中国科学院高能物理研究所

The evolution properties of the Crab pulsar

Speaker: Linli YAN (闫林丽)

Main Collaborators: M. Y. Ge, F. J. Lu ,S. J. Zheng, J. P. Yuan et al.

Email: yanlinli@ihep.ac.cn

Institute of High Energy Physics

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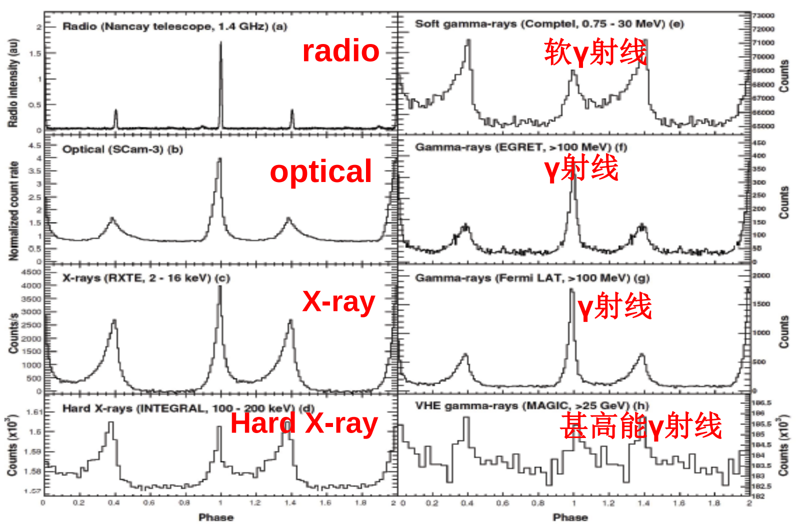
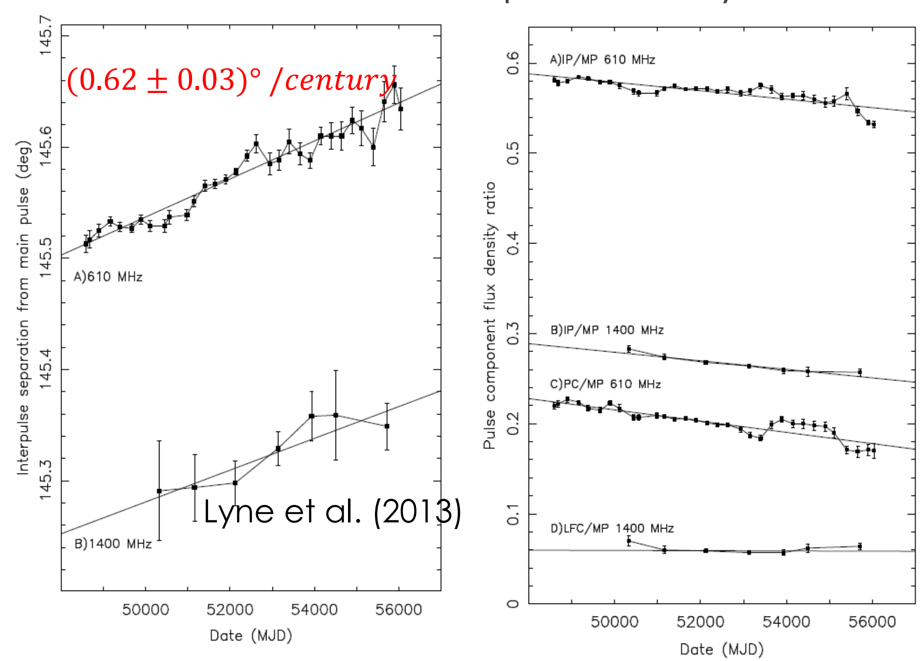
1. Introduction

Profile shape

- The pulse morphology of the Crab pulsar varies as a function of photon energy. (Abdo et al.2010, Ge et al. 2012)



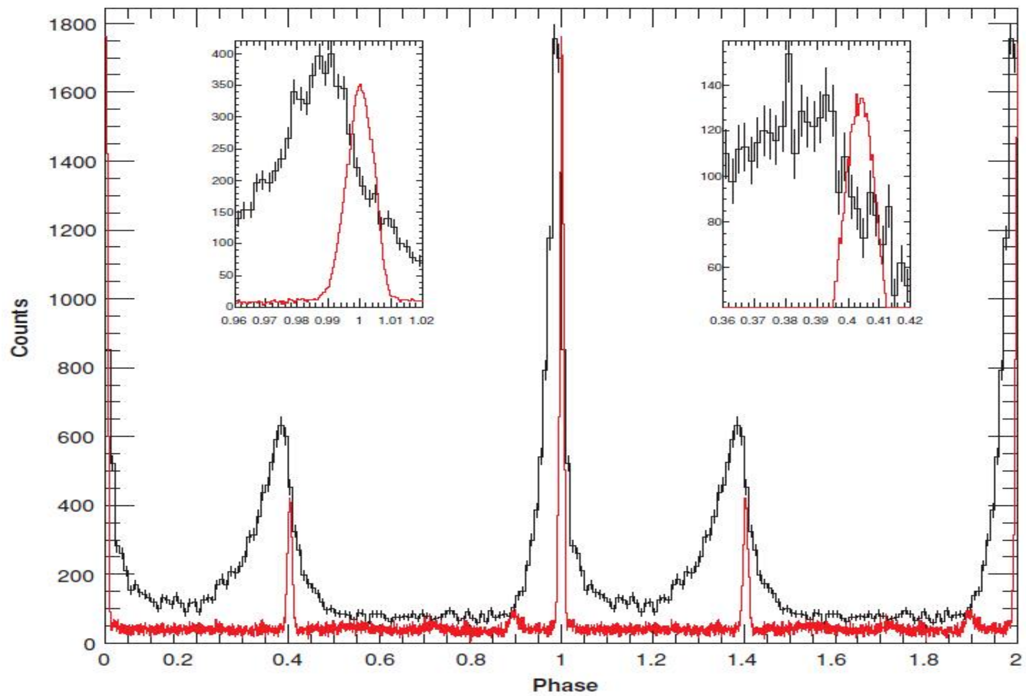
- The Crab pulsar's radio pulse profiles change with time. (Lyne et al. 2013)
  - ✓ The magnetic inclination angle α increases at 0.6° per century.



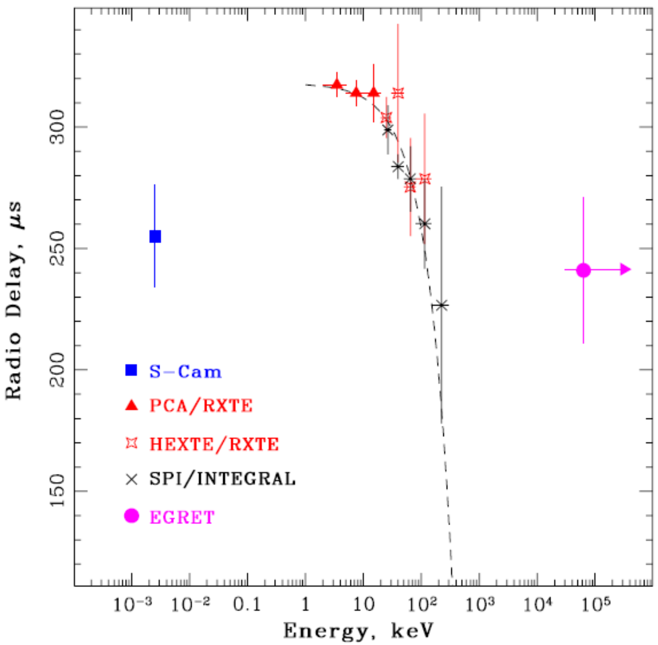
What about the evolution trend of X-ray pulse profile ?

Profile phase

- The arrival times of the pulses are not aligned in phase at different wavelengths. (Kuiper et al. 2003; Rots, Jahoda & Lyne. 2004; Oosterbroek et al. 2008; Abdo et al. 2010, Molkov, Jourdain & Roques 2010).



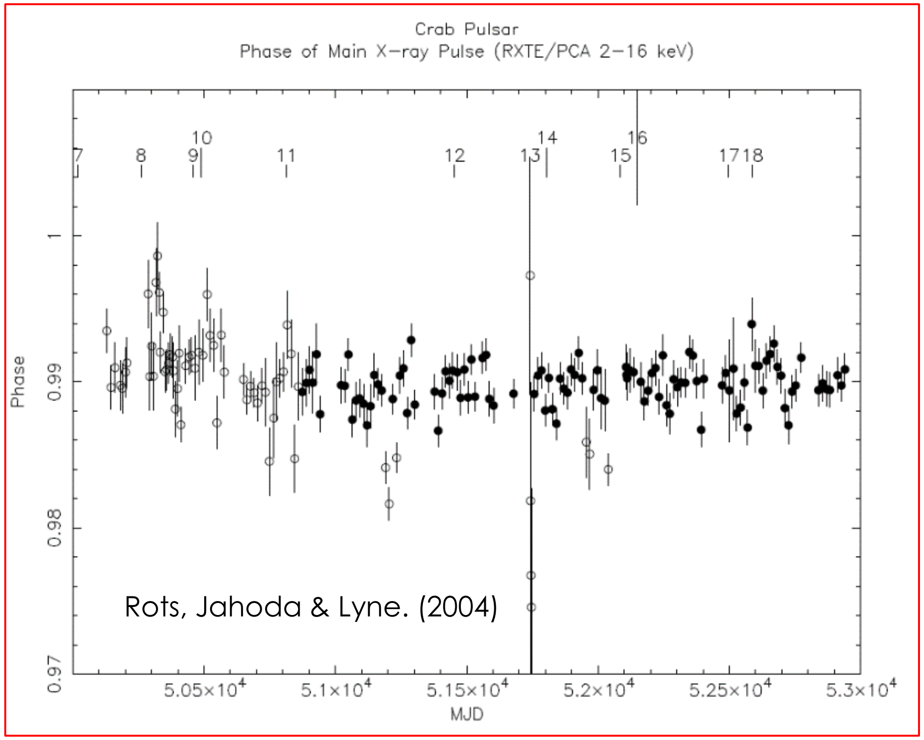
Abdo et al.(2010)



Molkov, Jourdain & Roques (2010).

Profile phase

➢The Crab pulsar's events in the 2 - 16 keV, X-ray leads the radio pulse by 0.0102 period in phase. (Rots, Jahoda & Lyne. 2004)

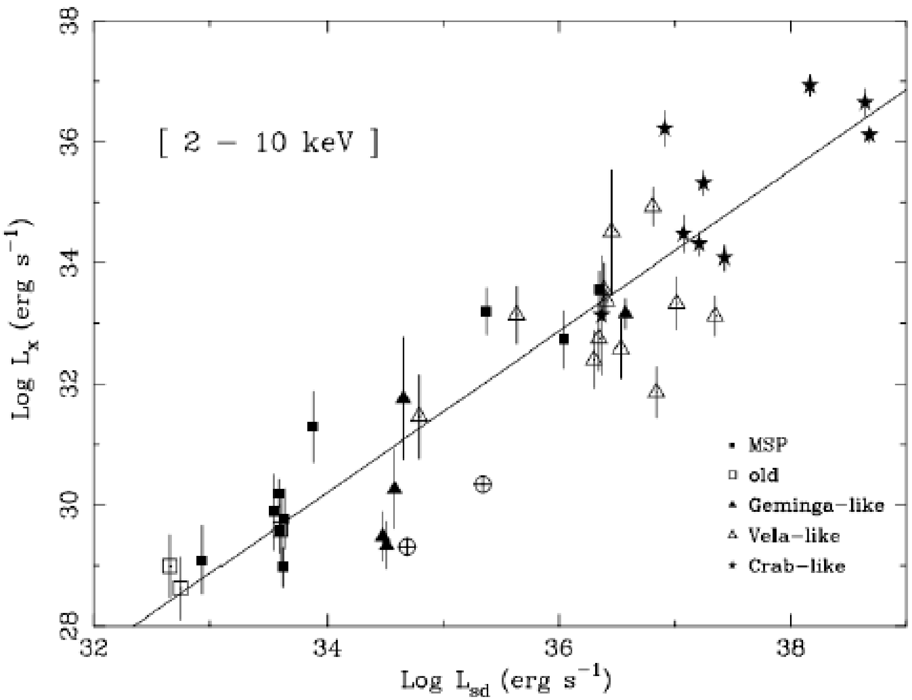


a) What the evolution trend of the profile phase for the Crab pulsar?

b) Why there are some outliers?

Spectrum

- Flux evolution: decreasing 0.2% per year(**Wilson-Hodge et al. 2011**)
- Lx-Lsd



能段	样本数目(颗)	关系	能谱来源
0.2-4.0 keV	22	$L_X \propto L_{sd}^{1.39}$	脉冲星+星云
0.1-2.4 keV	27	$L_X \propto L_{sd}^{1.03}$	脉冲星+星云
2.0-10 keV	39	$L_X \propto L_{sd}^{1.34\pm0.03}$ $L_X \propto L_{sd}^{1.02\pm0.1}$	脉冲星+星云 类Crab脉冲星+星云
2.0-10 keV	14	$L_X \propto L_{sd}^{1.15}$	脉冲星
2.0-10 keV	23	$L_X \propto L_{sd}^{1.35\pm0.2}$ $L_X \propto L_{sd}^{1.2\pm0.08}$	脉冲星+星云 脉冲星
2.0-10 keV	19	$L_X \propto L_{sd}^{1.17\pm0.02}$	脉冲星
2.0-10 keV	27	$L_X \propto L_{sd}^{0.92\pm0.04}$	脉冲星
0.3-10 keV 0.1-300 GeV	29	$L_X \propto L_{sd}^{1.04\pm0.09}$ $L_\gamma \propto L_{sd}^{1.43^{+0.31}_{-0.23}}$ ($L_{sd} < 3.72\times10^{35}$ erg s^{-1}) $L_\gamma \propto L_{sd}^{0.2^{+0.27}_{-0.31}}$ ($L_{sd} > 3.72\times10^{35}$ erg s^{-1})	脉冲星

- **What about this relationship for the Crab pulsar ?**
- **Verify different models ?**

Our works:

- Crab pulsar:
  - Studies: (1) Pulse profile shape;

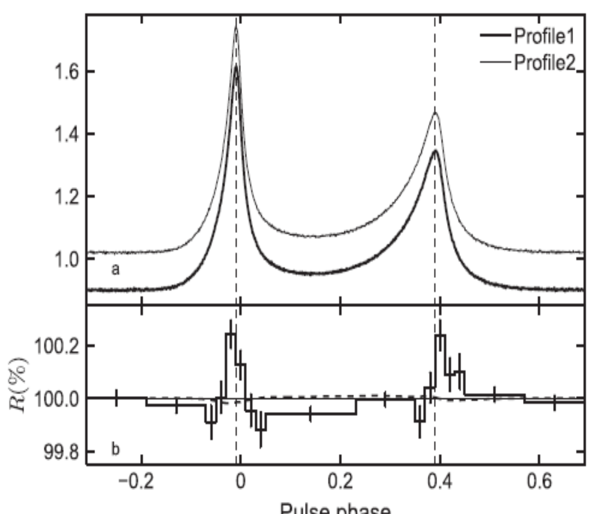
    (2) Phase comparison;

    (3) Spectrum evolution;
  - Aims: constraining radiation models and the structure of magnetosphere.

2.1 Evolution of the shape for X-ray pulse profile

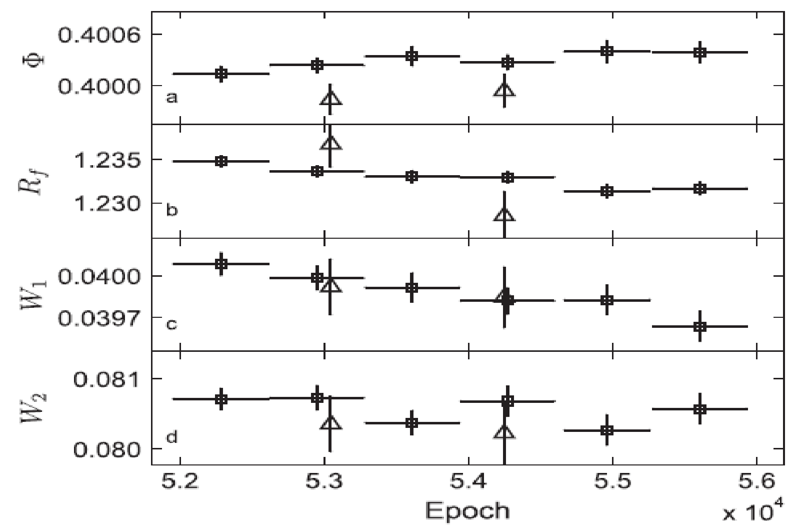
- **Observations: RXTE**
  - PCA（2-60keV）
  - HEXTE（15-250keV） (2001.02.15—2011.12.31)
- **Data reduction;**
- **Ephemeris:** Using Jodrell Bank monthly ephemeris to fold pulse profile

The ratio of two pulse profiles :

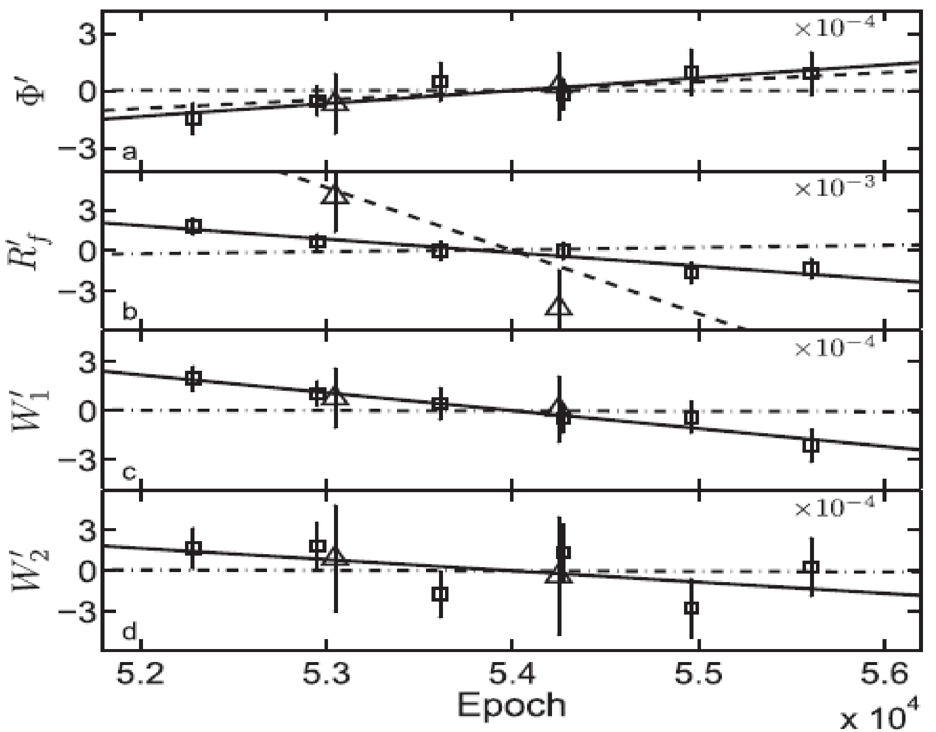


MJD 51302-54789
MJD 52570-55927

- **Parameterization of the X-Ray Profile**
  - Separation of two pulses
  - Flux ratio of two pulses
  - FWHM of two pulses



2.1 Evolution of the shape for X-ray pulse profile



Instrument	Φ (°/century)	R_f (10^{-2})	W_1 (°/century)	W_2 (°/century)
PCA	0.89 ± 0.26	−3.52 ± 0.64	−1.45 ± 0.19	−1.09 ± 0.95
All[a]	0.88 ± 0.20	−3.64 ± 0.86	−1.44 ± 0.15	−1.09 ± 0.73
Resp[b]	−0.004 ± 0.001	0.56 ± 0.01	−0.026 ± 0.001	−0.046 ± 0.001
Radio[c]	0.62 ± 0.03	−17.2 ± 0.8	···	···

- **Results :**
  - **The evolution trends in not from the aging of instruments.**
  - **The evolution of separation for X-ray profiles has the same trend and rate as radio results.**
  - **The evolution of flux ratio in X-ray has the same rend but different rate as radio results.**
  - **The FWHM of two pulses are decreasing with time but with large uncertainties.**

2.1 Evolution of the shape for X-ray pulse profile

- **Constraints:**

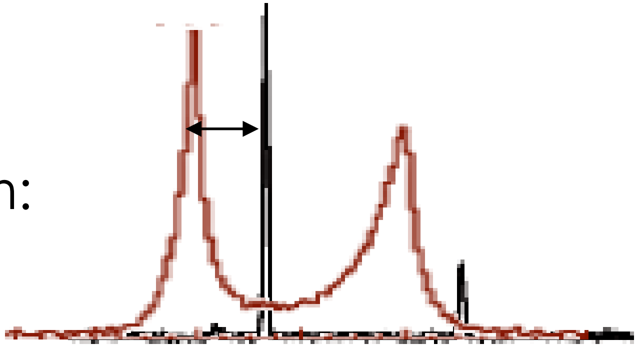
  - **The X-ray and radio radiation regions may be relational because the evolution trends of separation in two bands are the same.**
  - **The evolution of pulse profile in X-ray may be from the increasing of inclination angle.**

Ge, M. Y.; **Yan, L. L.**; Lu, F. J.; Zheng, S. J.; Yuan, J. P.; Tong, H.; Zhang, S. N.; Lu, Y., The Astrophysical Journal, 2016, 818(1), 48.

2.2 Evolution of the phase for X-ray pulse profile

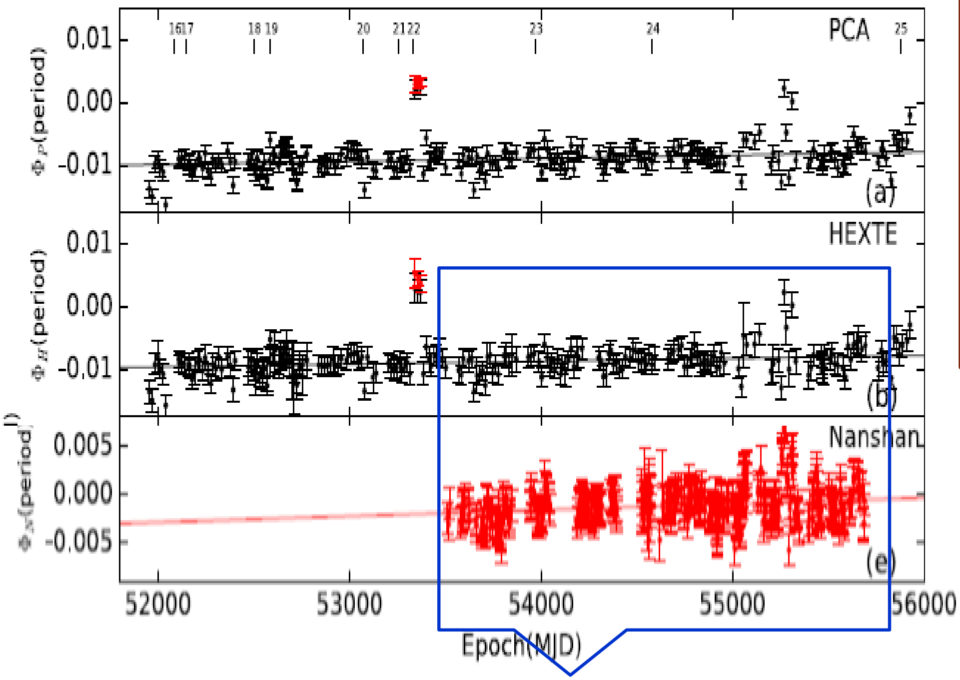
- **Observations ：**
  - ➢ **RXTE（2001.02.15—2011.12.31） (PCA and HEXTE)**
  - ➢ **Nanshan radio telescope in Urumqi （2005.05.10—2011.05.07)**
- **Data reductions;**
- **Ephemeris:** **Jodrell Bank Observatory's monthly ephemeris ;**
- **Reference TOAs：** **radio TOAs from Jodrell Bank Observatory**
- **To study : Phase evolution and timing noises in different energy bands.**

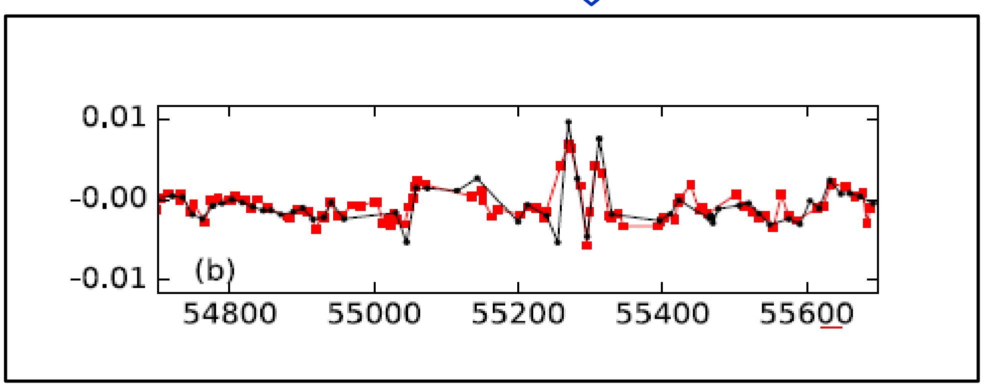
simplified diagram:



2.2 Evolution of the phase for X-ray pulse profile

The change of phase with time:





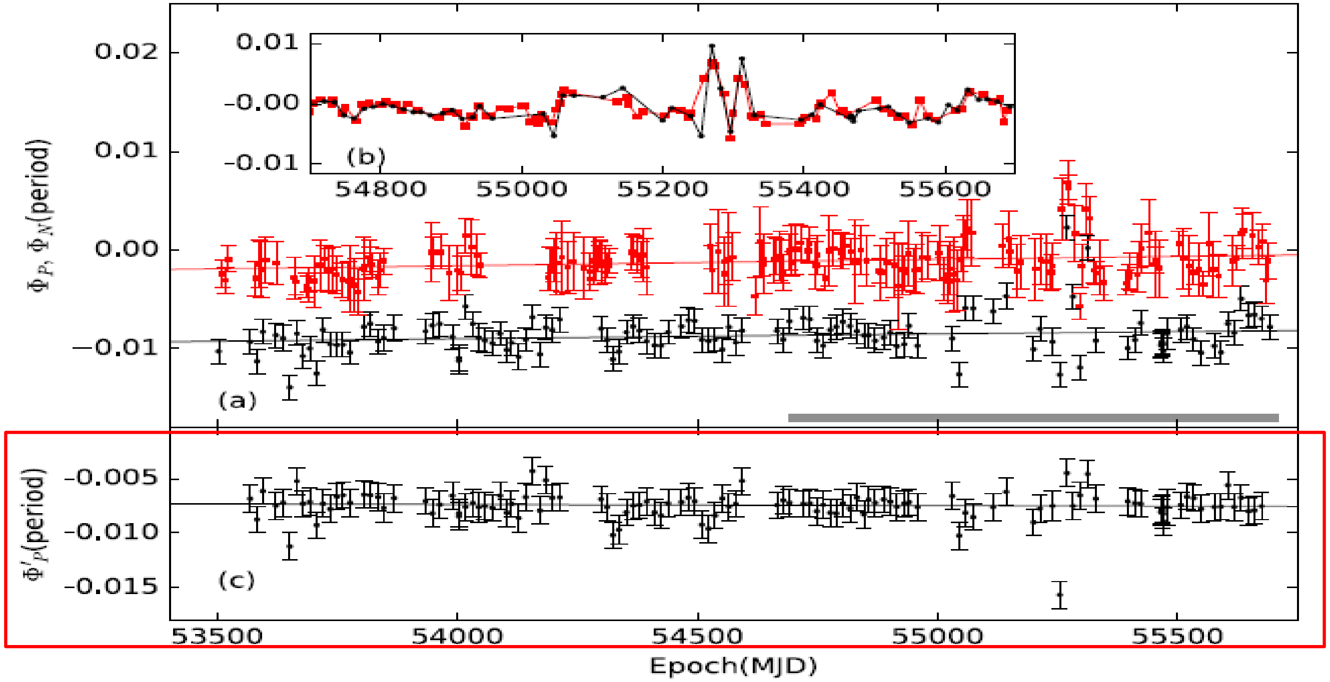
- **The phases in different energy bands have strong correlations;**
- **The radio phase from Nanshan changed with time obviously;**

- **To check evolution trend:**
  - **Clock of RXTE and Nanshan telescope** **no**
  - **Ephemeris:**
    - ✓ **period、proper motion、ISM** **no**
    - ✓ **Reference TOAs** **yes!**

2.2 Evolution of the phase for X-ray pulse profile

Red points： Nanshan
Black points： PCA

X-ray phase by using Nanshan TOAs as reference:



- **Constraints:**
  - ➢ **X-ray and radio emitting regions do not have significant relative changes.**
  - ➢ **Timing noises in different bands are the same and they are not from the ISM.**

Yan, L. L.; Ge, M. Y.; Yuan, J. P.; Zheng, S. J.; Lu, F. J.; Tuo, Y. L.; Tong, H.; Zhang, S. N.; Lu, Y.; Han, J. L.; The Astrophysical Journal, 2017, 845(2), 119.

2.3 Evolution of the spectrum

- **Observations:**
  - **RXTE (2001.02.15—2011.12.31)**
  - **FGST (2008.11.01—2017.08.01)**

    PCA: 5-60keV
    HEXTE: 15-250keV
    LAT : 0.1-300 GeV
- **Data reduction;**
- **Fitting spectrum**
  - **subtract PWN and nebula background**
- **To study:**
  - **Photon index and flux evolution;**
  - **The relation of High energy luminosity and spin down power**

X-ray:

$$\frac{dN}{dE} = e^{-N_{\rm H}\sigma(E)} \times N_0(E)^{-\Gamma} \quad \mathrm{counts\,cm^{-2}\,s^{-1}\,keV^{-1}}$$

γ-ray:

$$\frac{dN}{dE} = N_0(E_{GeV})^{-\Gamma} e^{-E/E_c} \quad \mathrm{counts\,cm^{-2}\,s^{-1}\,MeV^{-1}}$$

⇩

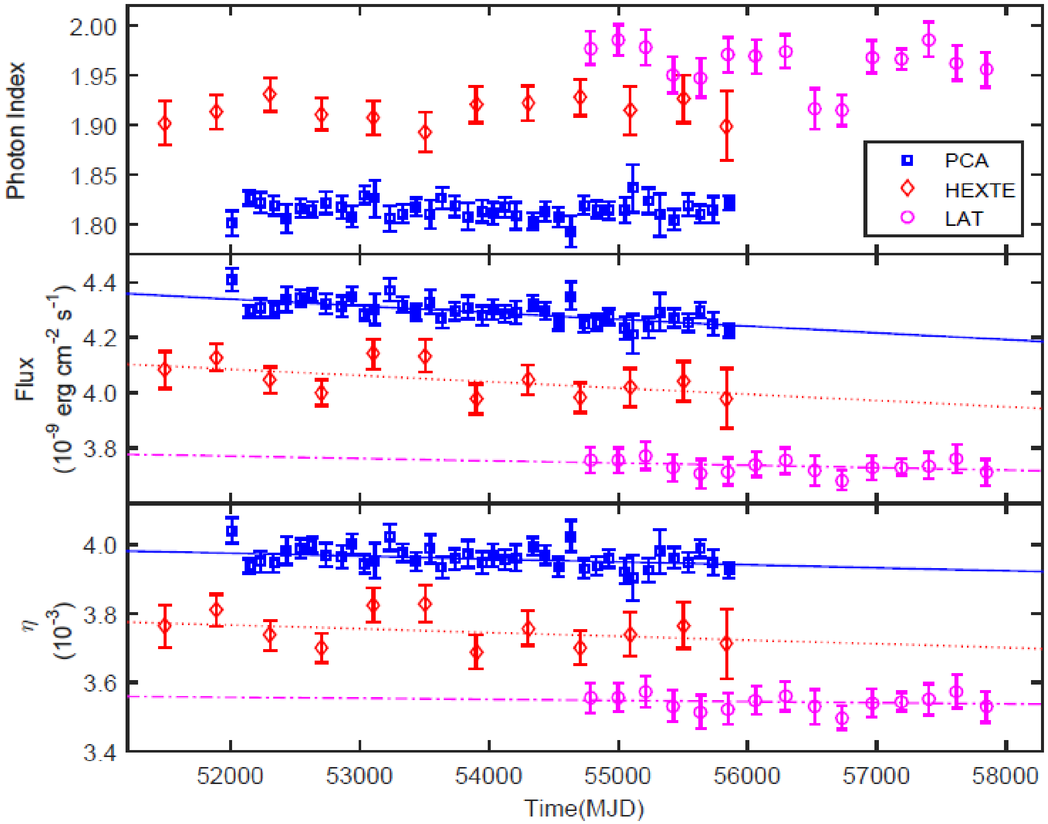
$$L_{X,\gamma} = 4\pi d^2 f_{X,\gamma} F_{X,\gamma}$$

Spin down power: **Lsd**

$$-\dot{E} = \frac{dE}{dt} = -\frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = -I\Omega\dot{\Omega} = \frac{4\pi^2 I\dot{P}}{P^3}$$

2.3 Evolution of the spectrum

The change of spectrum parameters with time:

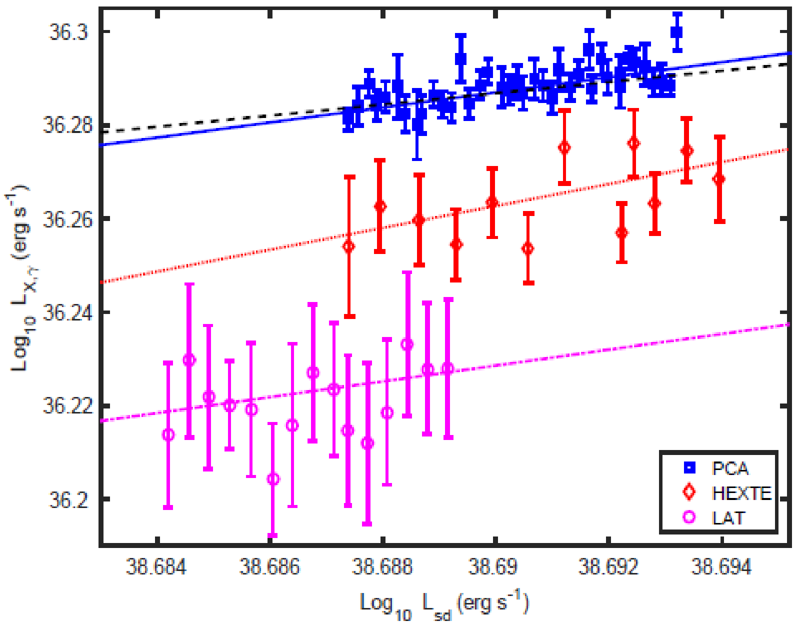


仪器	能量范围	流量(erg cm^{-2} s^{-1})		能量转换效率η	
		Rate (10^{-14}/day)	Intercept (10^{-9})	Rate (10^{-9}/day)	Intercept (10^{-3})
PCA	5–60 keV	-2.4 ± 0.4	4.3 ± 0.01	-8.5 ± 3.8	4.0 ± 0.01
HEXTE	15–250 keV	-2.3 ± 1.8	3.1 ± 0.04	-11.0 ± 16.5	2.9 ± 0.03
LAT	0.1–300 GeV	-0.8 ± 0.7	1.3 ± 0.01	-3.1 ± 6.3	1.2 ± 0.01

- **X-ray flux decreased with time;**
- $\eta_{X,\gamma} = \frac{L_{X,\gamma}}{L_{sd}}$ **decreased with time but with large uncertainties.**
- **In gamma-ray, the evolution trend are not obvious.**

2.3 Evolution of the spectrum

Lx, γ vs Lsd



- $L_x \propto L_{sd}^{1.6\pm0.3}$, which is well consistent with some previous studies(such as Vink et al. 2011).

- $$L_{sd}^{(OG)} = 3.8\times10^{31} B_0(\mathrm{G})^2 P(\mathrm{s})^{-4} \mathrm{erg\,s^{-1}}$$

  $$L_{X,th}^{(OG)} = 5.5\times10^{-4}\left(\frac{\tan\alpha}{\tan 55^\circ}\right)^4 B_{0\,12}^{0.13} P_{-1}^{-0.8} L_{sd}^{(OG)}$$

  Cheng et al. (1998)

- **5–60 keV** $L_{X,th}^{(OG)} \propto L_{sd}^{(OG)\,1.2}$

Group	Instrument		Parameter1		Parameter2	m	$\mathrm{Log}_{10}\, n$	ρ
1	PCA	5–60 keV	L_X	vs.	L_{sd}	1.6 ± 0.3	-26.1 ± 10.4	0.69
2	HEXTE	15–250 keV	L_X	vs.	L_{sd}	2.3 ± 1.5	-54.4 ± 56.1	0.59
3	LAT	0.1–300 GeV	L_γ	vs.	L_{sd}	1.7 ± 1.4	-29.7 ± 54.1	0.30

Yan, L. L.; Ge, M. Y.; Lu, F. J. ;Zheng S. J. ; Tuo Y. L. Song L. M. Qu J. L. Li Z. J. The Astrophysical Journal , 2018. Under Reviewing

3. Summaries

- （1） The evolution trend of X-ray profile for the Crab pulsar is similar with radio results and may be from the increasing of inclination angle.

- （2） The X-ray phases are constant with time, so X-ray and radio emitting regions do not have significant relative changes and timing noises are not from the ISM.

- （3） The X-ray flux decreased with time, and the X-ray luminosities in 5-60 keV with spin down power have a relation $L_x \propto L_{sd}^{1.6\pm0.3}$, and the prediction of outer gap model in Cheng et al 1998 is consistent with observations.

Thanks！