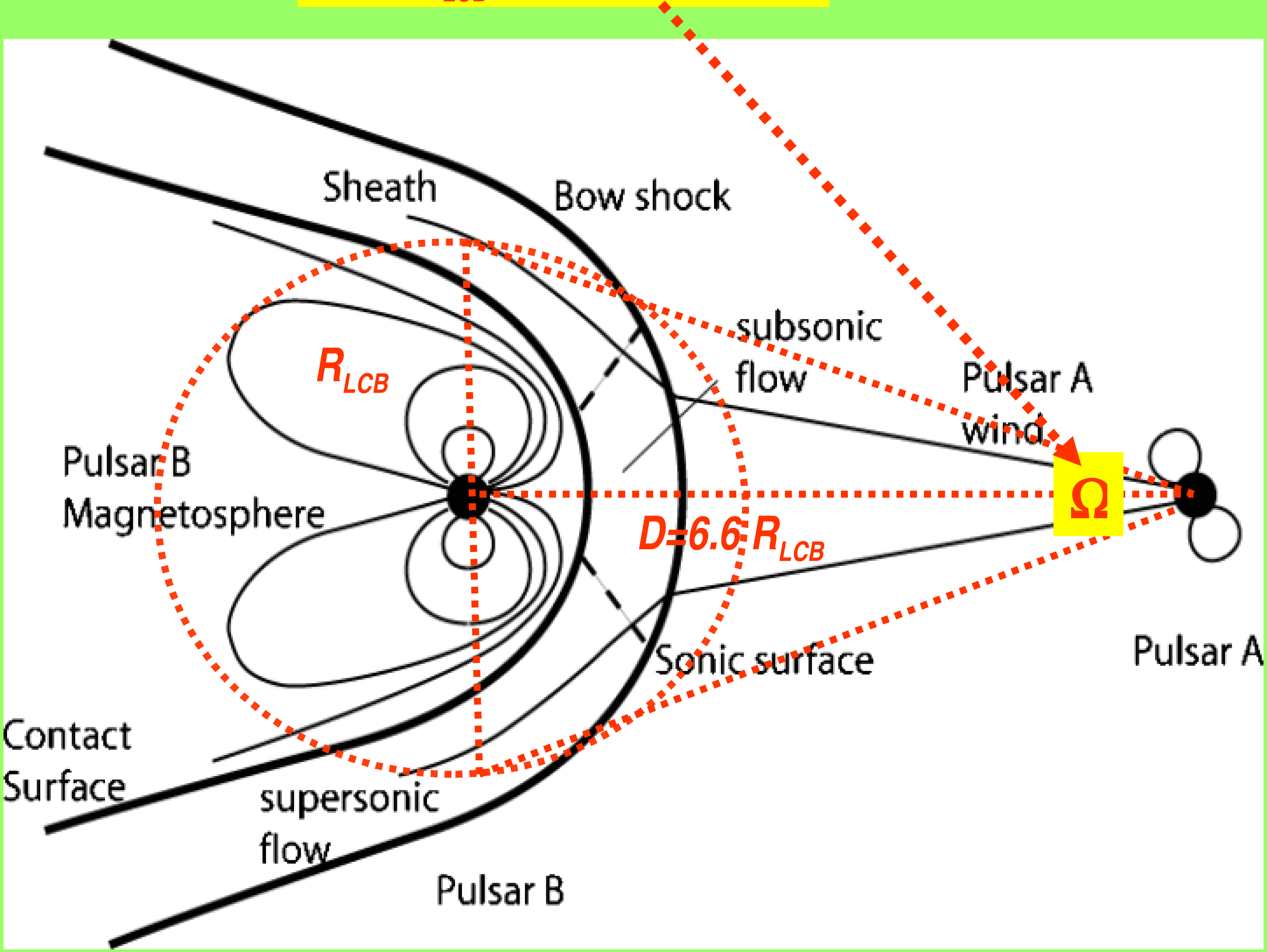


Wind pressure (PSR A)=magnetic pressure (PSR B) at R_{EQ}=0.2 lt-s from B



Wind pressure (PSR A)=magnetic pressure (PSR B) at R_{EQ}=0.2 lt-s from B

$\Omega=\pi(R_{LCB}/D)^2=0.07\ sr$

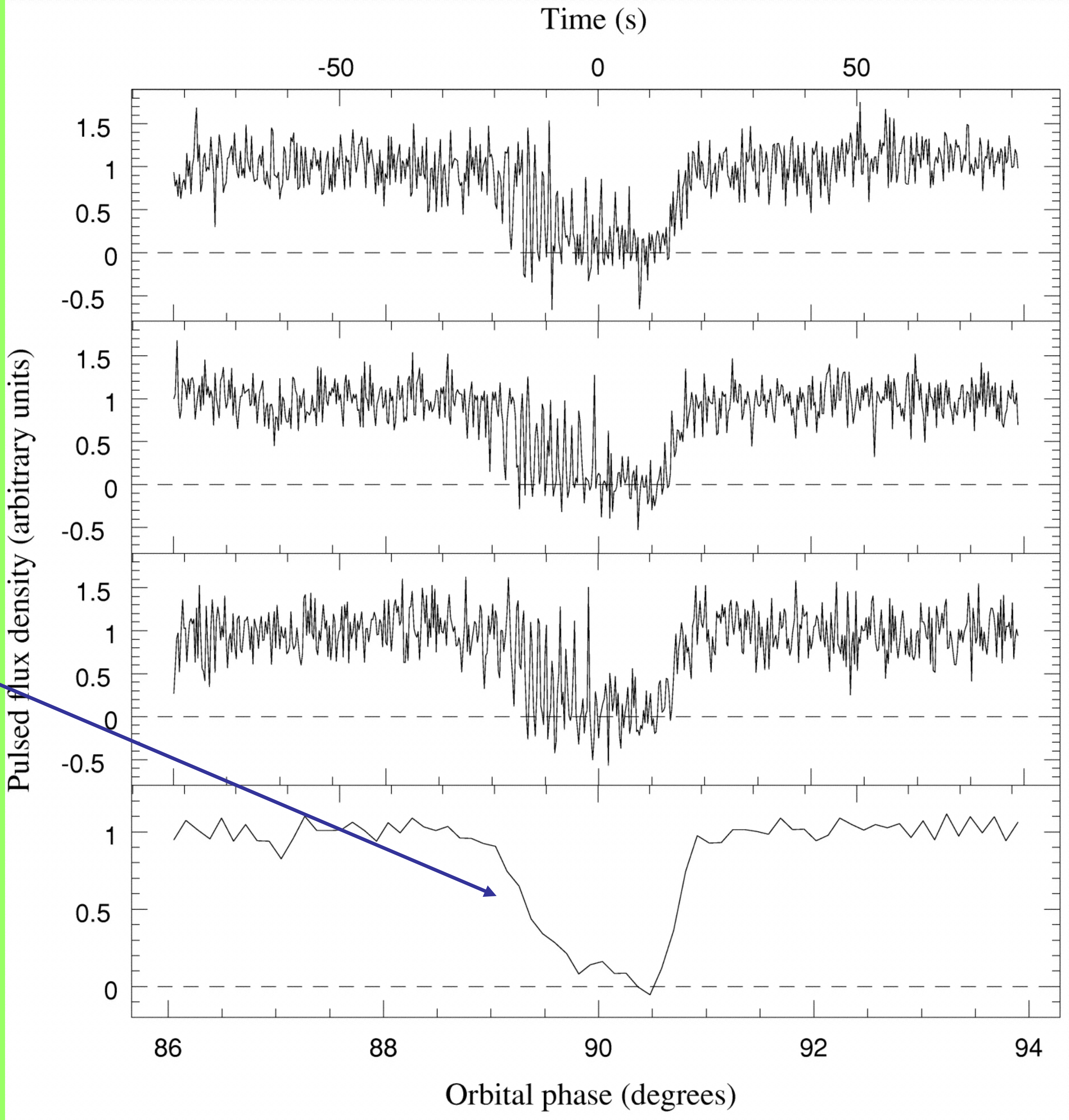


$E_{SHOCK} > E_{ROT}\Omega/4\pi = 10^{31}$ erg/s $= 10^{-2}\text{-}10^{-3}\ E_{ROT}$ erg/s

Double neutron star system 0737-3039

PSR A eclipsed at its superior conjunction for 30 s

McLaughlin, 2004



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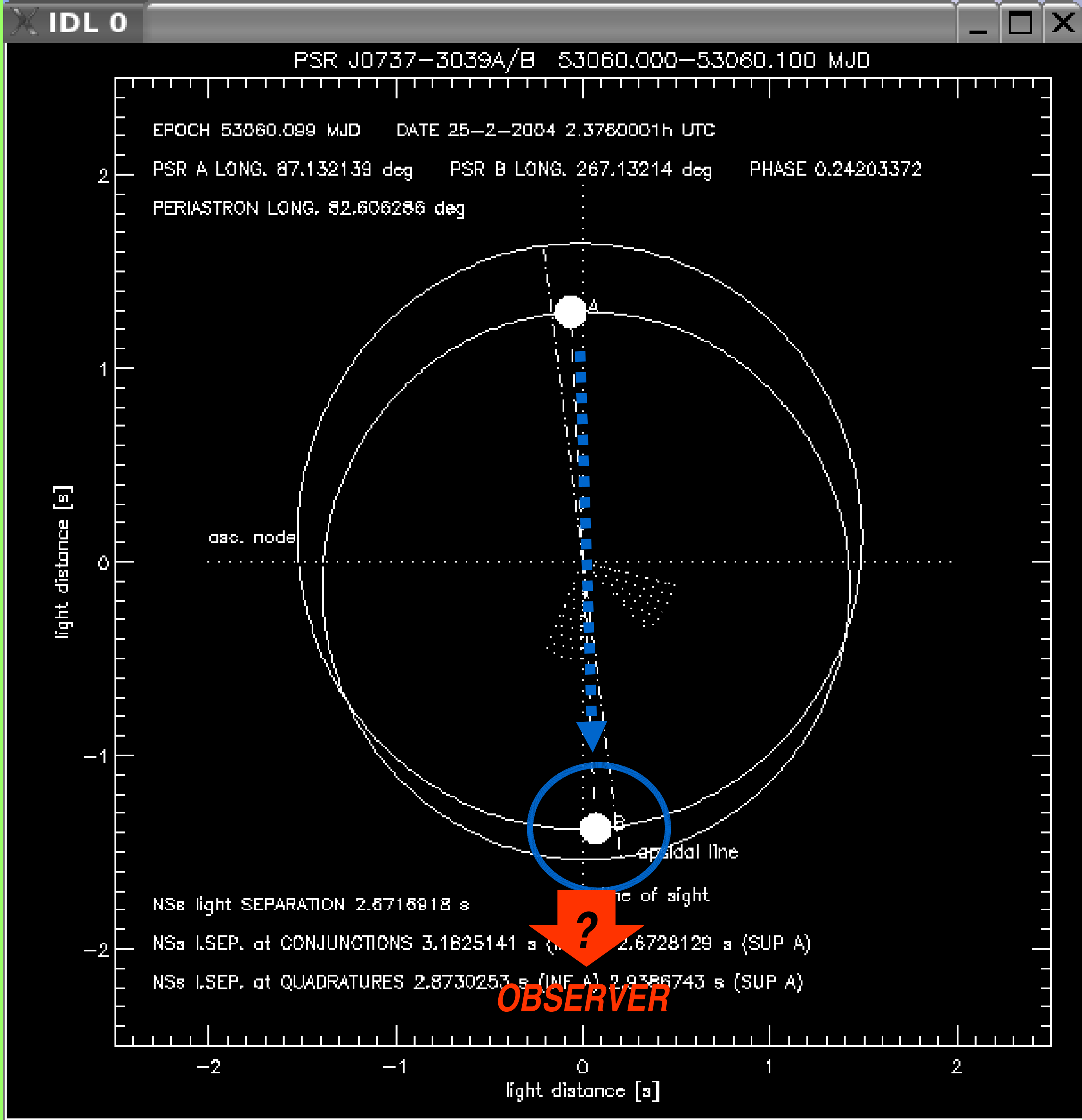


Shock properties inferred from radio observations (eclipses of PSR A): [Arons 2004; Lyutikov, 2004]

Synchrotron absorption *in the magnetosheath forming when A's relativistic wind impacts B's magnetosphere*

Magnetic field = few Gauss

Lorentz factor of shocked particles < 100 (it "should be" 10^6 !)

Particle density >=10^4 cm^{-3} (it "should be" 1 cm^{-3} !)

wind magnetization parameter: σ <= 1

Synchrotron absorption *in the magnetosheath forming when A's relativistic wind impacts B's magnetosphere*

Magnetic field <= few Gauss

B=3 sqrt(σ/(1+σ)) x sqrt(2L/cD^2) <= 21 G (Kennel & Coroniti, 1994)

Lorentz factor of shocked particles < 100 (it "should be" 10^6 !)

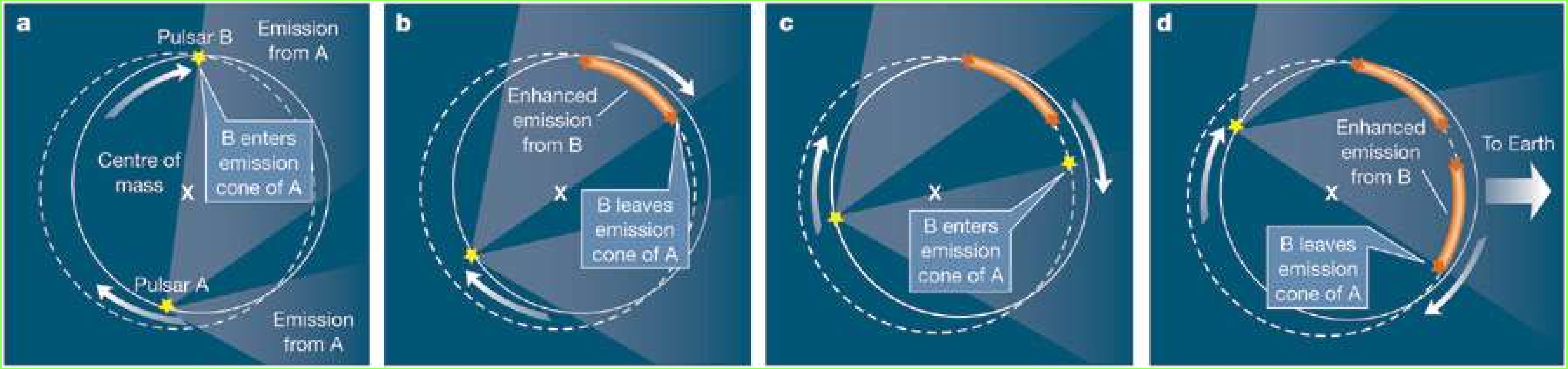
γ=*sqrt*(ν_{OBS}/ν_B)=*sqrt(GHz/MHz)=30*

Particle density >=10^4 cm^{-3} (it "should be" 1 cm^{-3} !)

In order to produce an optical depth >=1 a GHz

wind magnetization parameter: σ <= 1

Shock properties inferred from radio observations (eclipses of PSR A and bright phases of PSR B):



www.physics.mcgill.ca/-ransom/0737_Bflux_model.mpg

PSR B strongly detected in two orbital phase ranges of 10 min each

Double neutron star system 0737-3039

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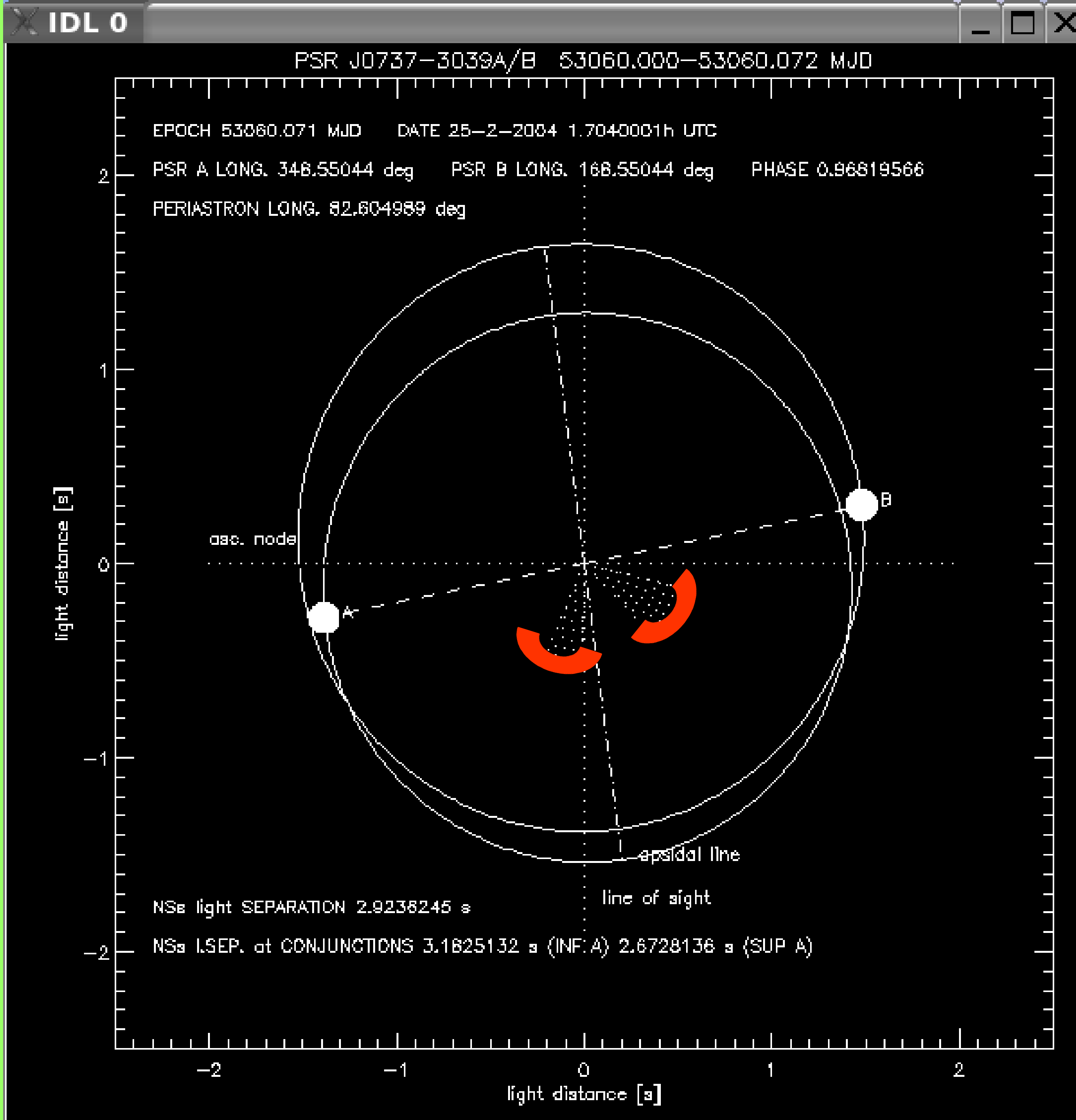

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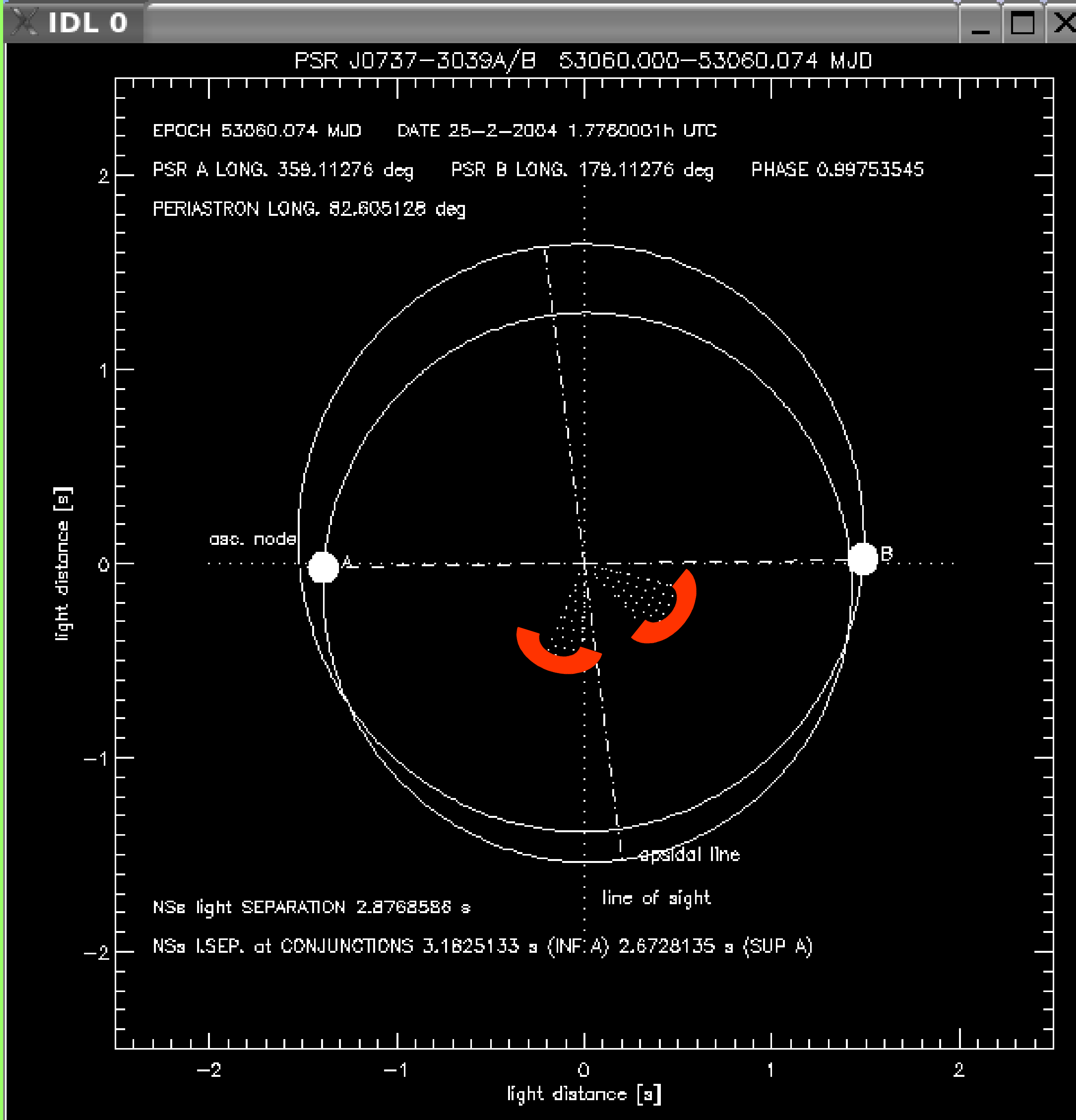

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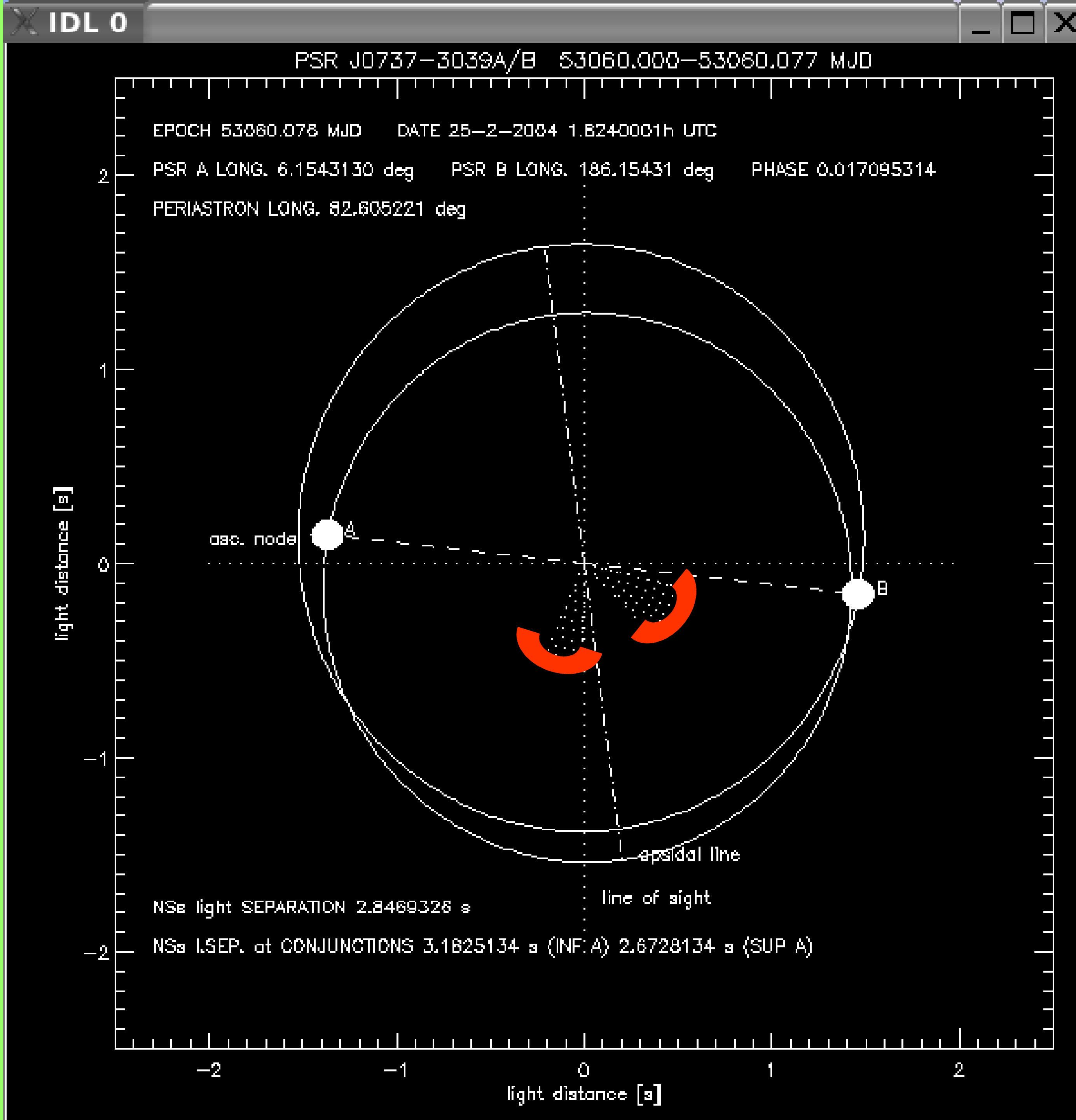

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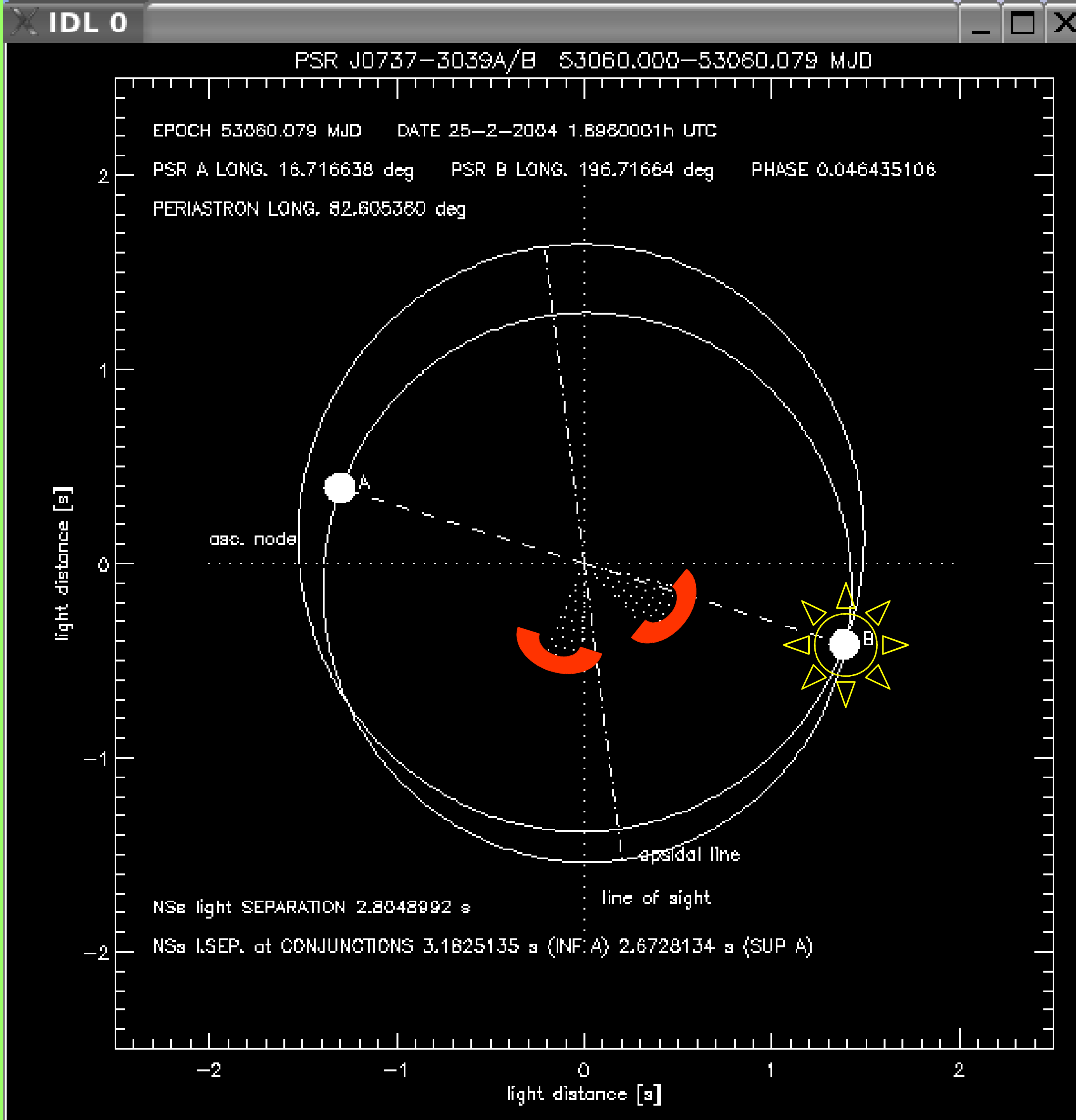

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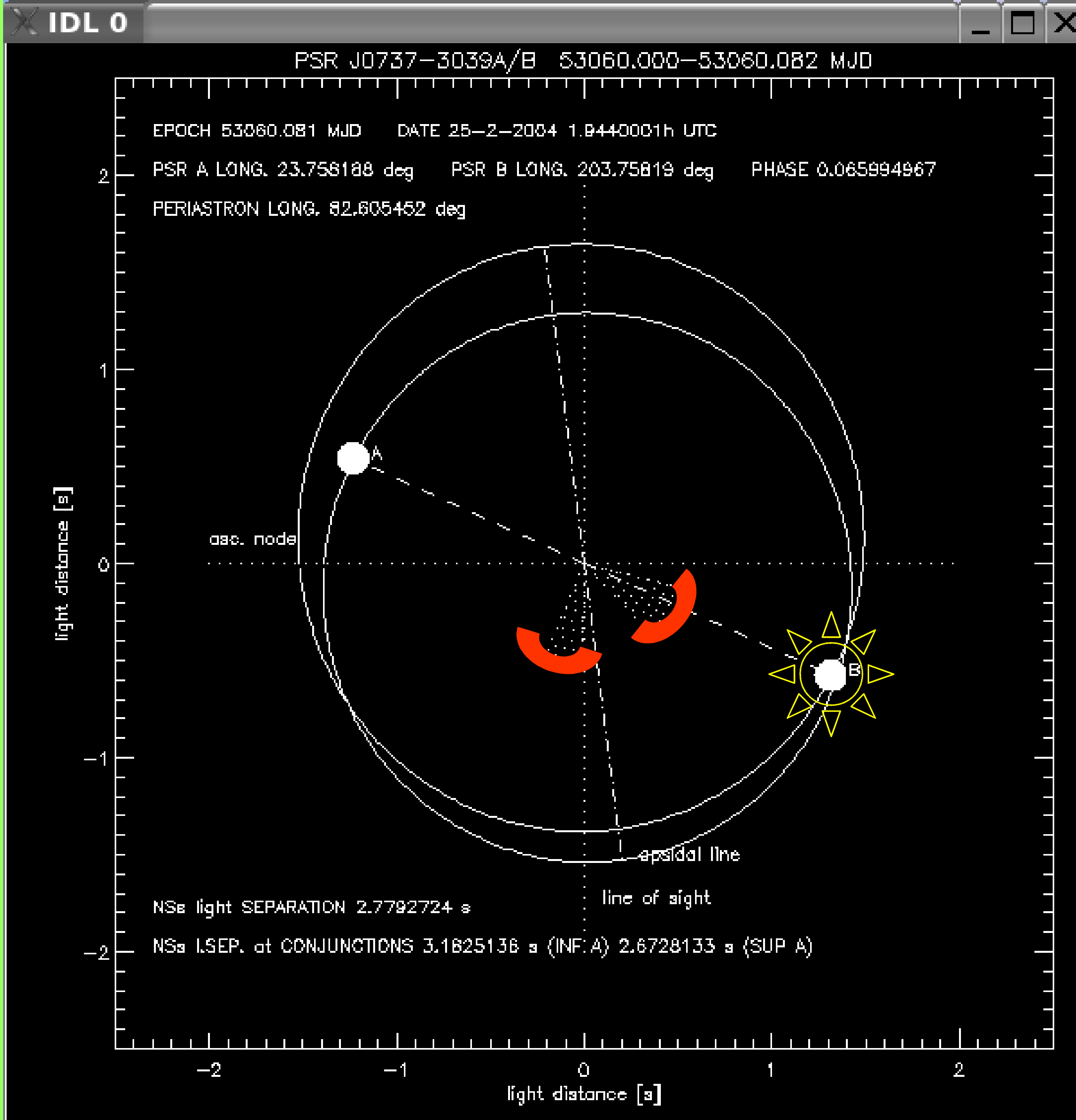

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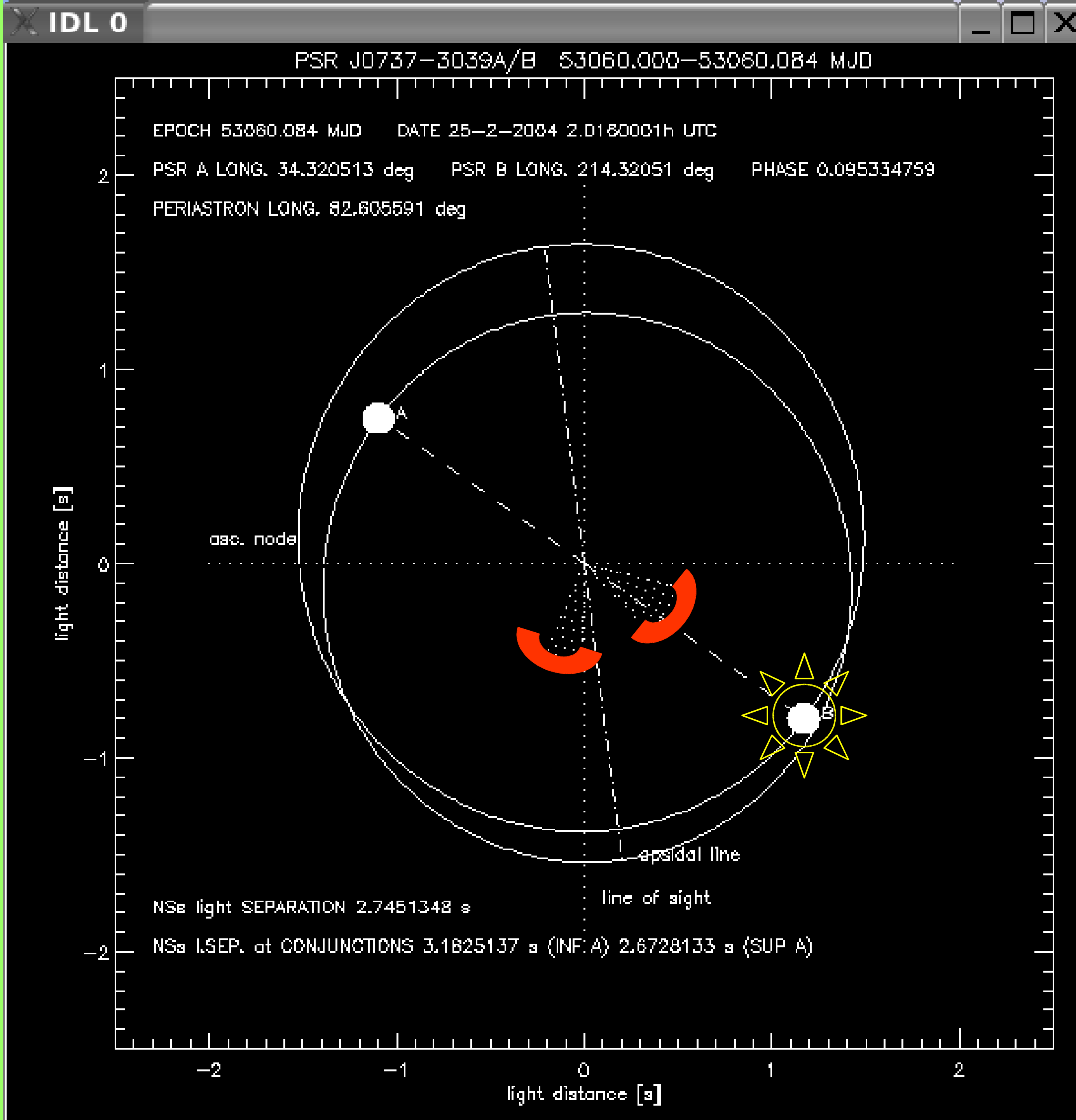

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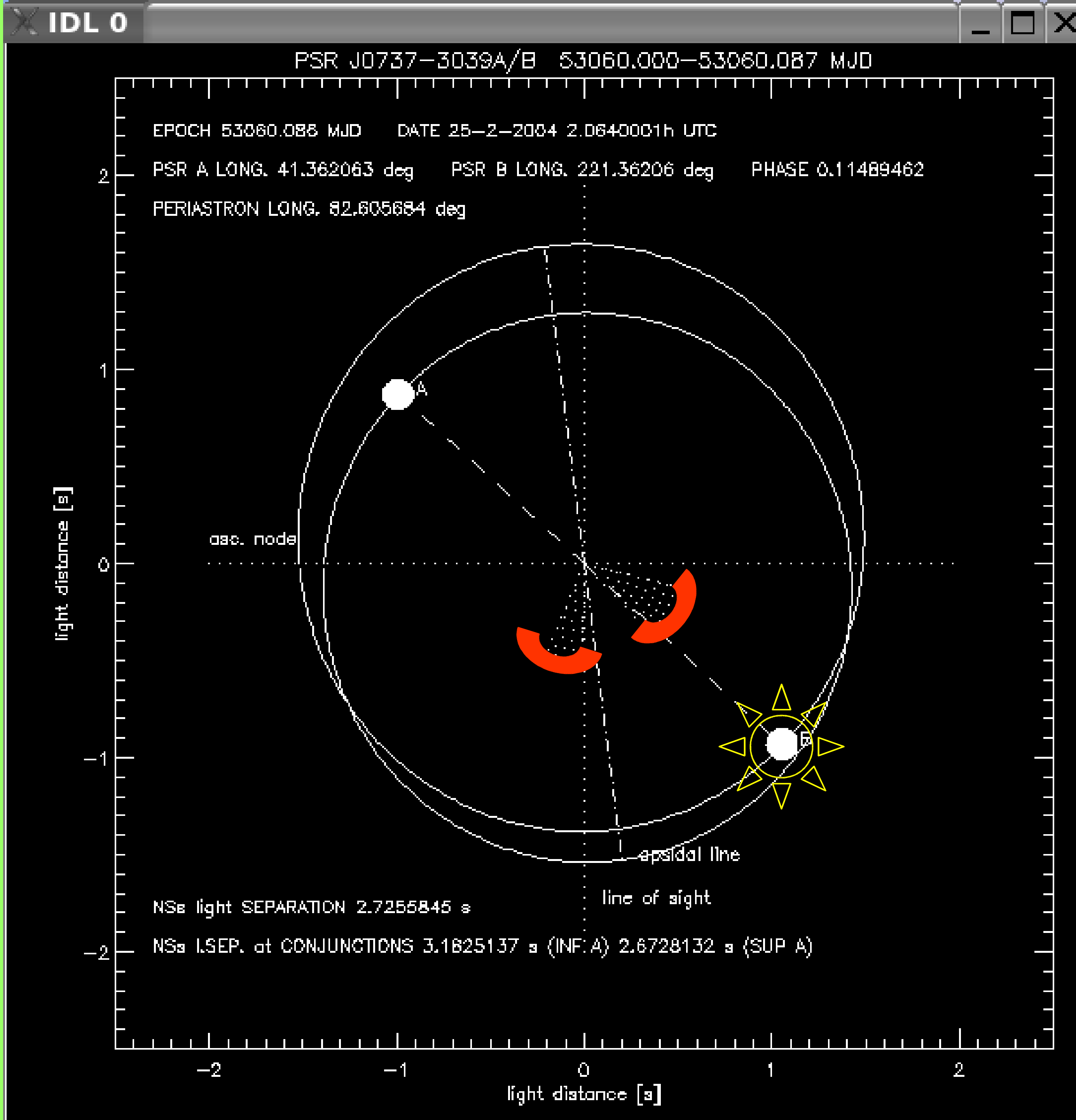

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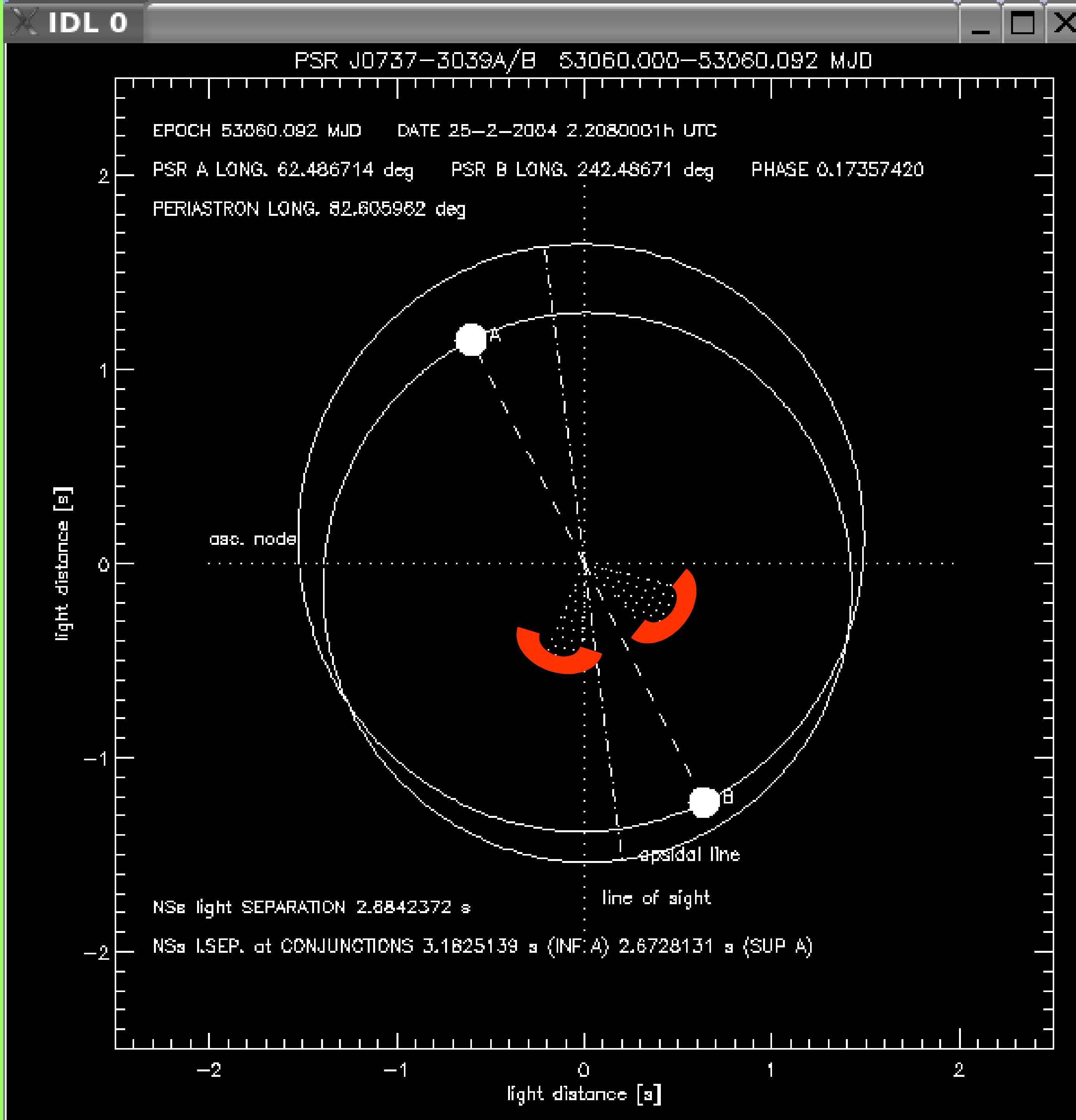

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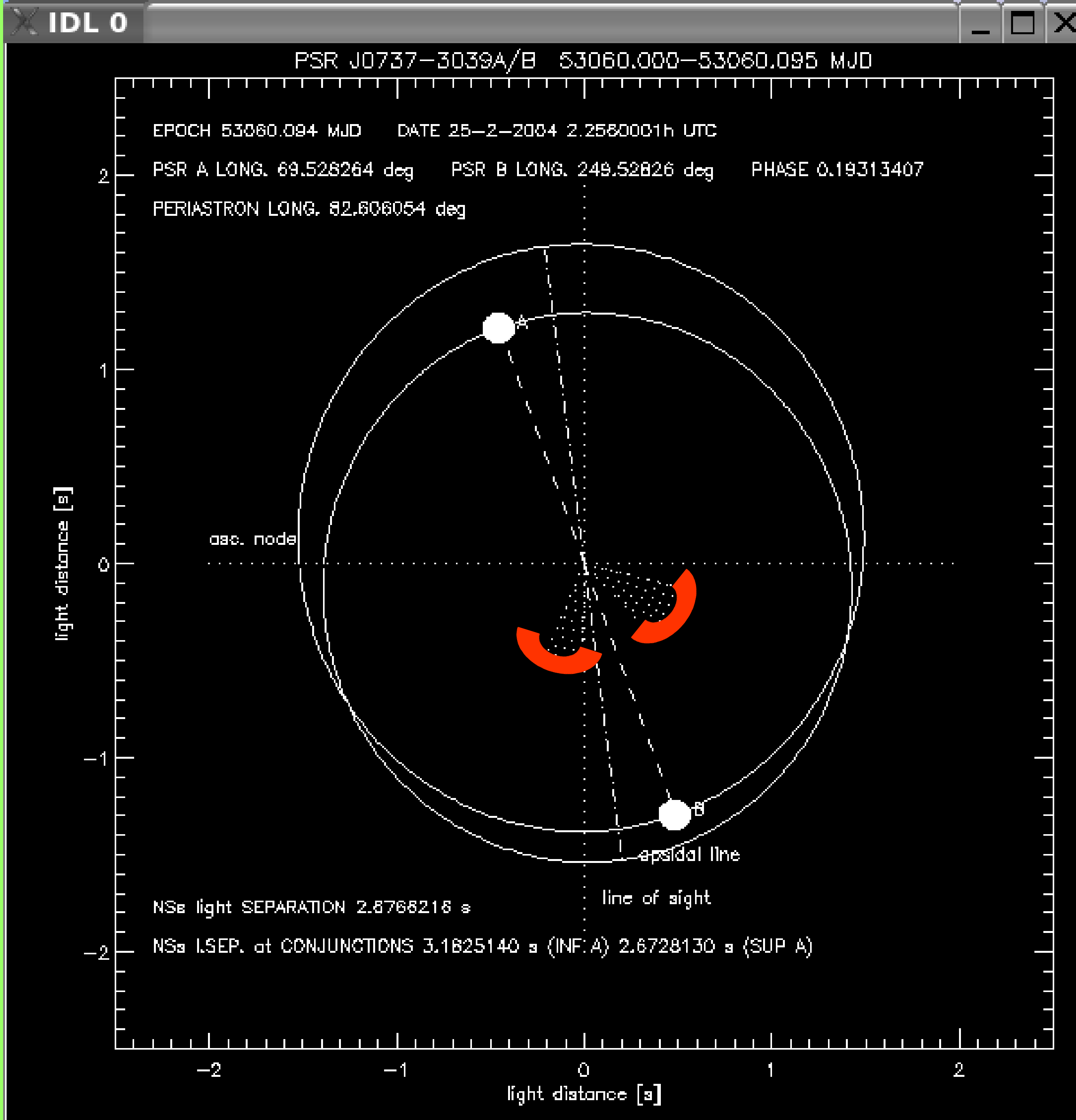
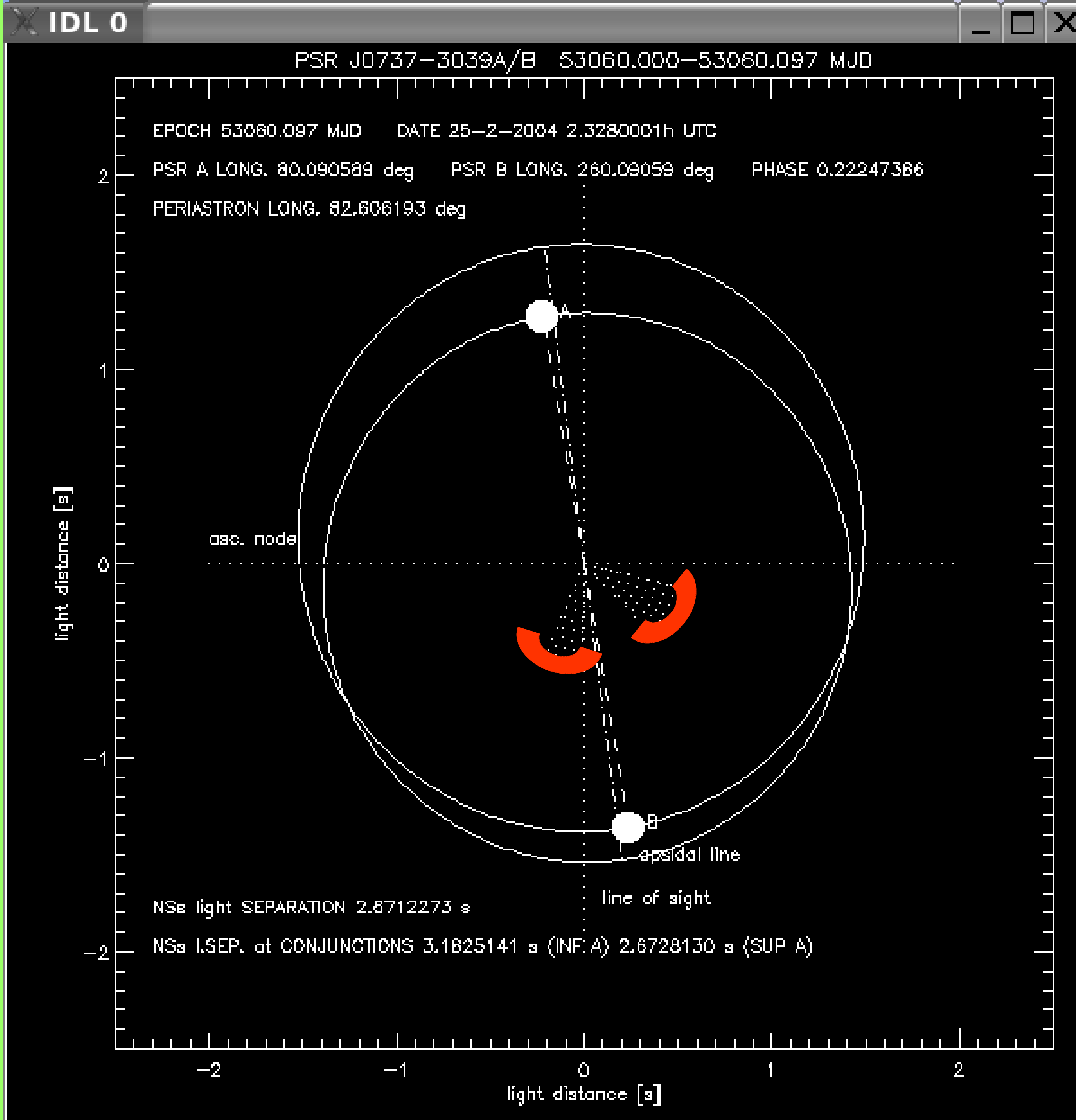


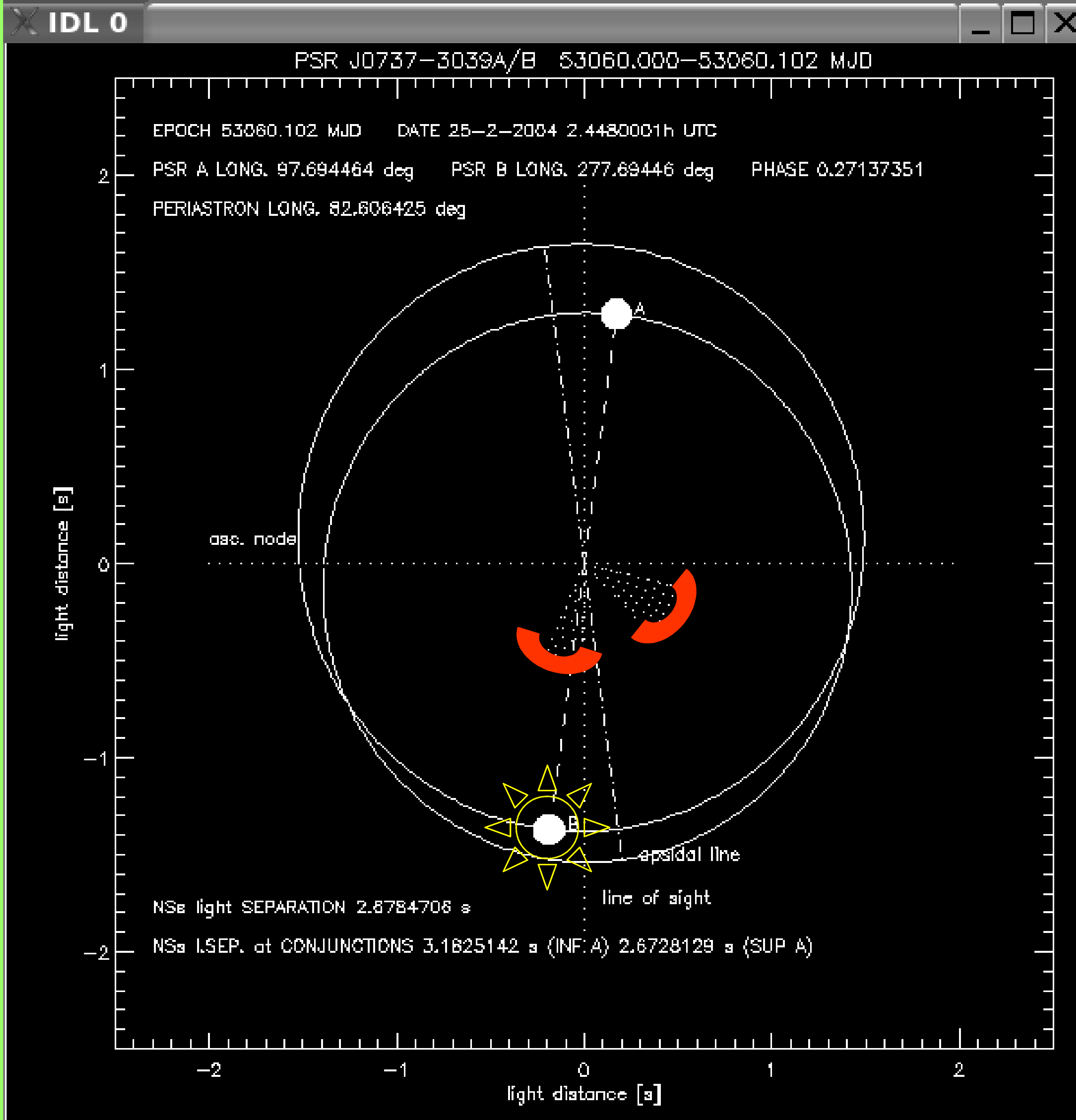
Double neutron star system 0737-3039

PSR B strongly detected in two orbital phase ranges of 10 min each



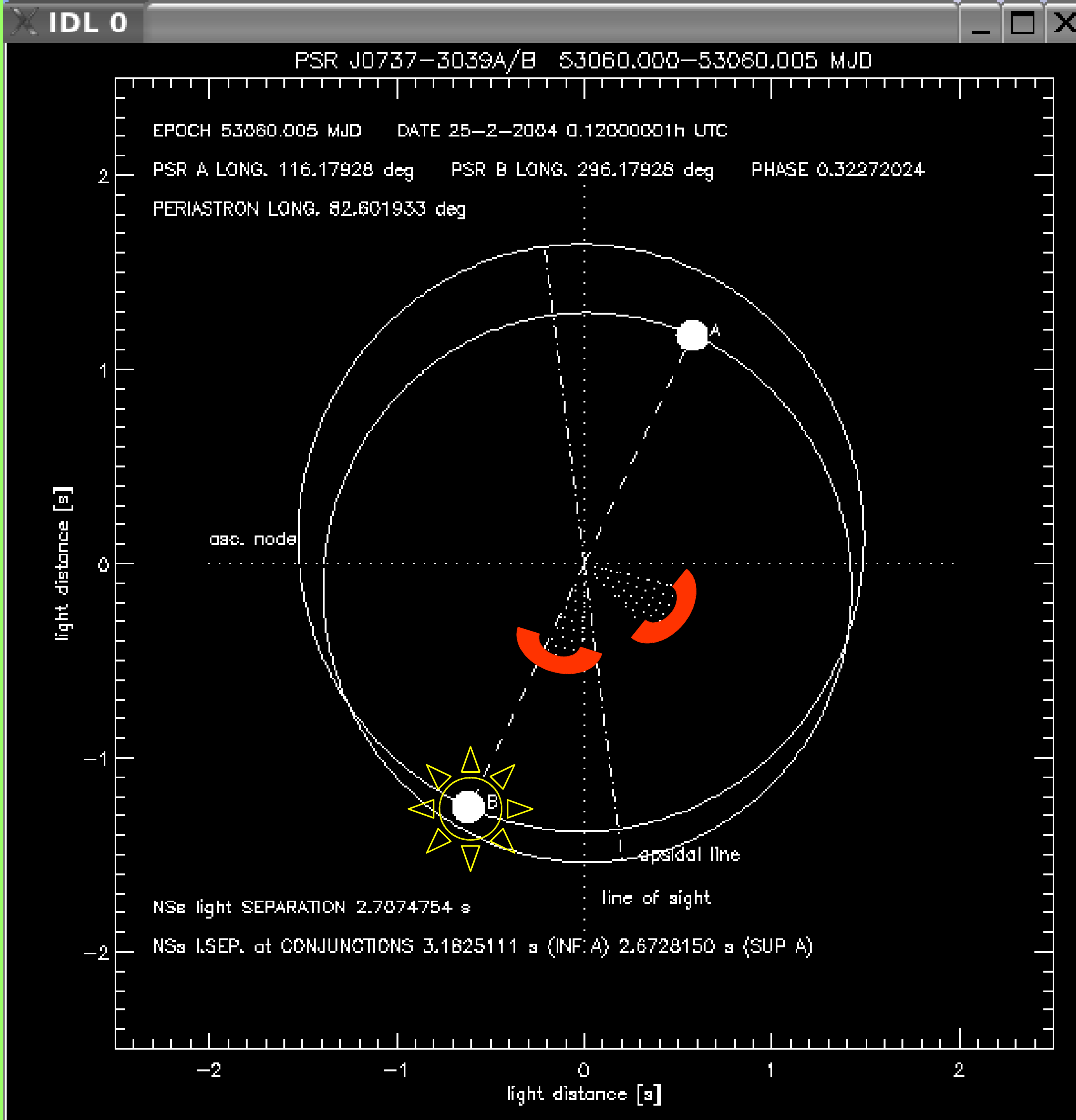
Double neutron star system 0737-3039

PSR B strongly detected in two orbital phase ranges of 10 min each



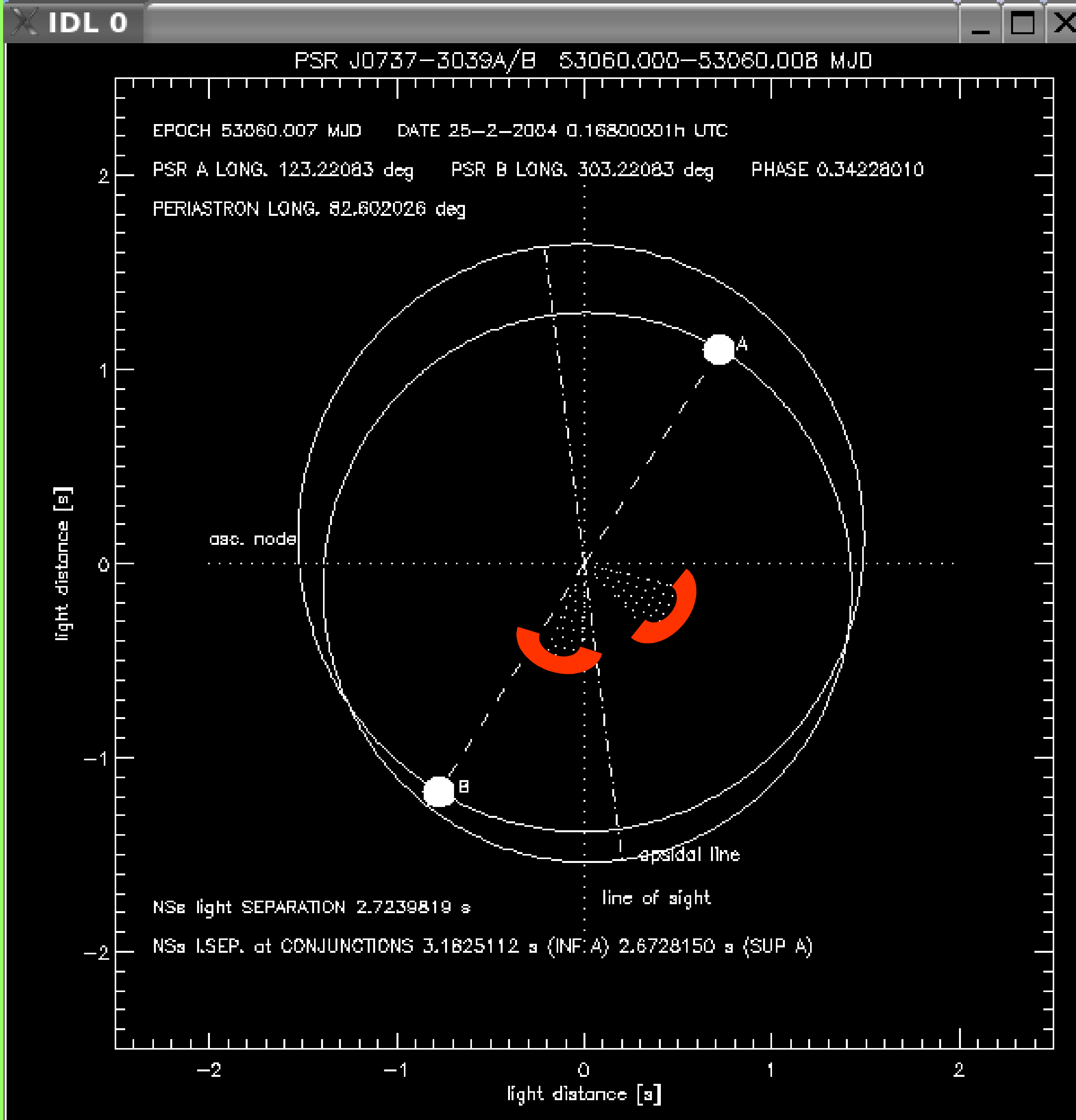
Double neutron star system 0737-3039

PSR B strongly detected in two orbital phase ranges of 10 min each



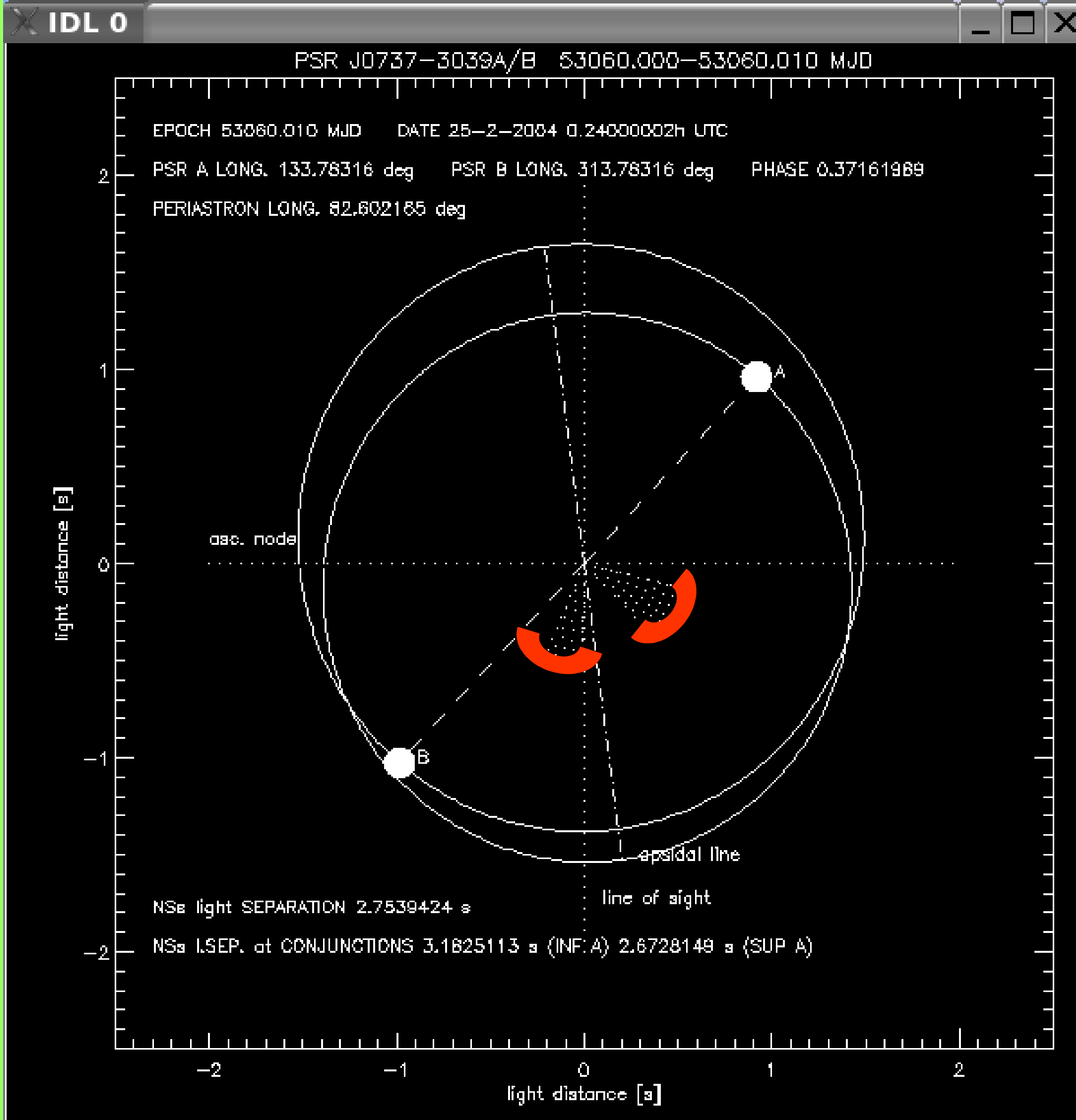
Double neutron star system 0737-3039

PSR B strongly detected in two orbital phase ranges of 10 min each



Double neutron star system 0737-3039

PSR B strongly detected in two orbital phase ranges of 10 min each



Single pulses from PSR B show features drifting at the beat frequency between the periods of the two pulsars reflecting the direct impact of electromagnetic radiation from A on B (McLaughlin, 2004)….
Then…

Most of the spin-down energy seems to be carried by the poyinting flux rather than by energetic particles:

$$\sigma > 1$$

Lyutikov 2005

Rafikov & Goldreich 2005

Synchrotron absorption causing PSR A eclipses is occurring within the magnetosphere of pulsar B not in the magnetosheath

Synchrotron absorption *in the magnetosheath forming when A's relativistic wind impacts B's magnetosphere*

Magnetic field <= few Gauss

???

B=3 sqrt(σ/(1+σ)) x sqrt($2L/cD^2$) <= 21 G (Kennel & Coroniti, 1994)

Lorentz factor of shocked particles < 100 (it "should be" 10^6 !)

γ=*sqrt*(ν_{OBS}/ν_B)=*sqrt(GHz/MHz)=30*

???

Particle density >=10^4 cm^{-3} (it "should be" 1 cm^{-3} !)

In order to produce an optical depth >=1 a GHz

wind magnetization parameter: σ <= 1

???

WHERE DO X-RAYS COME FROM?

- *Emission originating from magnetosphere and surface of PSR A*
- *Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM*
- *Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A's relativistic wind and B's magnetosphere*
- ***Thermal emission from PSR B heated by A through magnetospheric absorption (PSR B "illumination model")***
- *…*

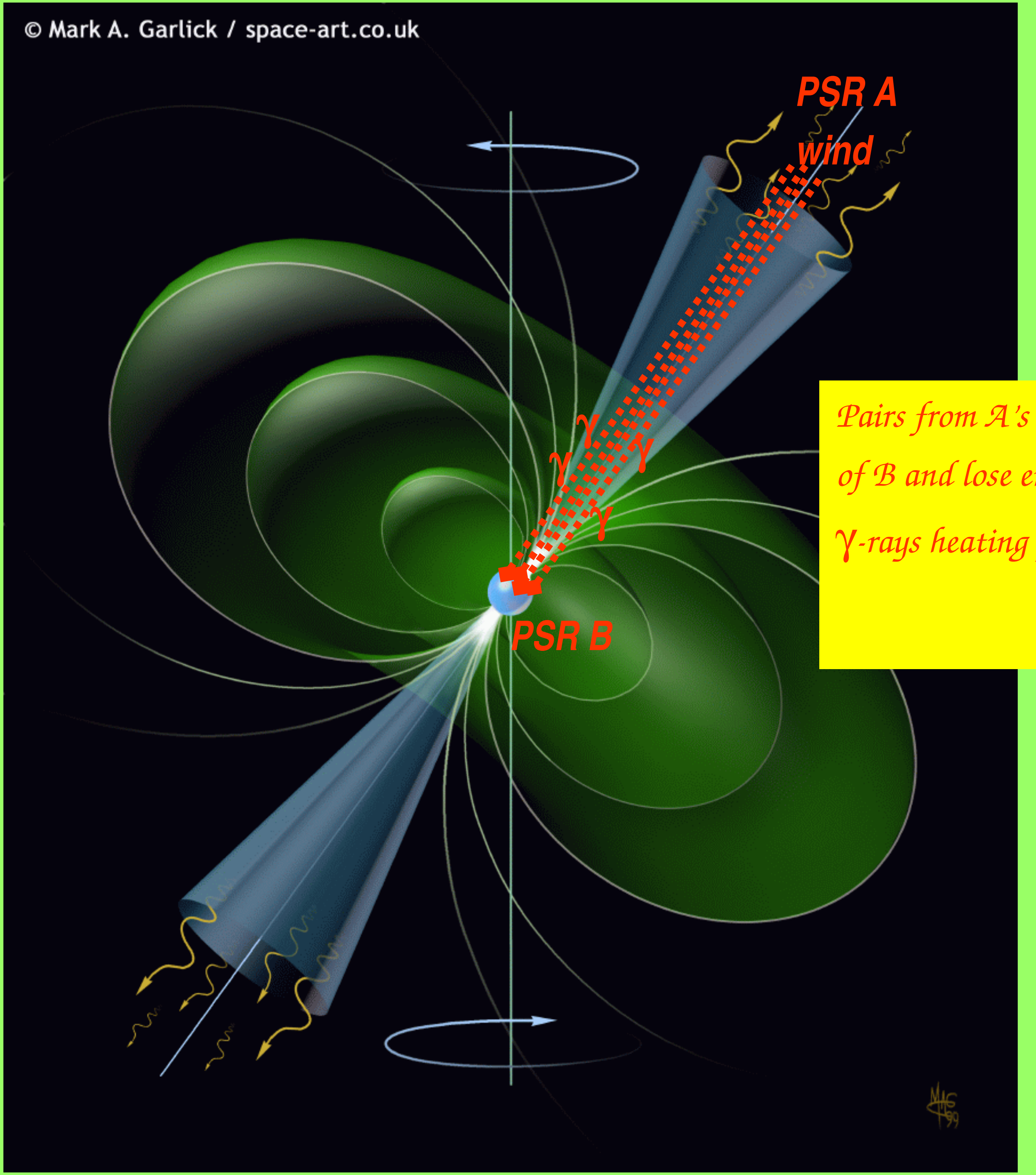
Thermal emission from PSR B heated by A through magnetospheric absorption *(Zhang & Loeb, 2004)*

Part of PSR A's wind energy is absorbed by B's magnetosphere and driven towards B surface:

Pairs from A's wind flow into the open field line region of B and lose energy via curvature radiation and IC → γ*-rays heating polar cap region*

Energy input 10^{31} *erg/s transferred with an efficiency >=10% at PSR B's surface*

→ *thermal emission* $L_X = 10^{30}$ **erg/s** $= 10^{-4}-10^{-3}\ E_{ROT}$ **erg/s** *(kT = 0.2 keV)*



Pairs from A's wind flow into the open field line region of B and lose energy via curvature radiation and IC → γ-rays heating polar cap region

COMPOSITE SCENARIO?

- *Emission originating from magnetosphere and surface of PSR A* **($L_X=10^{-4}$-10^{-3} E_{ROT})**

- *Synchrotron emission from the bow-shock formed near pulsar B owing to the collision between A's relativistic wind and B's magnetosphere* **($L_X<10^{-2}$-10^{-3} E_{ROT})**

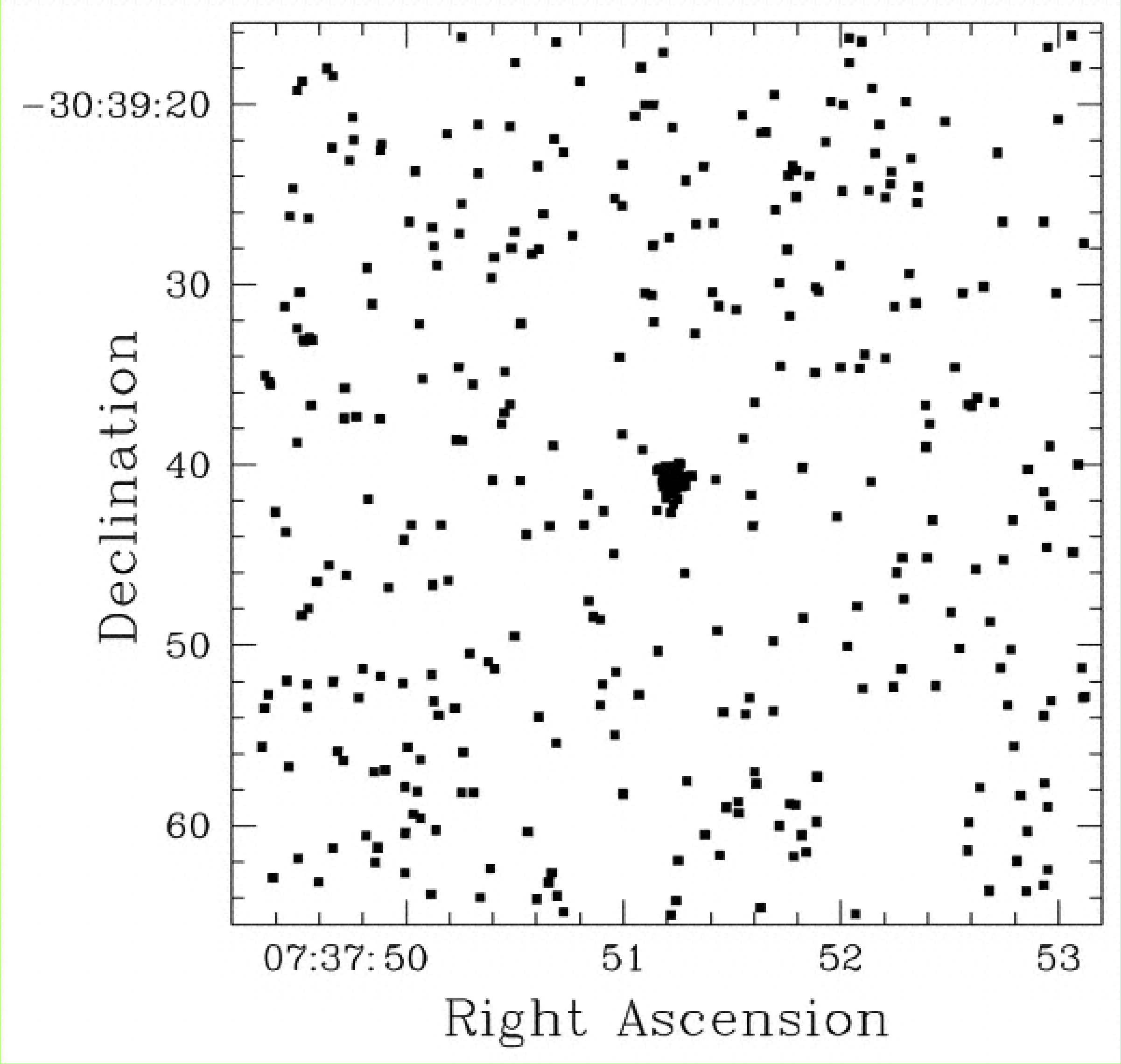
- *Synchrotron emission from PSR A wind just behind the bow-shock caused by the systemic motion in the ISM* **($L_X=10^{-4}$ E_{ROT})**

- *Thermal emission from PSR B heated by A through magnetospheric absorption* **($L_X=10^{-4}$-10^{-3} E_{ROT})**

- …

X-RAYS OBSERVATIONS OF THE DOUBLE PULSAR

McLaughlin et al., 2004 (Chandra/ACIS-S, 10 ks, 1 orbit):

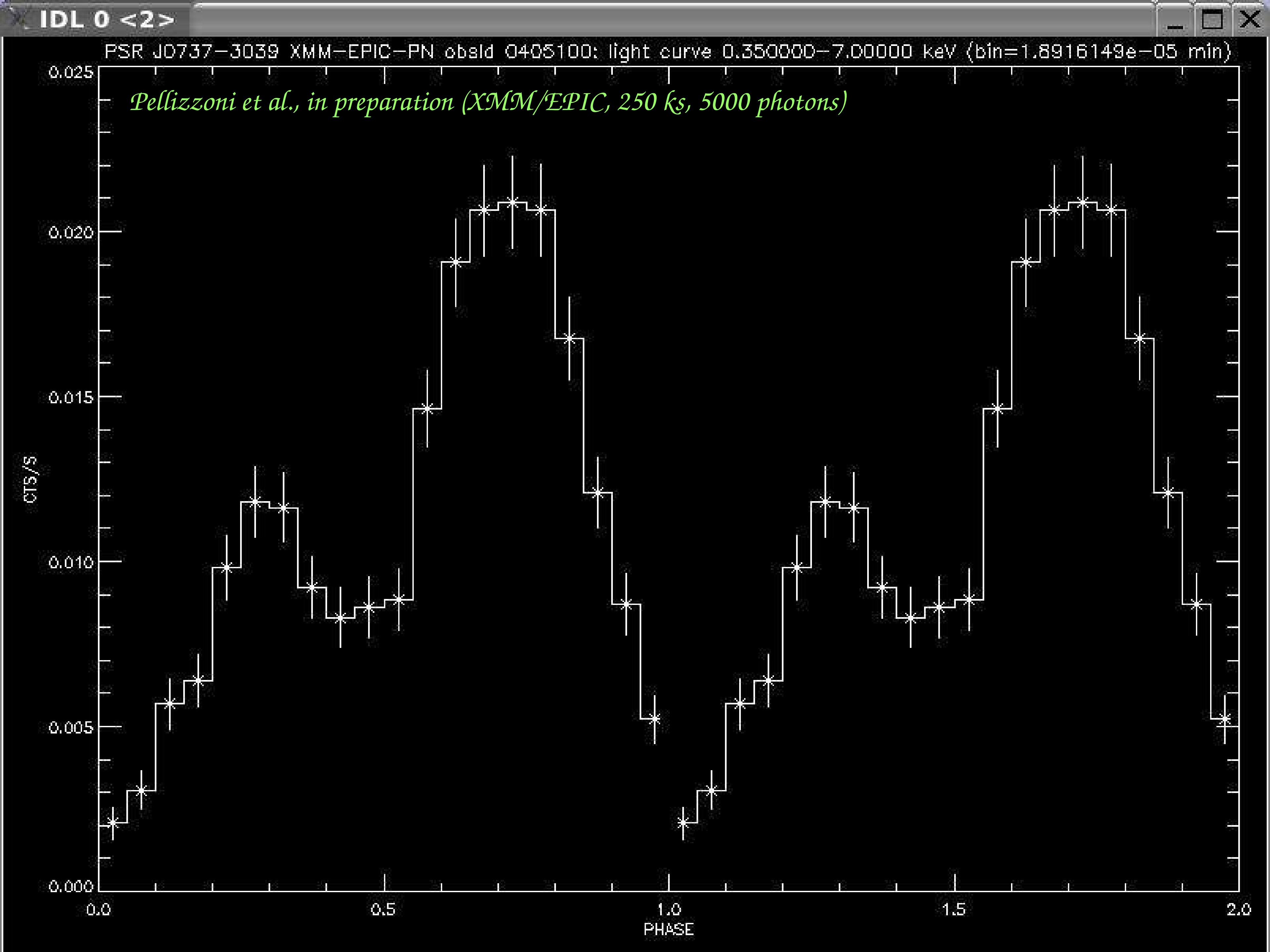


Soft spectrum: Γ*=2.9*

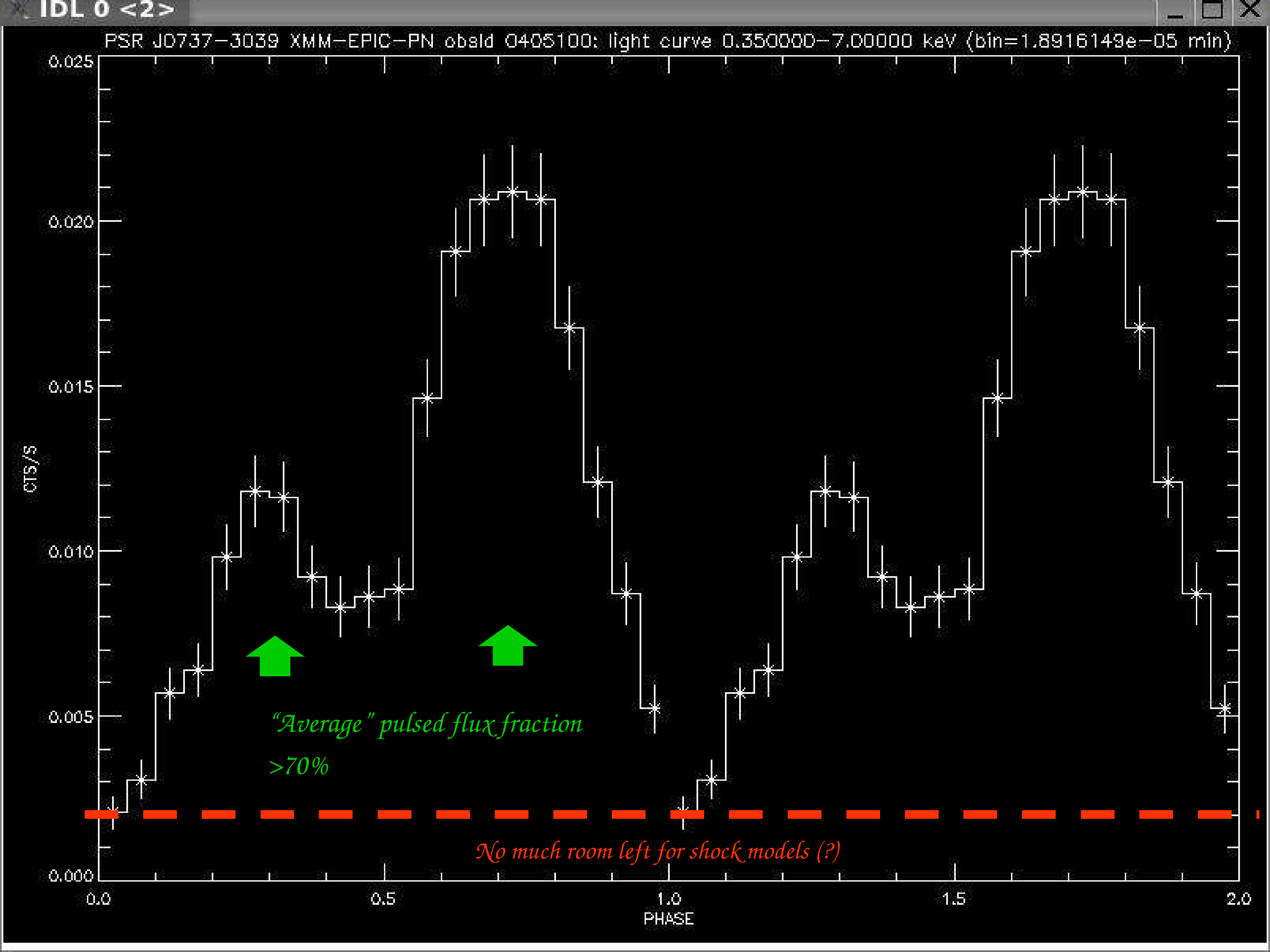
$L_X = 2 \times 10^{30}$ *erg/s (0.2-10 keV, 0.5 kpc)=* **4×10^{-4} E_{ROT}**

No significant orbital variability

First detection of a DBNS in X-rays, 80 source photons



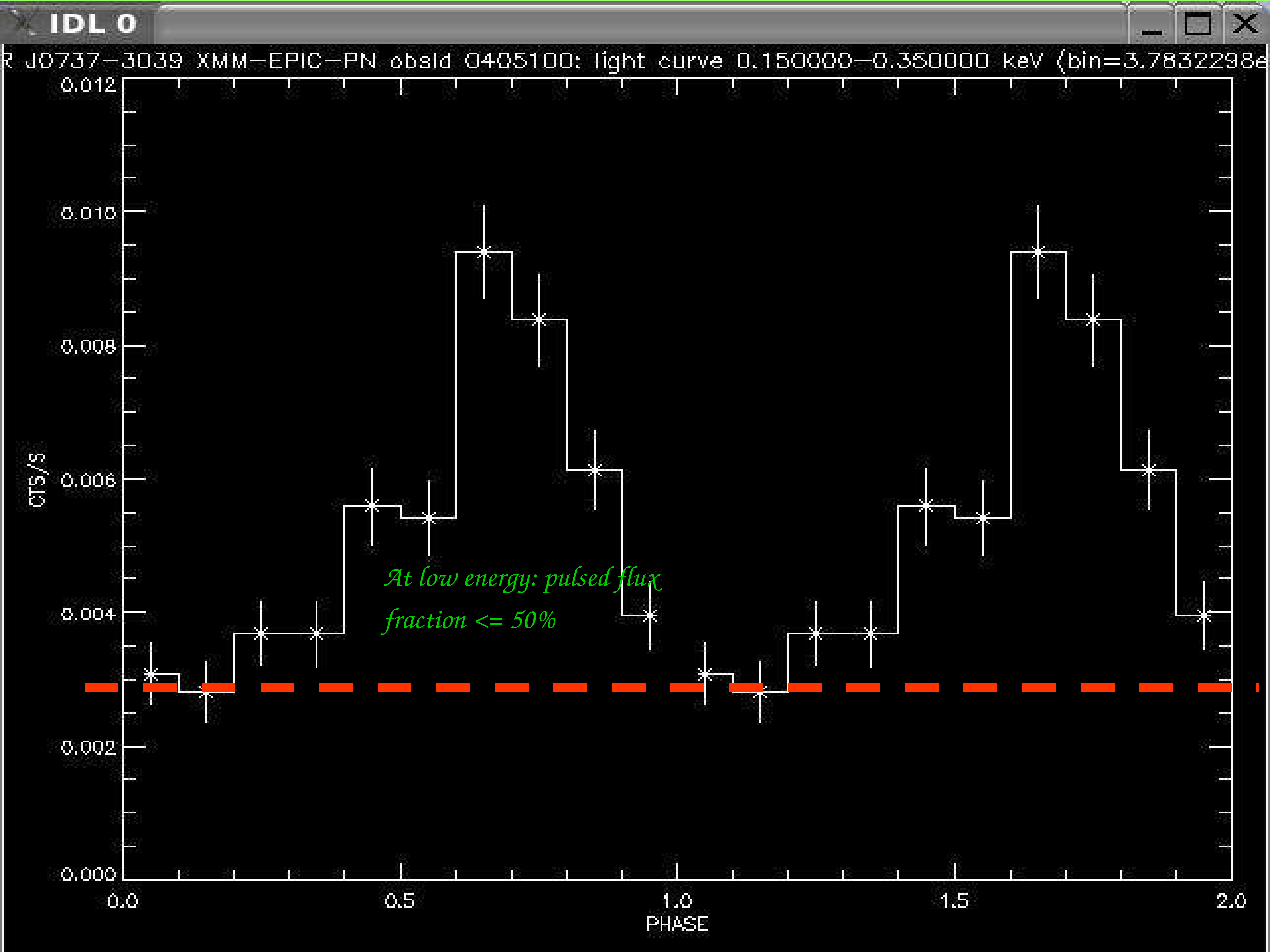
IDL 0 <2>
PSR J0737-3039 XMM-EPIC-PN obsid 0405100: light curve 0.350000-7.00000 keV (bin=1.8916149e-05 min)
Pellizzoni et al., in preparation (XMM/EPIC, 250 ks, 5000 photons)
CTS/S
PHASE
0.000
0.005
0.010
0.015
0.020
0.025
0.0
0.5
1.0
1.5
2.0

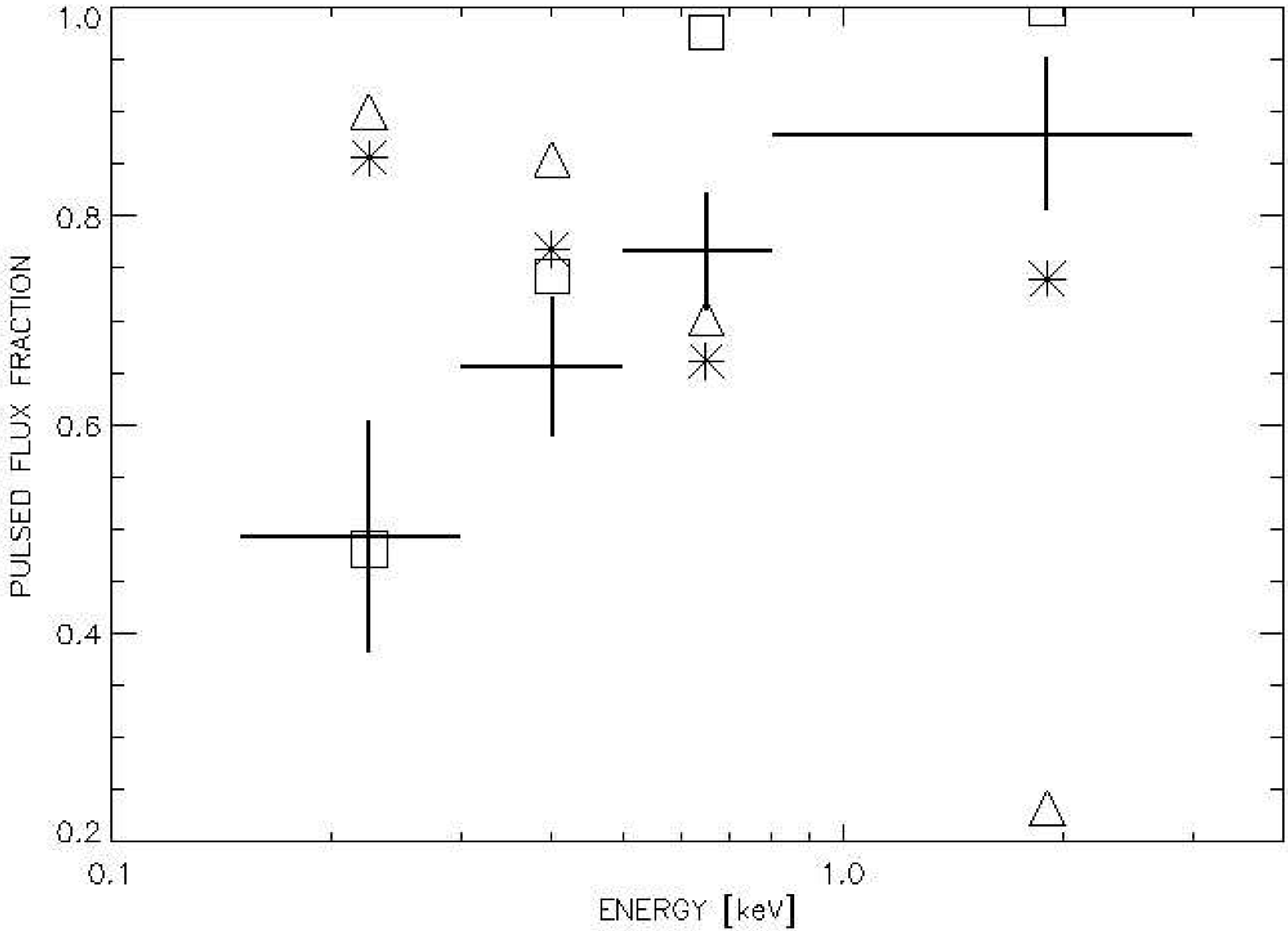

IDL 0 <2>
PSR J0737-3039 XMM-EPIC-PN obsId 0405100: light curve 0.350000-7.00000 keV (bin=1.8916149e-05 min)
0.025
0.020
0.015
0.010
0.005
0.000
CTS/S
0.0
0.5
1.0
1.5
2.0
PHASE
"Average" pulsed flux fraction
>70%
No much room left for shock models (?)

WHERE DO X-RAYS COME FROM?

No significant emission from the interaction between PSR A wind and PSR B magnetosphere:

PSR A wind magnetization parameter $\sigma > 100$ (in agreement with most of wind models)


IDL 0
R J0737-3039 XMM-EPIC-PN obsId 0405100: light curve 0.150000-0.350000 keV (bin=3.7832298e
CTS/S
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.5
1.0
1.5
2.0
PHASE
At low energy: pulsed flux
fraction <= 50%



1.0
0.8
0.6
0.4
0.2
PULSED FLUX FRACTION
0.1
1.0
ENERGY [keV]

But…

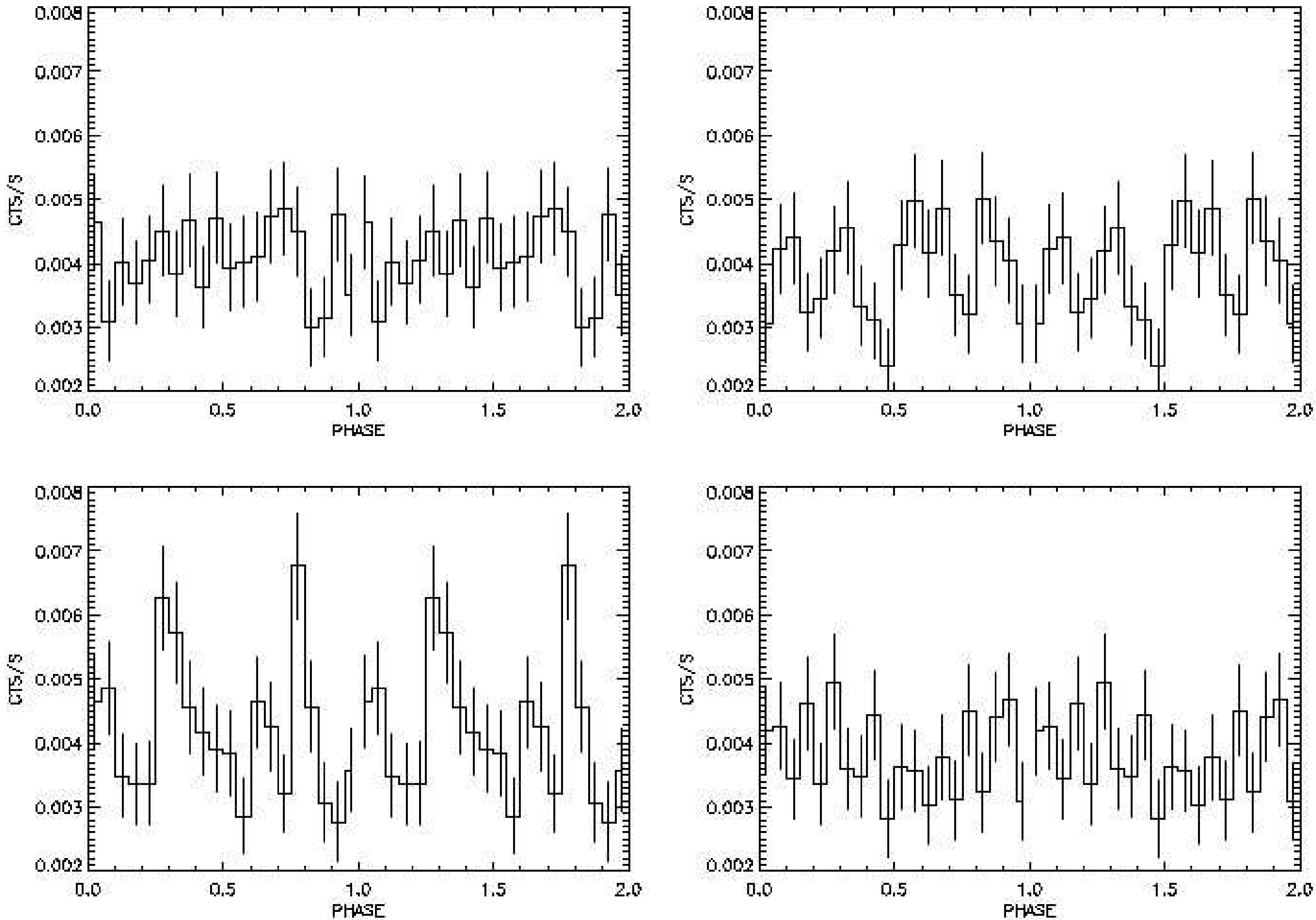
We can further constrain interaction parameters and structure (magnetic field, electrons Lorentz factor, σ …) analyzing scattering/absorption process of PSR A X-ray flux by the magnetosheath…

Which kind of scattering/absorption processes?

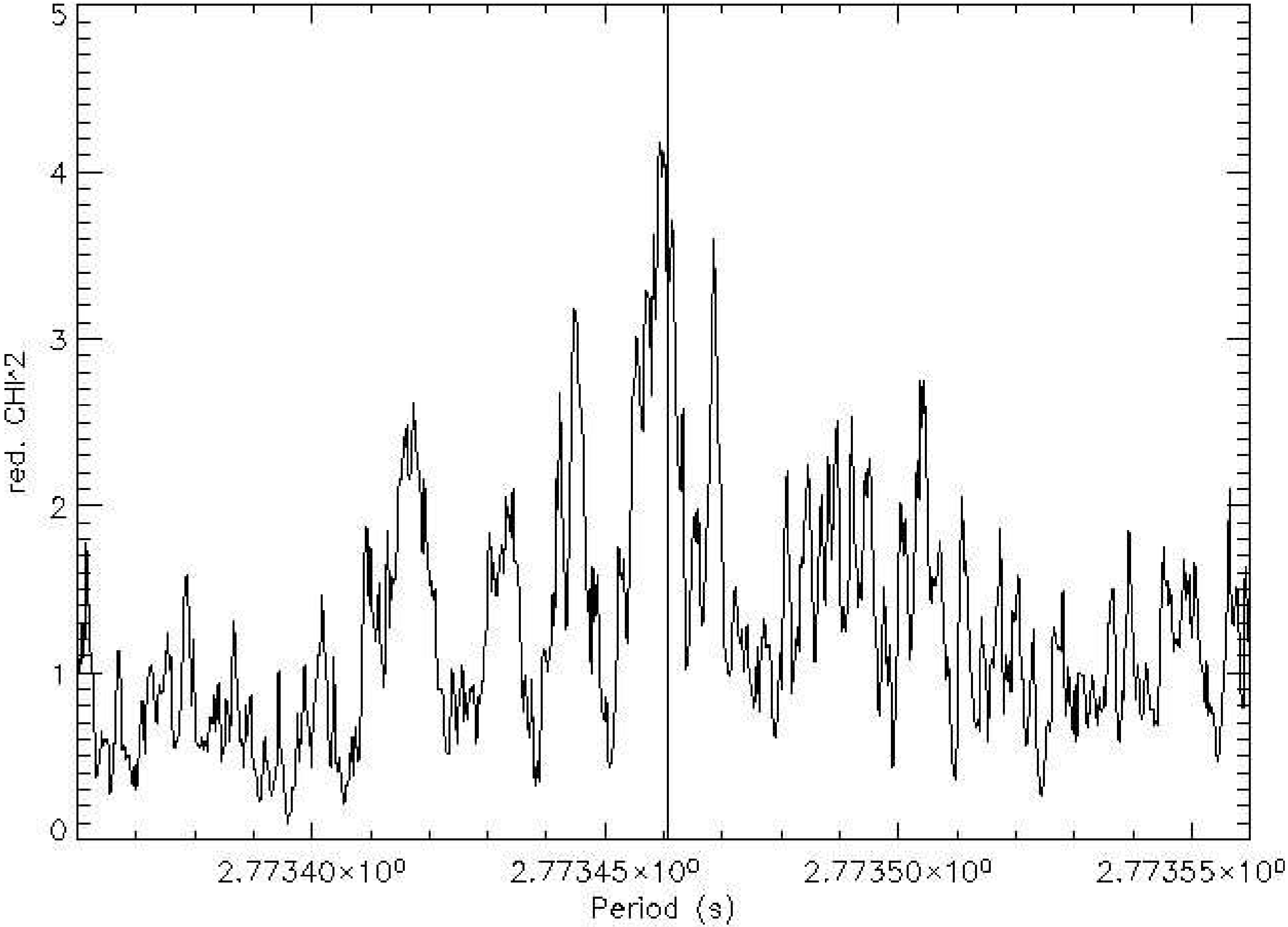
Synchrotron absorption?

Compton scattering?

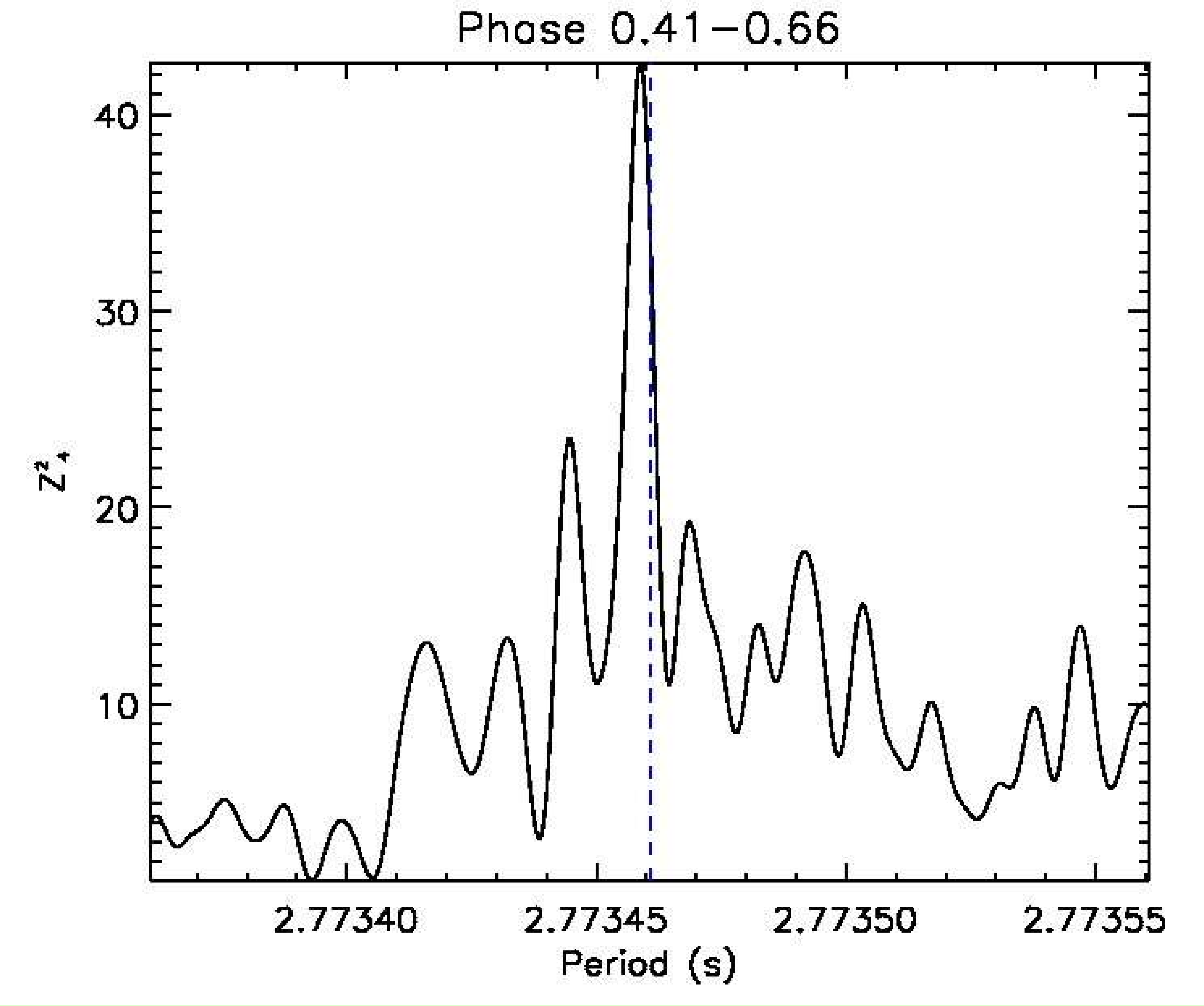
Which size for the absorber nebula?



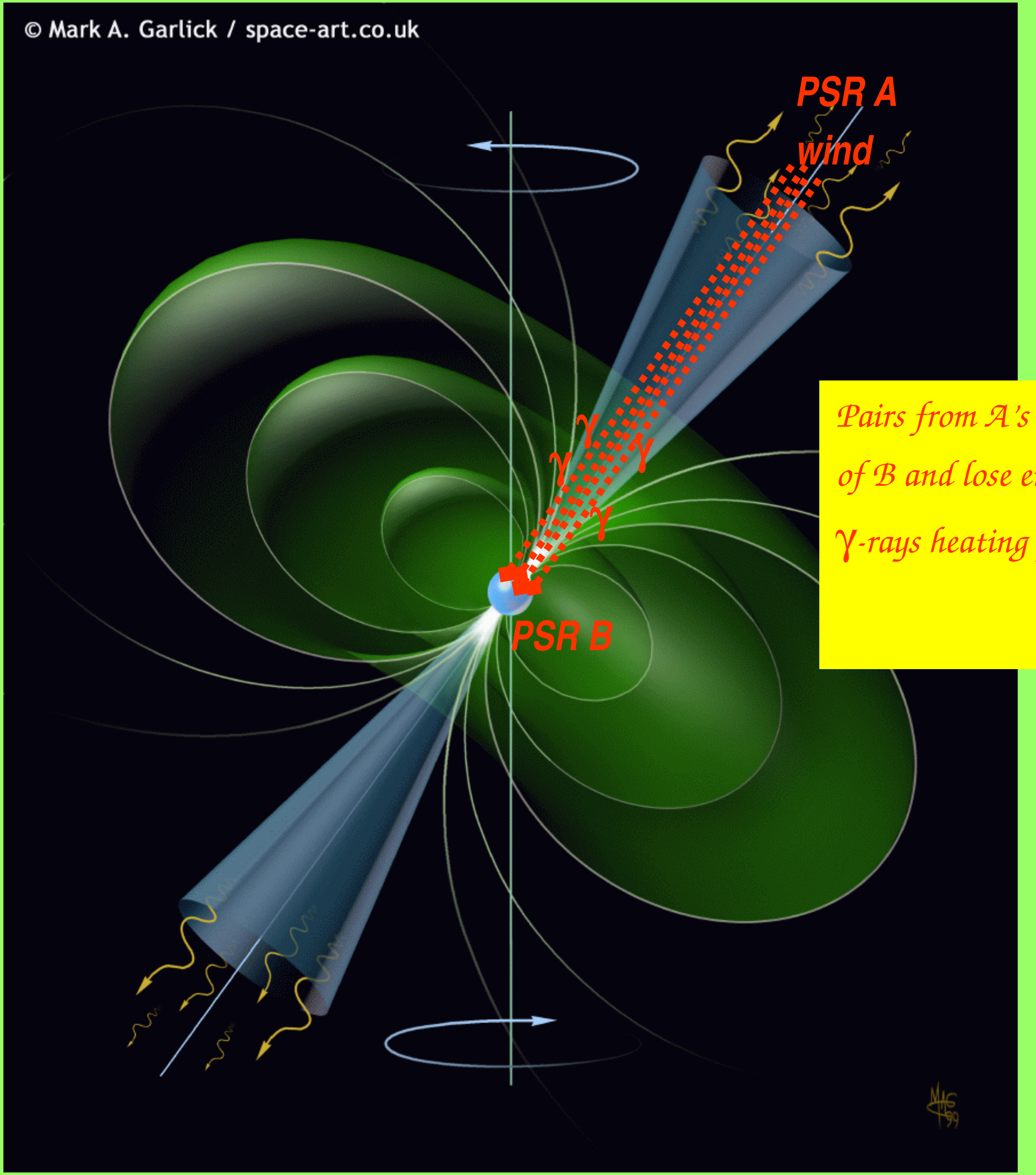
CTS/S
PHASE
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.0
0.5
1.0
1.5
2.0



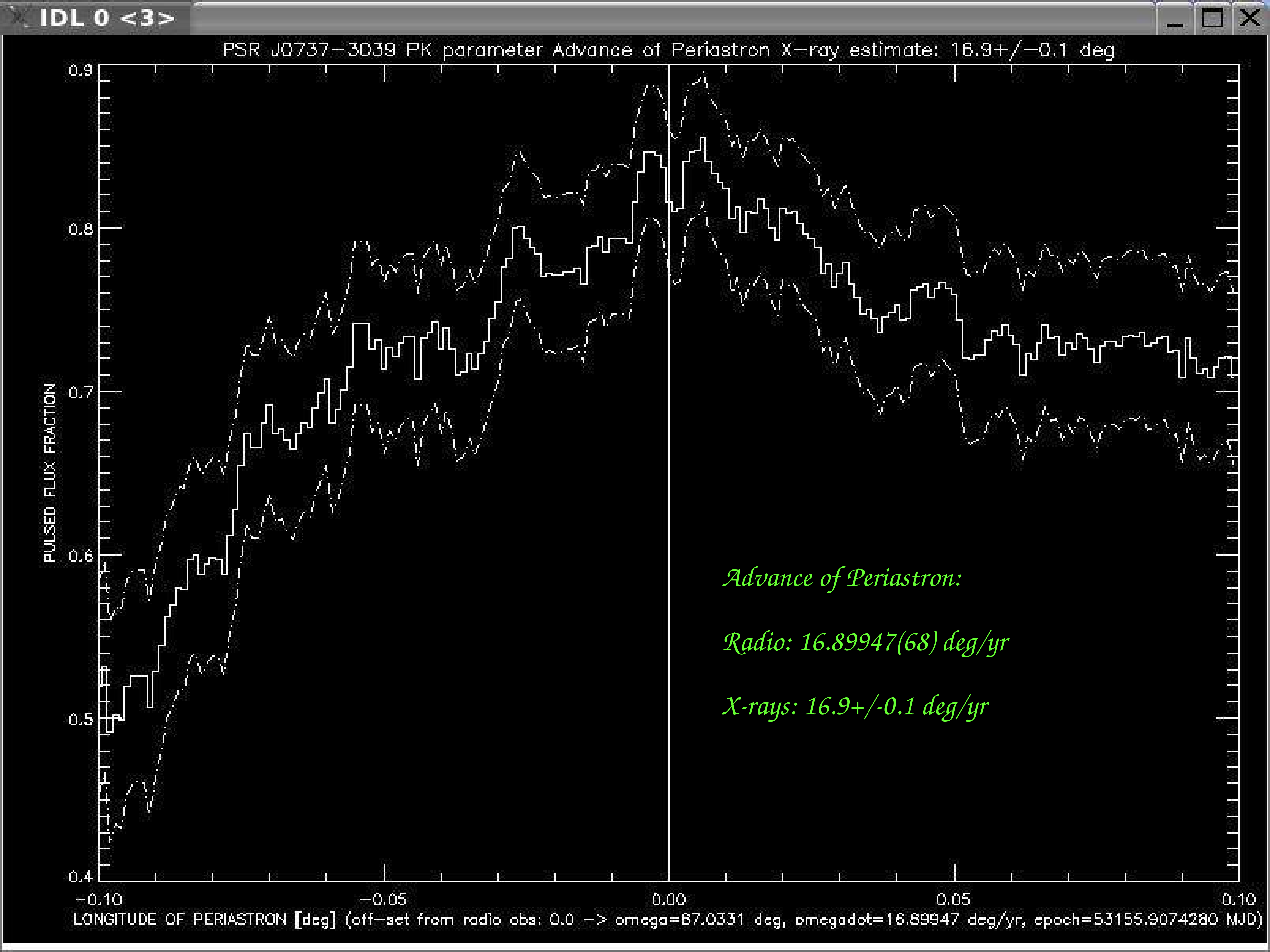
5
4
3
2
1
0
red. CHI^2
2.77340×10⁰
2.77345×10⁰
2.77350×10⁰
2.77355×10⁰
Period (s)



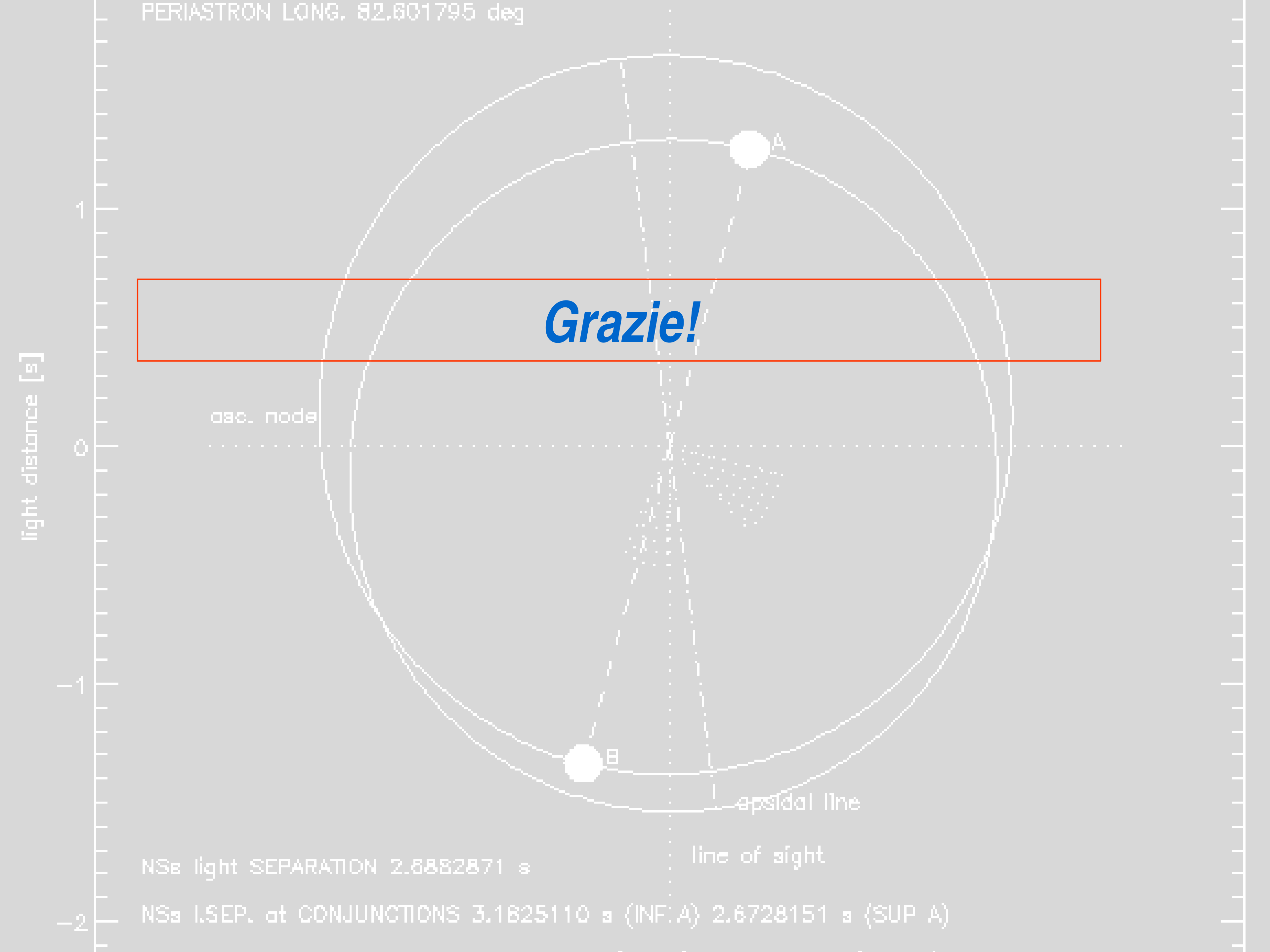
Phase 0.41−0.66
40
30
20
10
Z²₄
2.77340
2.77345
2.77350
2.77355
Period (s)



Pairs from A's wind flow into the open field line region of B and lose energy via curvature radiation and IC → γ-rays heating polar cap region


IDL 0 <3>
PSR J0737-3039 PK parameter Advance of Periastron X-ray estimate: 16.9+/-0.1 deg
PULSED FLUX FRACTION
0.9
0.8
0.7
0.6
0.5
0.4
-0.10
-0.05
0.00
0.05
0.10
LONGITUDE OF PERIASTRON [deg] (off-set from radio obs: 0.0 -> omega=87.0331 deg, omegadot=16.89947 deg/yr, epoch=53155.9074280 MJD)
Advance of Periastron:
Radio: 16.89947(68) deg/yr
X-rays: 16.9+/-0.1 deg/yr

Grazie!



PERIASTRON LONG. 82.601795 deg
A
B
asc. node
apsidal line
line of sight
light distance [s]
1
0
−1
−2
NSs light SEPARATION 2.6882871 s
NSs l.SEP. at CONJUNCTIONS 3.1625110 s (INF A) 2.6728151 s (SUP A)