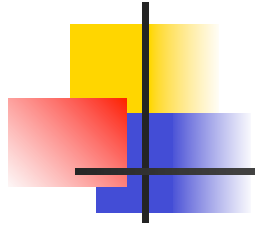


# *High Mass X-ray Binaries*





# *High Mass X-ray Binaries*

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*Biswajit Paul*



# *High Mass X-ray Binaries*

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*Biswajit Paul*

*Raman Research Institute, Bangalore*



# *High Mass X-ray Binaries*

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*Biswajit Paul*

*Raman Research Institute, Bangalore*



# *High Mass X-ray Binaries*

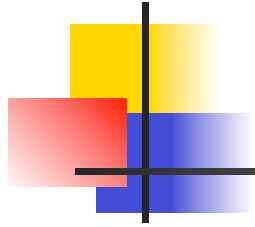
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*Biswajit Paul*

*Raman Research Institute, Bangalore*

*Harsha Raichur, Sachi Naik,  
Chetana Jain, Ramanpreet Kaur,  
Jincy Devasia, Marykutty James,  
Chandreyee Maitra*

# *High Mass X-ray Binaries*





# *High Mass X-ray Binaries*

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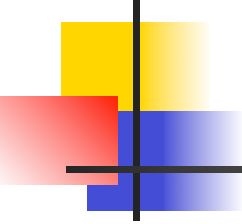
## *Black Hole Binaries*

### *Accretion Powered Pulsars*

- *Quasi Periodic Oscillations*
- *Orbital Evolution (poster-02)*
- *Energy Dependent Pulse Profile*
  - / Phase Resolved Spectroscopy (poster 07/08)*
- *Broadening of Pulse Peak (poster-03)*

### *Supergiant Fast X-ray Transients*

- *Short Orbital Period*
- *Orbital Phase Locked Flares*



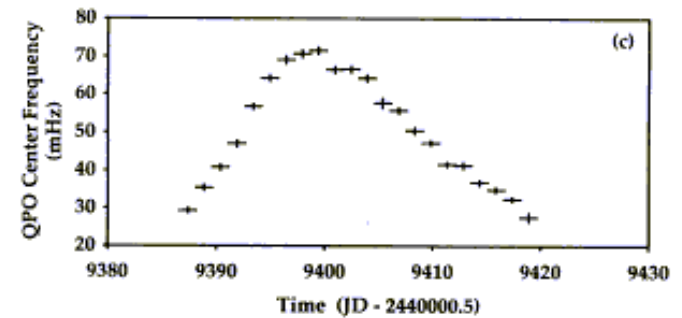
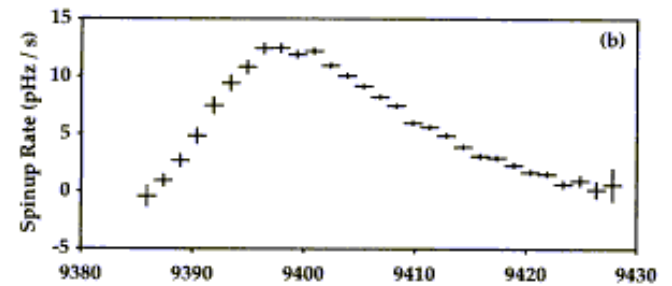
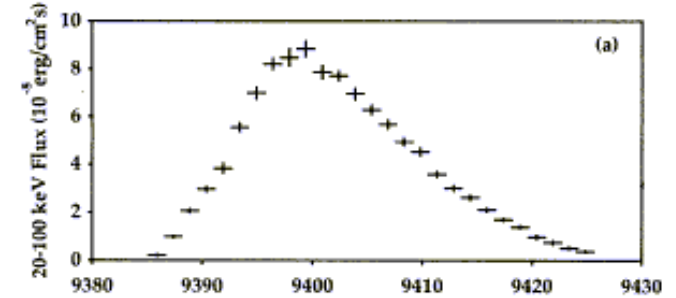
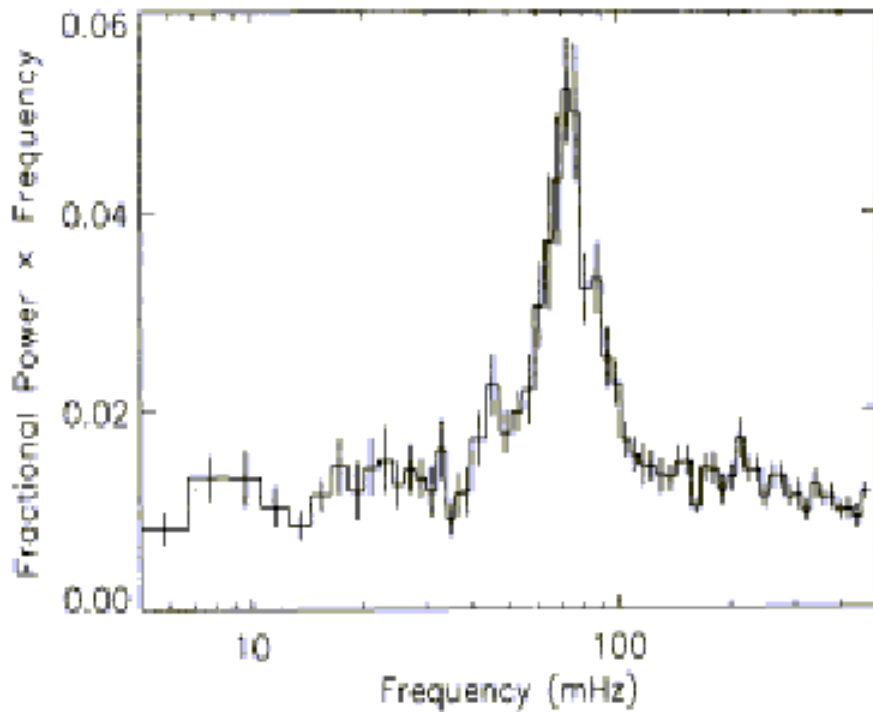
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$$\mathbf{r_M} = M^{1/7} R^{-2/7} L^{-2/7} \mu^{4/7}$$

$$v_{\mathbf{qpo}} = (1/2\pi) (GM/r_M^3)^{1/2}$$

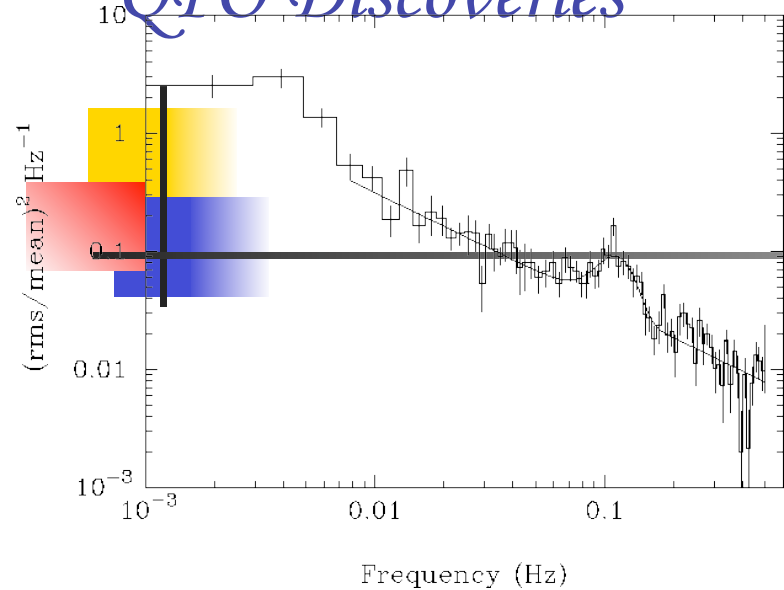
$$v_{\mathbf{qpo}} = (1/2\pi) (GM/r_M^3)^{1/2} - v_{\mathbf{spin}}$$

# QPOs: Luminosity dependence

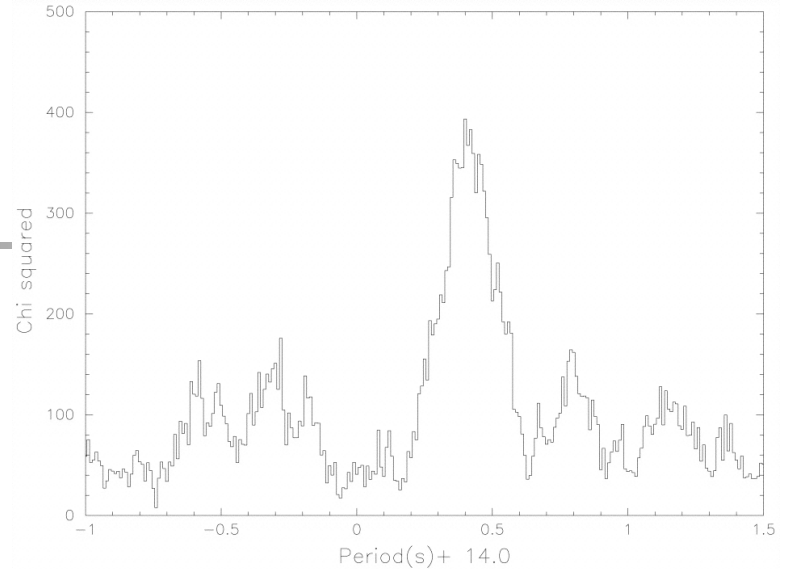


*A 0535+262: Finger et al., (1996), Ghosh (1996)*

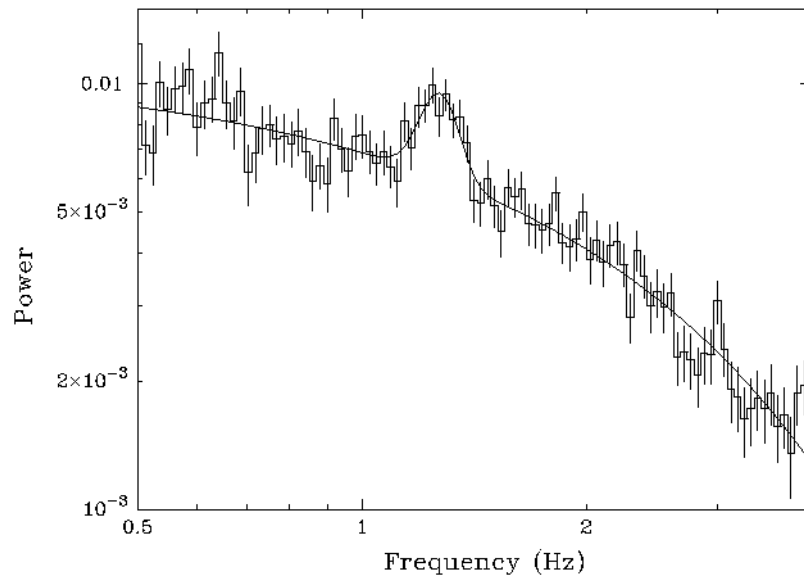
# QPO Discoveries



*XTE J1858+034: Paul et al. (1998)*

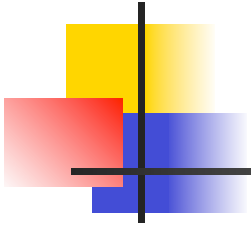


*4U 1907+09: Mukherjee et al. (2001)*



*XTE J0111.2-7317 (Ramanpreet et al. 2007)*

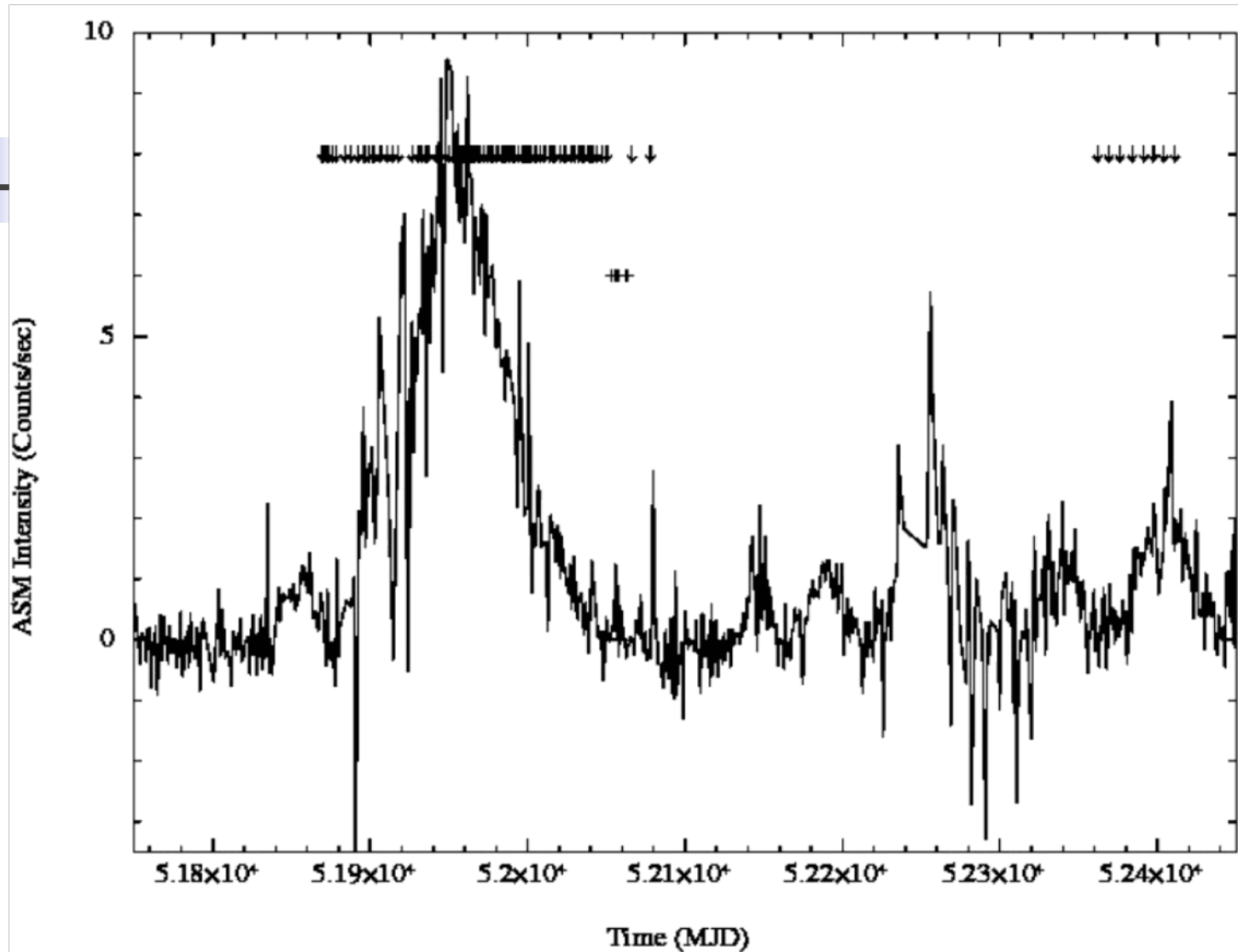
# *Recent QPO Discoveries*



*KS 1947+300*

*Marykitty James et al. 2010*

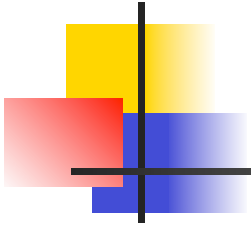
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*KS 1947+300*

*Marykuty James et al. 2010*

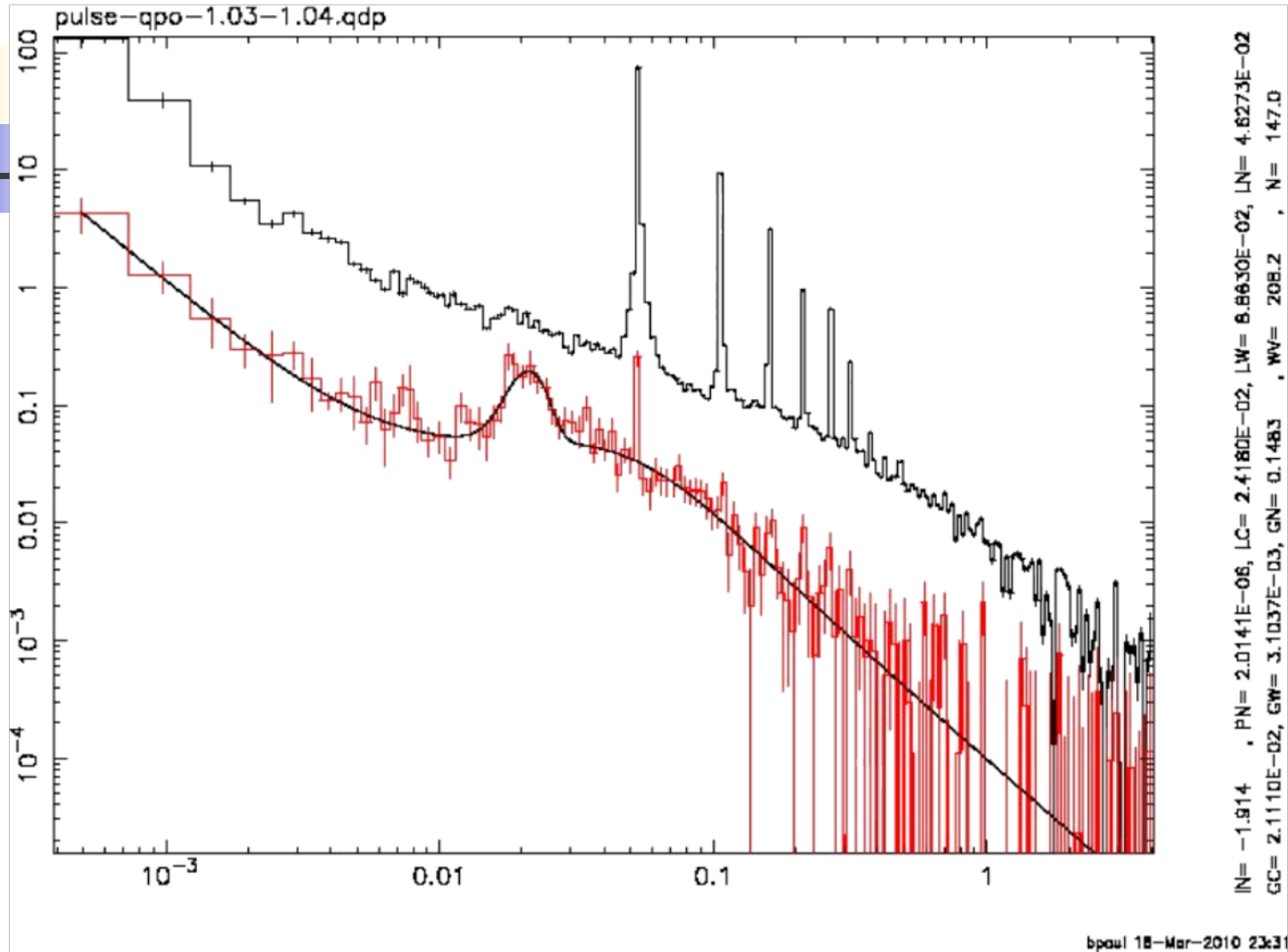
# *Recent QPO Discoveries*



*KS 1947+300*

*Marykitty James et al. 2010*

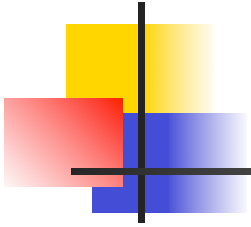
# Recent QPO Discoveries



*KS 1947+300*

*Marykuty James et al. 2010*

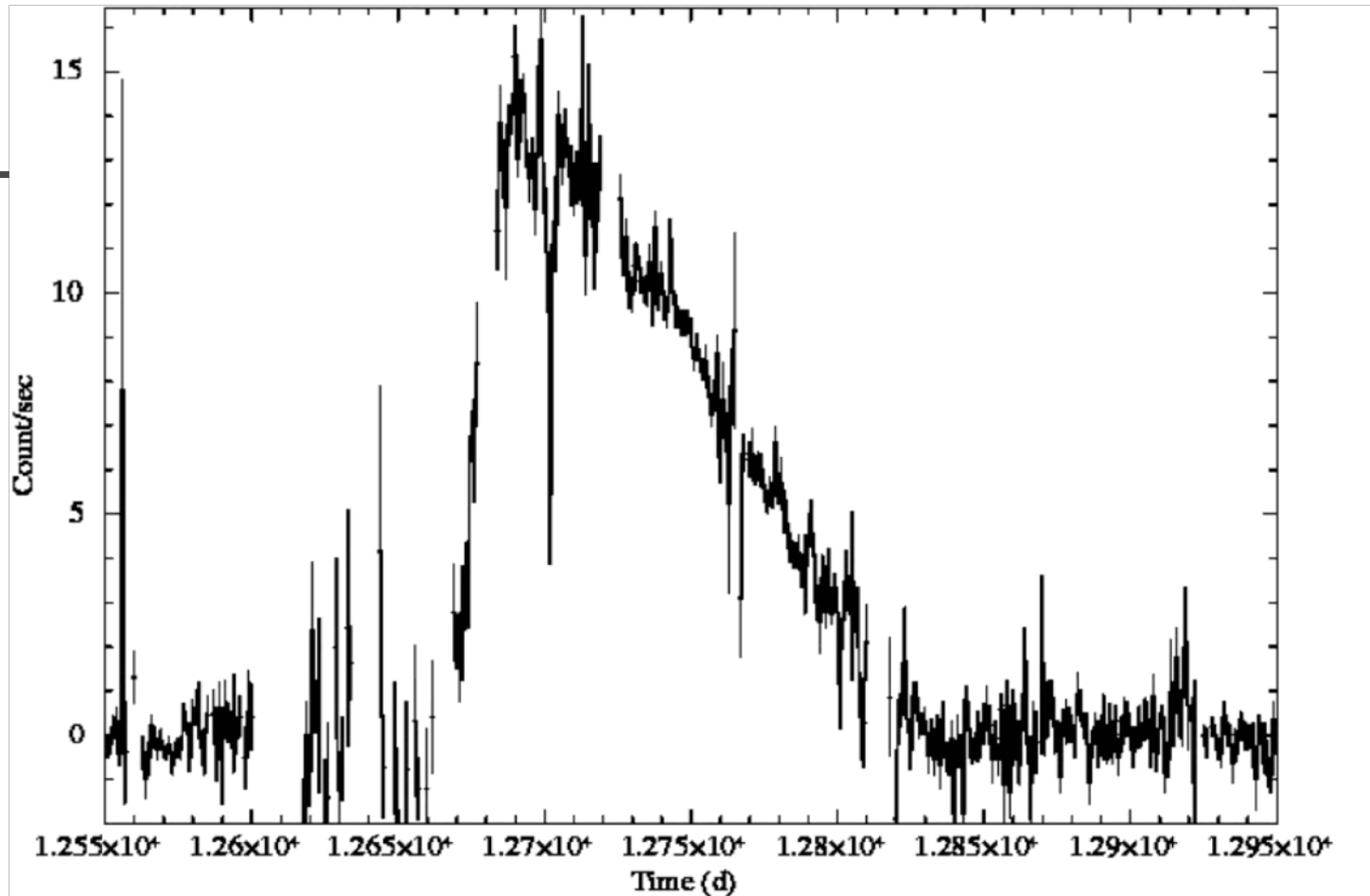
# *Recent QPO Discoveries*



*4U 1901+031*

*Marykitty James et al. 2010*

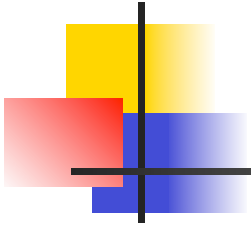
# Recent QPO Discoveries



*4U 1901+031*

*Marykuty James et al. 2010*

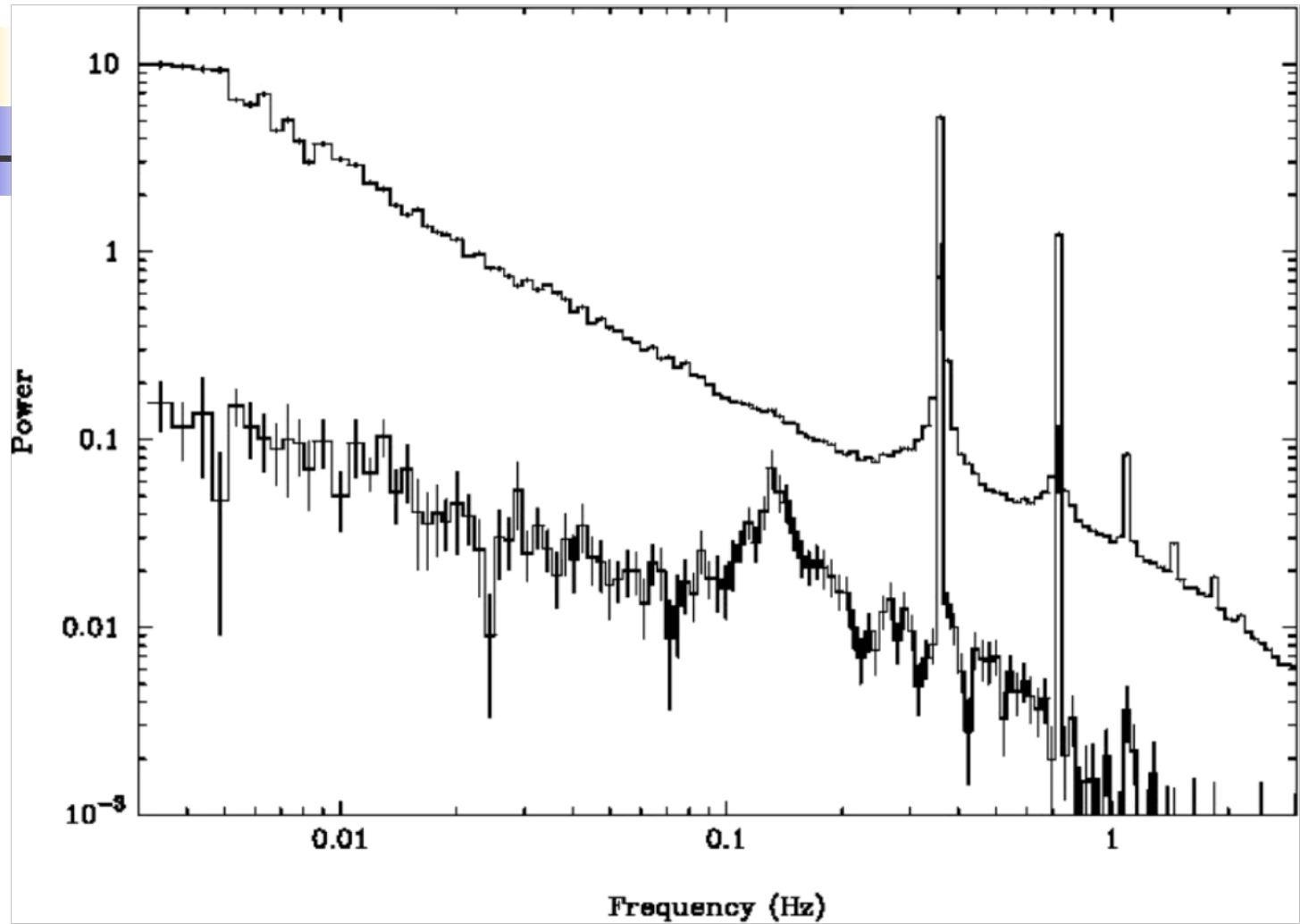
# *Recent QPO Discoveries*



*4U 1901+031*

*Marykitty James et al. 2010*

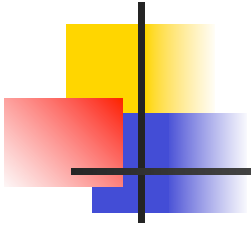
# Recent QPO Discoveries



*4U 1901+031*

*Marykuty James et al. 2010*

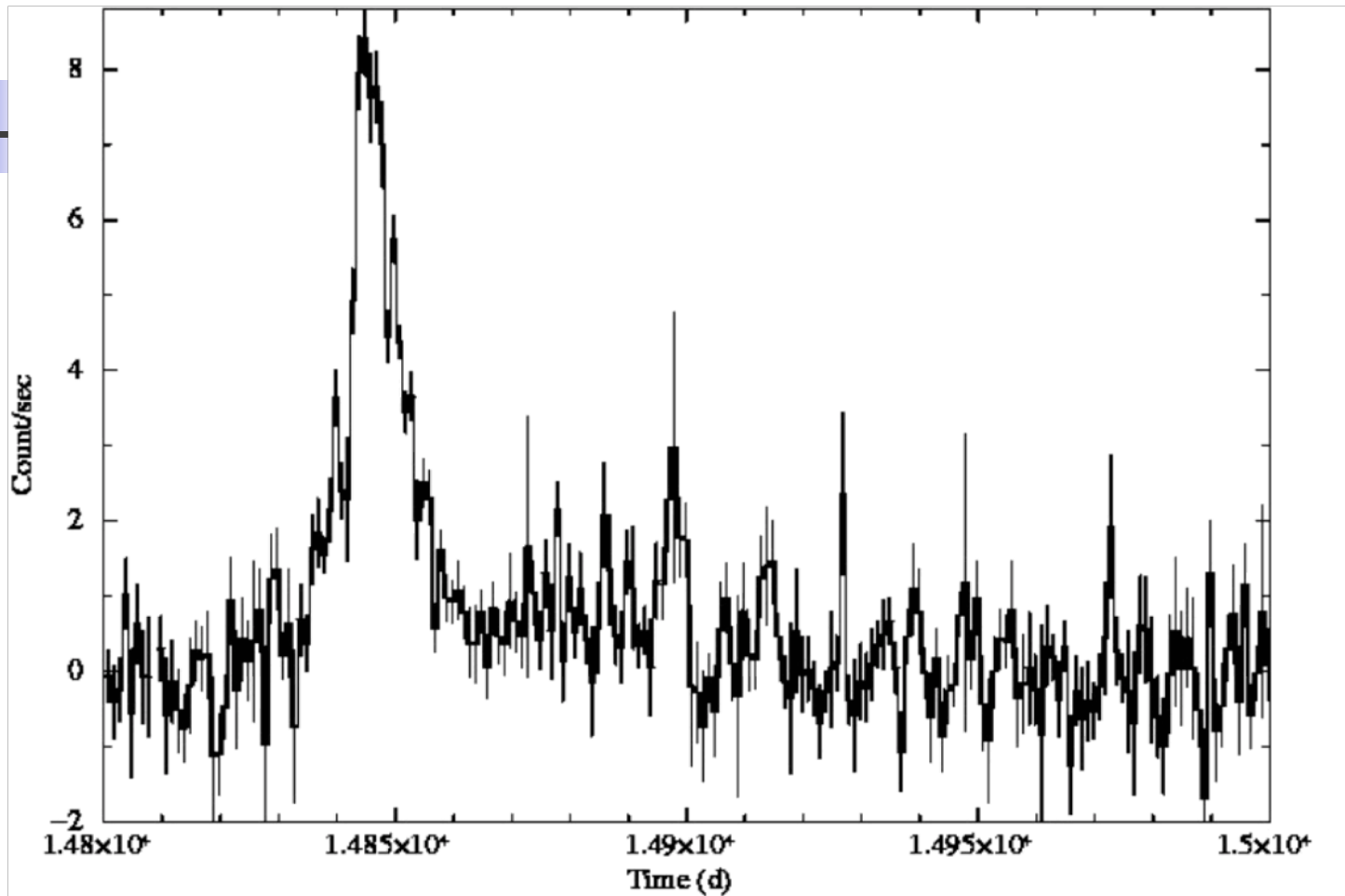
# *Recent QPO Discoveries*



*4U 1118-616*

*Marykitty James et al. 2010*  
*Nespoli and Reig, 2011*

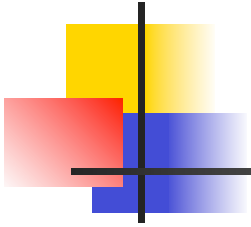
# Recent QPO Discoveries



*4U 1118-616*

*Marykuty James et al. 2010  
Nespoli and Reig, 2011*

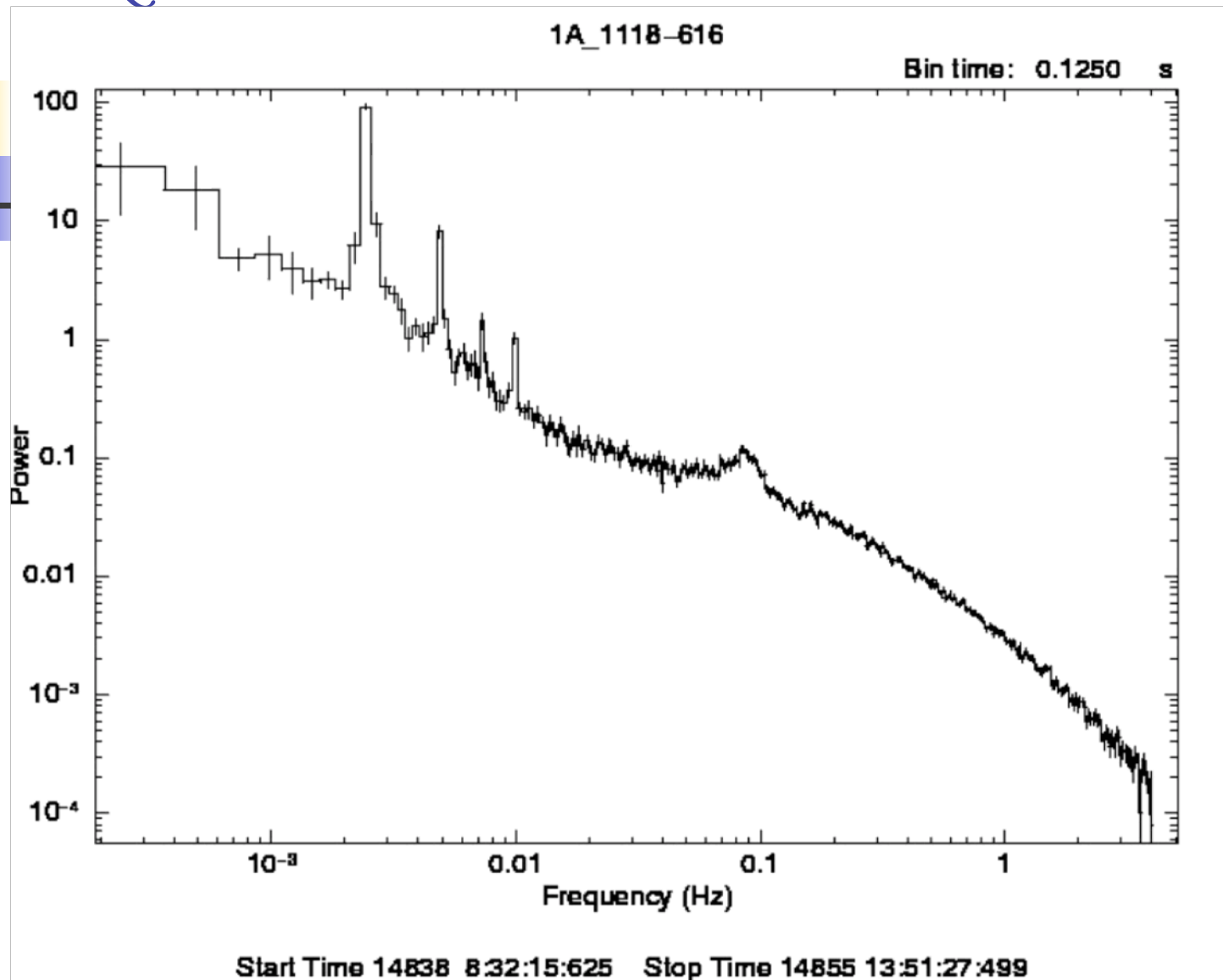
# *Recent QPO Discoveries*



*4U 1118-616*

*Marykitty James et al. 2010*  
*Nespoli and Reig, 2011*

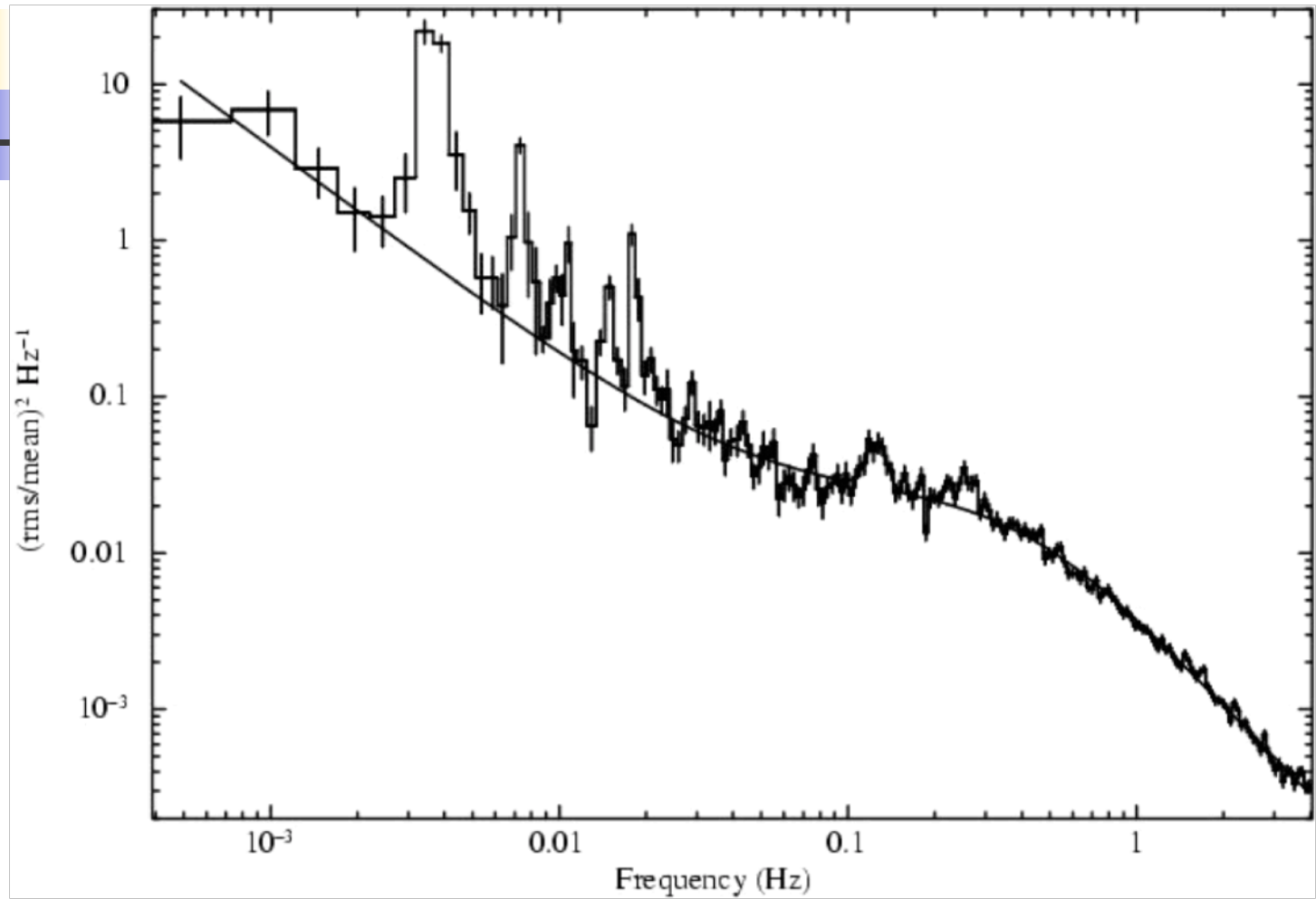
# Recent QPO Discoveries



*4U 1118-616*

*Marykuty James et al. 2010*  
*Nespoli and Reig, 2011*

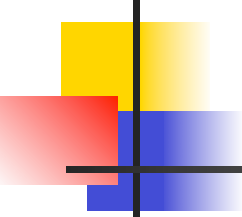
# Recent QPO Discoveries



*GX 304-1*

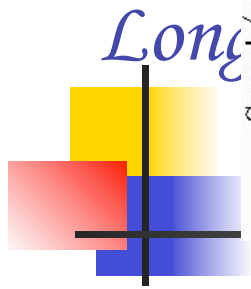
*Devasia et al. 2011*

# QPO census

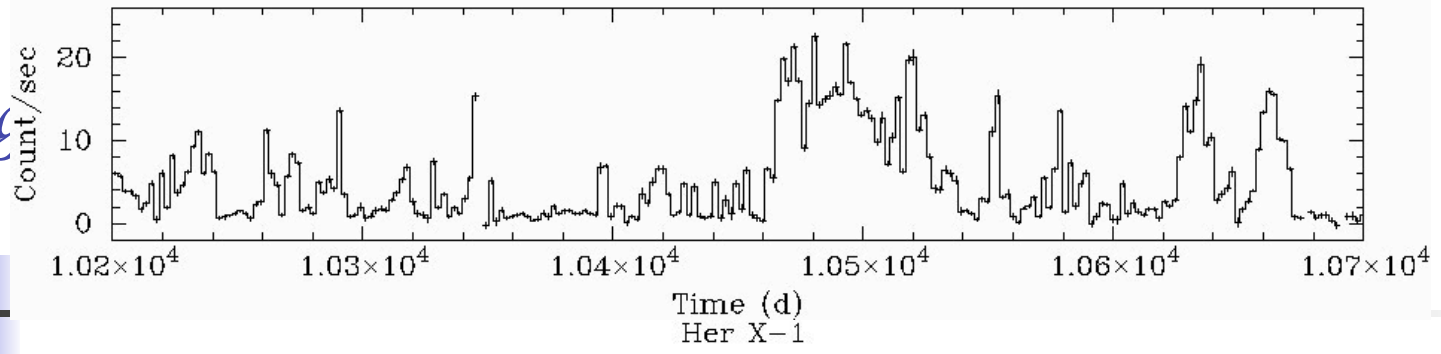


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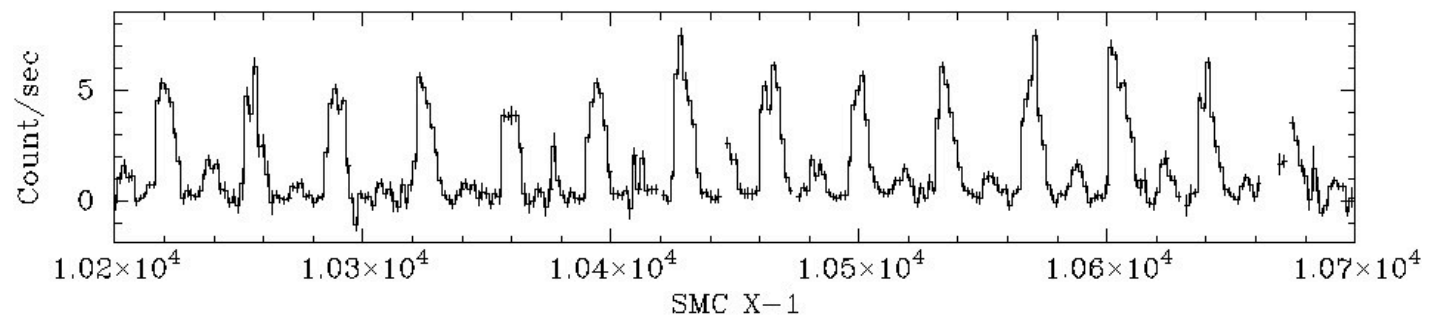
Source	Type	Pulse freq	QPO freq	Ratio
<b>KS 1947+300</b>	<b>HMXB/Be</b>	<b>53</b>	<b>20</b>	<b>0.38</b>
SAX J2103.5+4545	HMXB/?	2.79	44	15.77
A 0535+26	HMXB/Be	9.7	50	5.15
V 0332+53	HMXB/Be	229	51	0.223
4U 0115+63	HMXB/Be	277	62	0.224
<b>1A 1118-616</b>	<b>HMXB/Be</b>	<b>2.5</b>	<b>92</b>	<b>36.8</b>
<b>XTE J1858+034</b>	<b>HMXB/Be</b>	<b>4.53</b>	<b>110</b>	<b>24.3</b>
<b>4U 1901+03</b>	<b>HMXB/?</b>	<b>361.9</b>	<b>130</b>	<b>0.359</b>
EXO 2030+375	HMXB/Be	24	200	8.33
SWIFT J1626.6-5156	HMXB/Be	65	1000	15.38
<b>XTE J0111.2-7317</b>	<b>HMXB/B0.5-B1Ve</b>	<b>32</b>	<b>1270</b>	<b>39.68</b>
GRO J1744-28	LMXB	2100	20000	9.52
<b>GX 304-1</b>	<b>HMXB</b>	<b>3.63</b>	<b>120</b>	<b>33</b>
MAXI J1409-619	HMXB	2.0	192	95
-----				
SMC X-1	HMXB/B0	1410	10	0.0071
Her X-1	LMXB	806	13	0.016
LMC X-4	HMXB/O-type	74	0.65-20	0.0087-0.27
<b>Cen X-3</b>	<b>HMXB/O-type</b>	<b>207</b>	<b>35</b>	<b>0.17</b>
<b>4U 1626-67</b>	<b>LMXB</b>	<b>130</b>	<b>48</b>	<b>0.37</b>
X Per	HMXB/Be	1.2	54	45
<b>4U 1907+09</b>	<b>HMXB/OB</b>	<b>2.27</b>	<b>69</b>	<b>30.4</b>



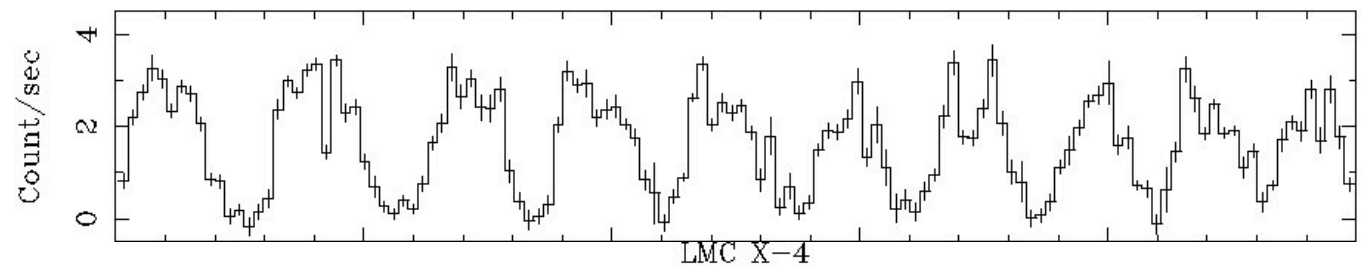
Cen X-3



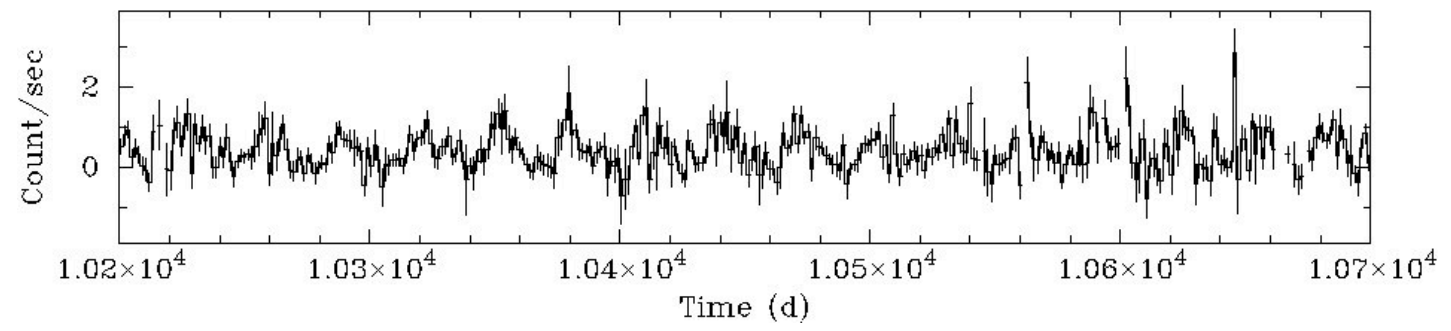
Her X-1



SMC X-1



LMC X-4

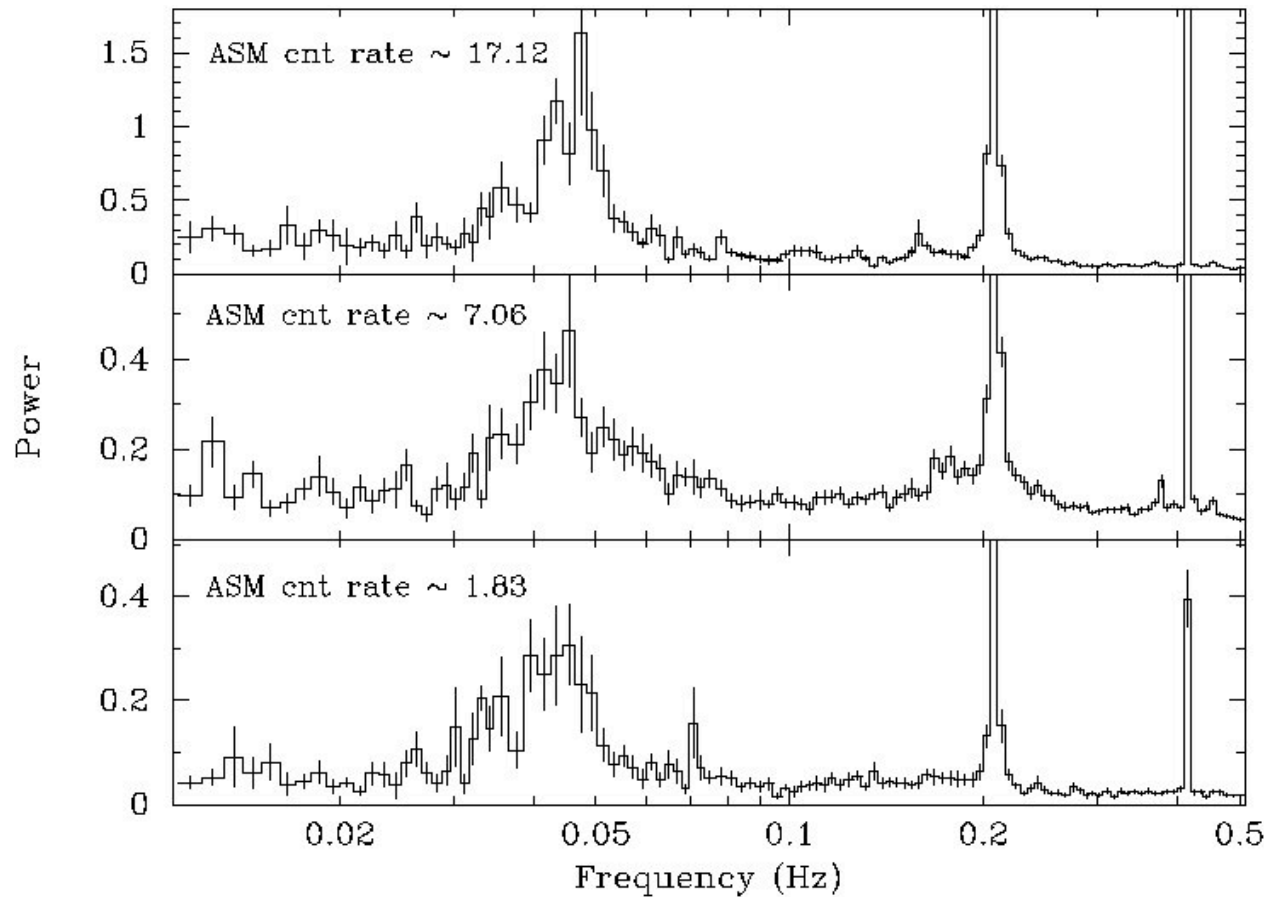


*Long term intensity variations in Cen X-3  
and the quasi-periodic oscillations*

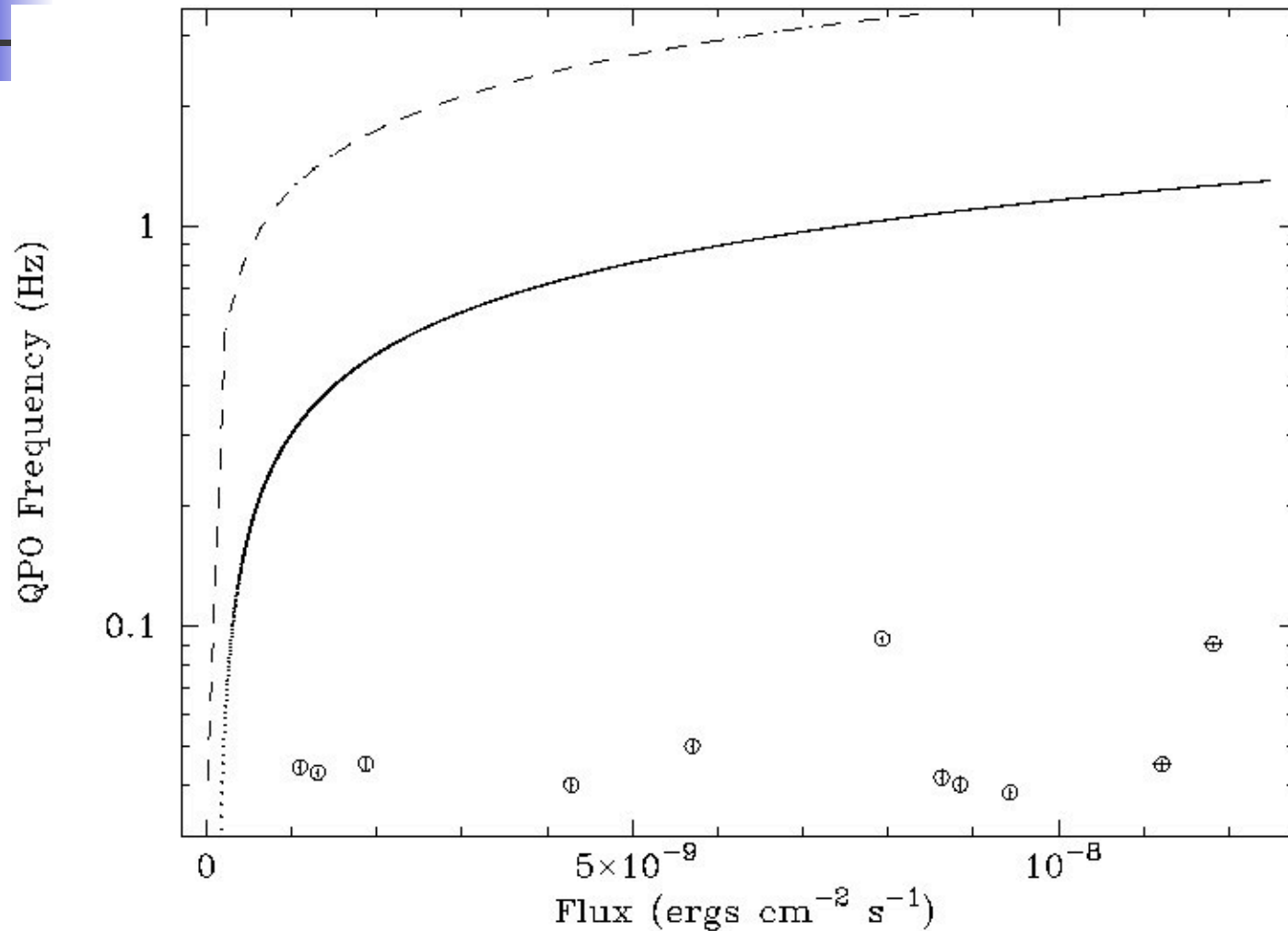


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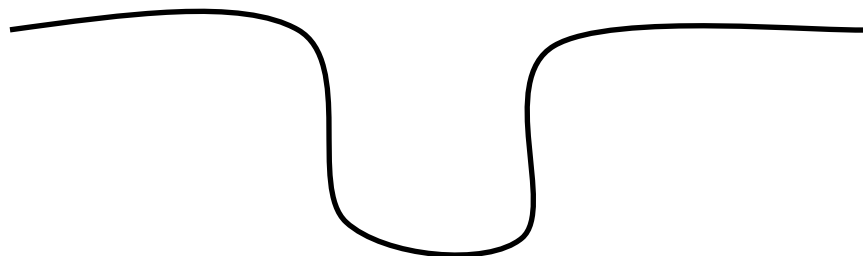
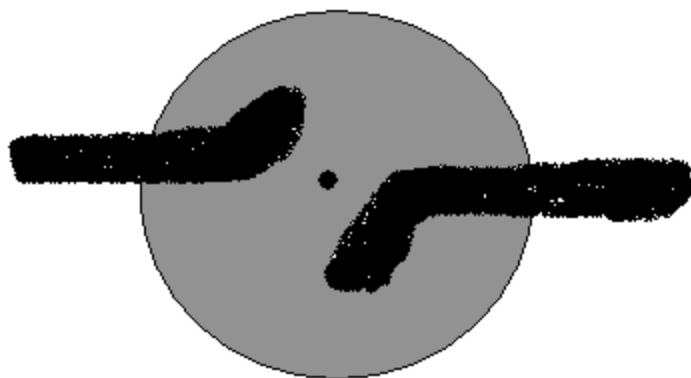
# *Long term intensity variations in Cen X-3 and the quasi-periodic oscillations*



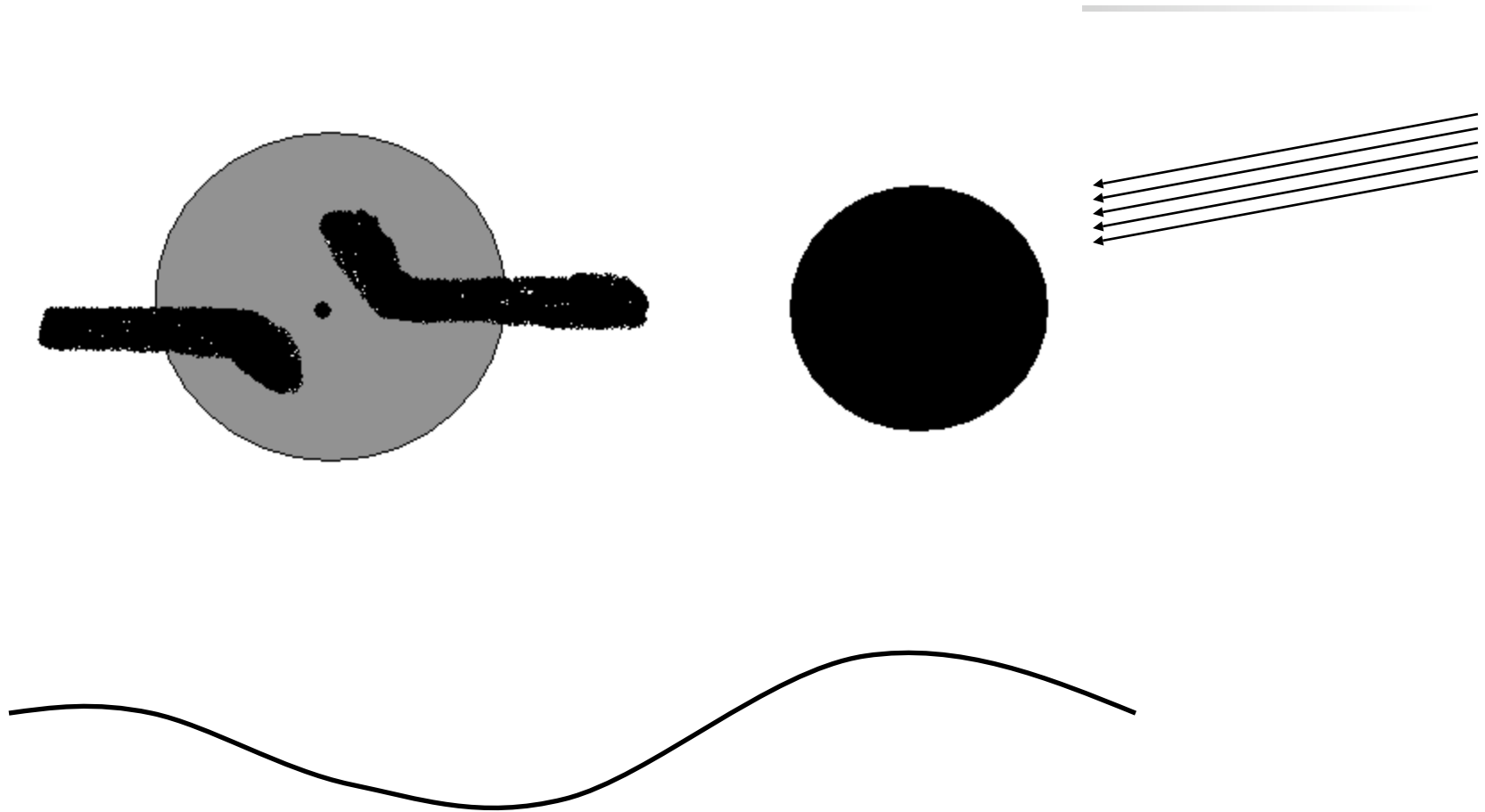
# Long term intensity variations in Cen X-3 and the quasi-periodic oscillations



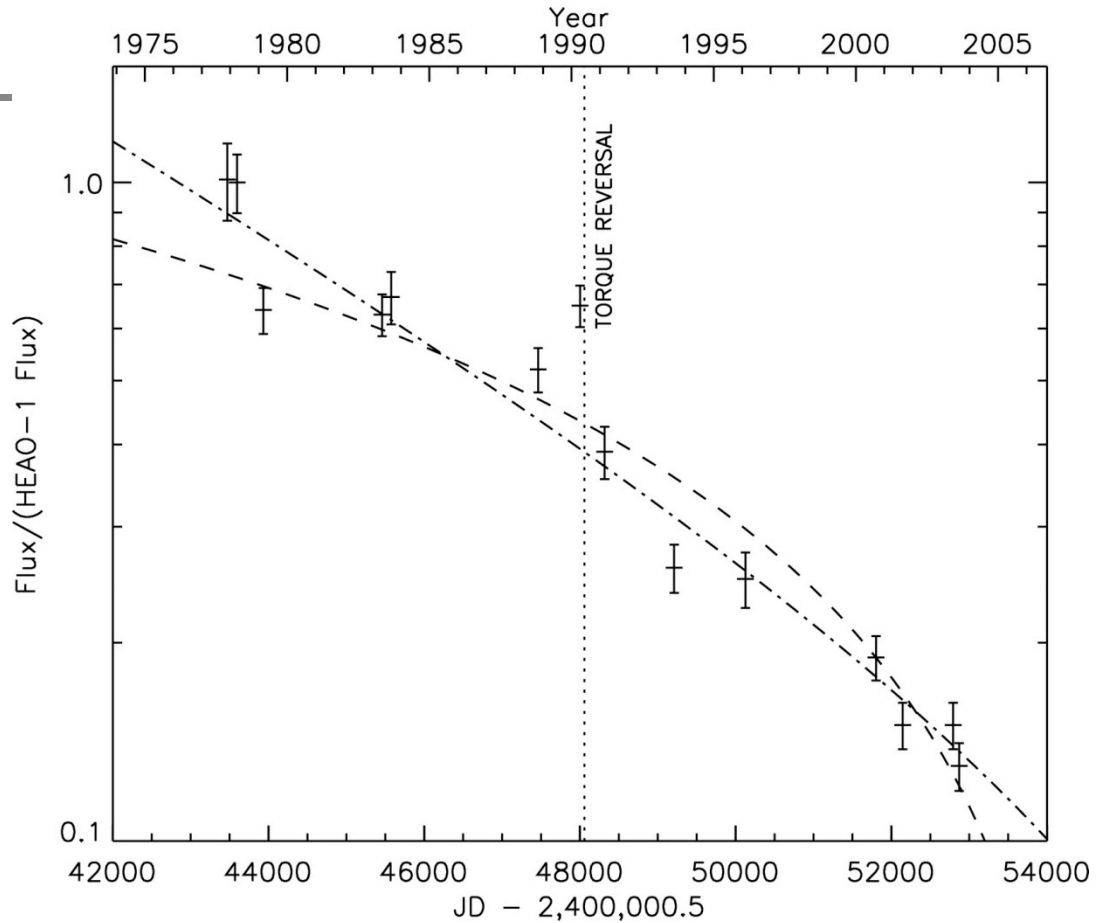
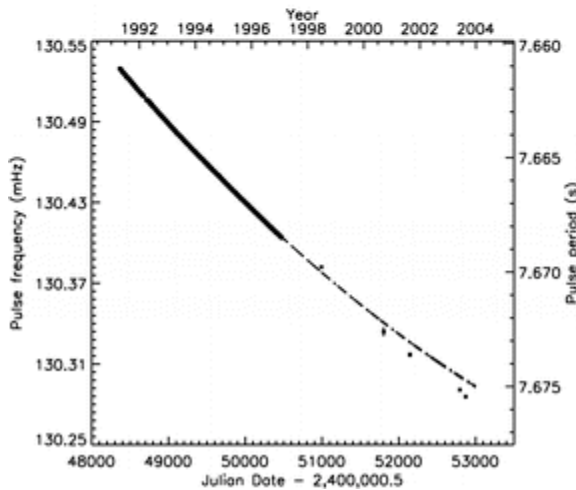
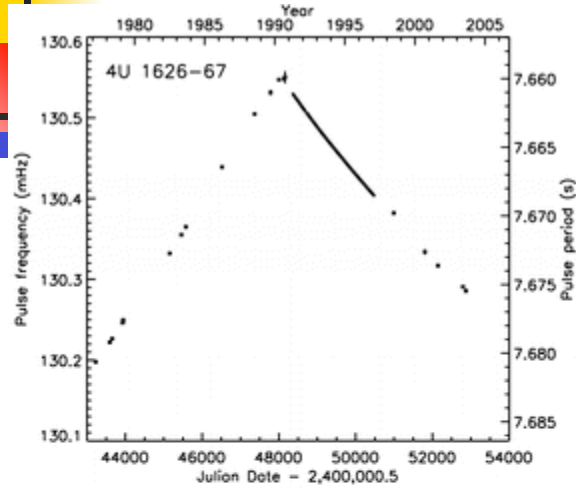
# *Gen X-3: Precessing Warped Accretion Disk??*



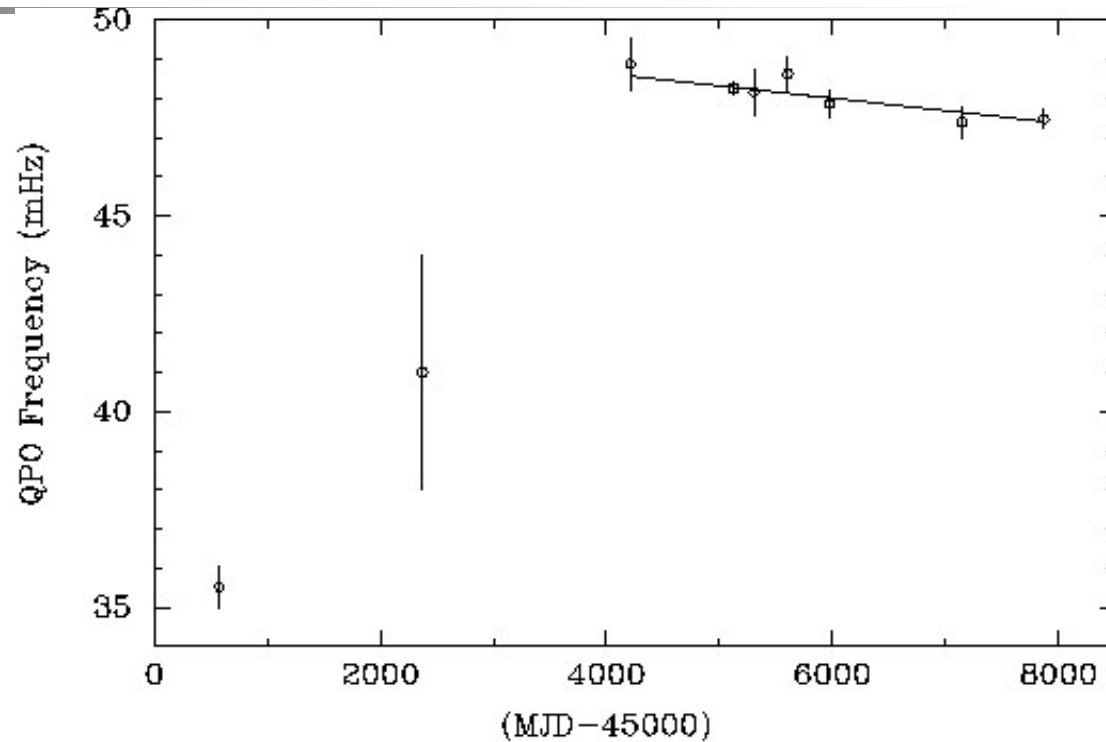
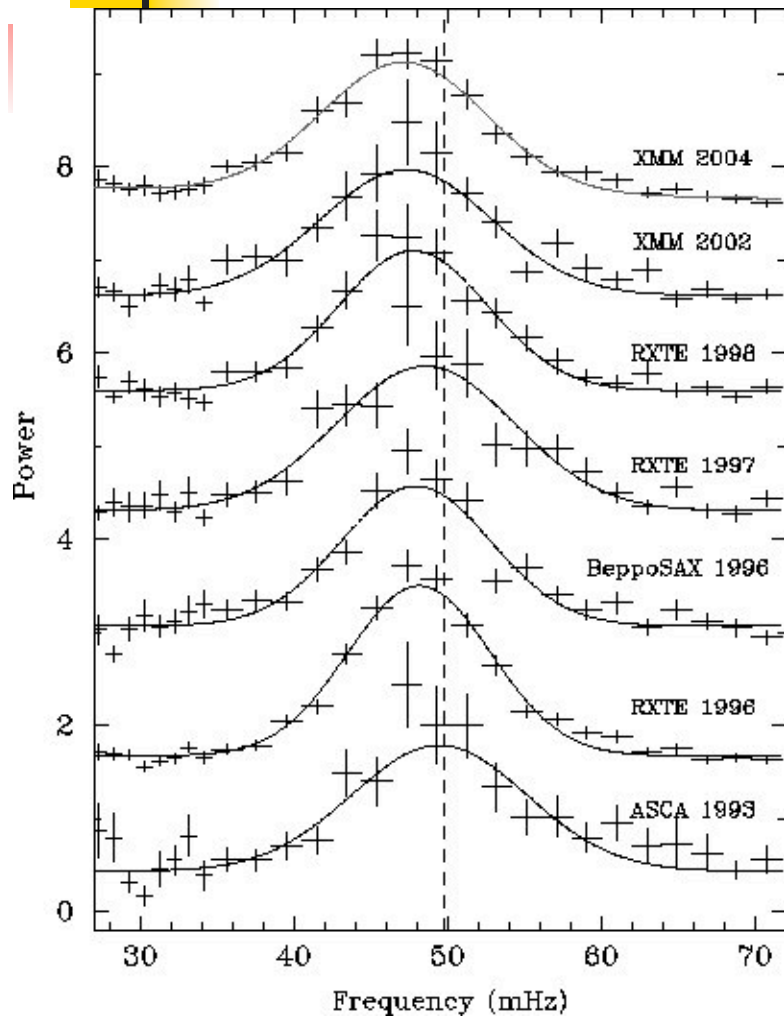
# *Gen X-3: Precessing Warped Accretion Disk??*



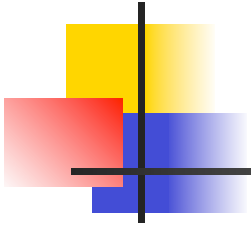
# *4U 1626-67 : Period and flux evolution*



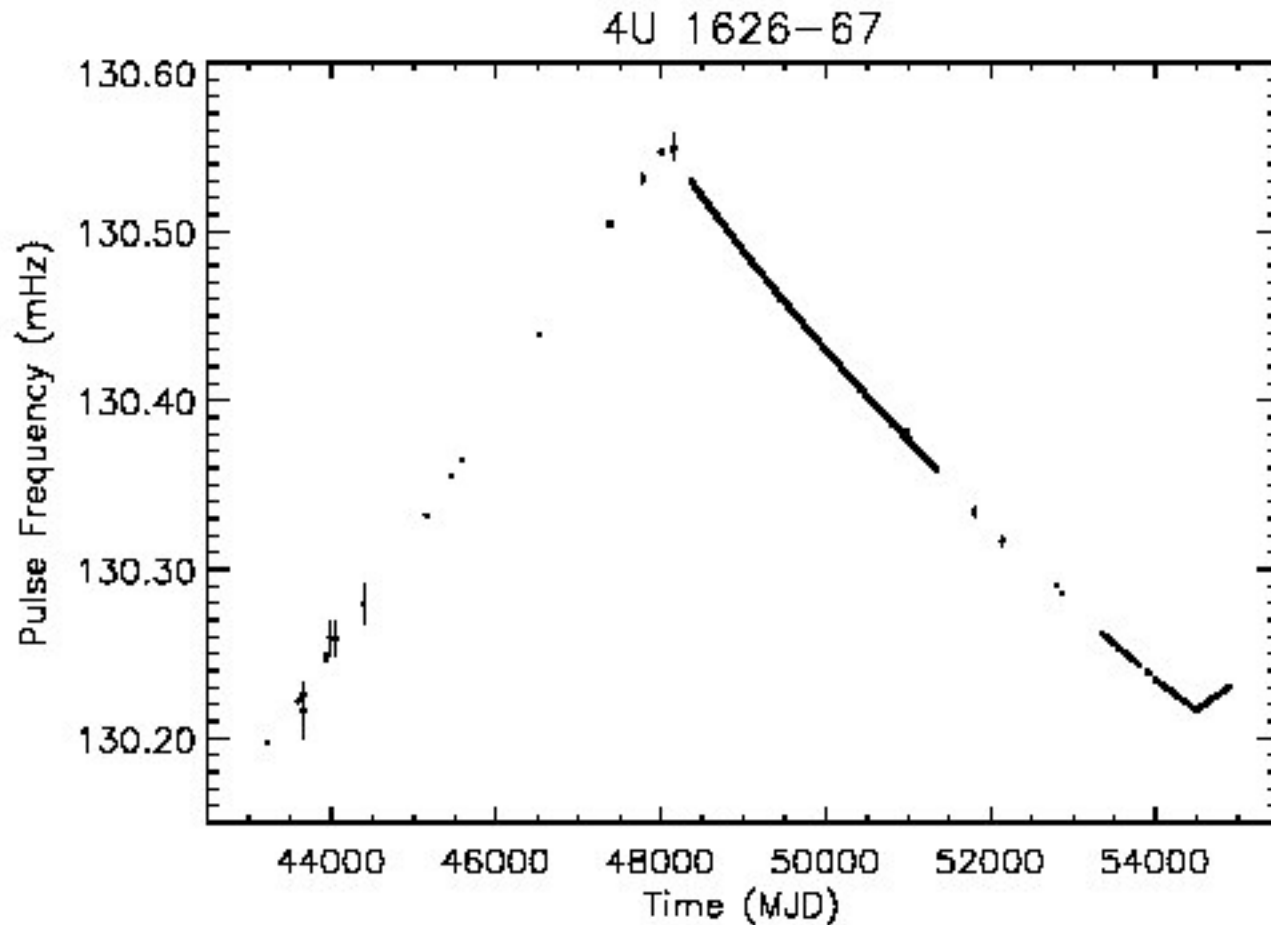
# 4U 1626-67 : QPO evolution



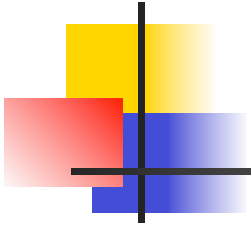
# *4U 1626-67 : A New Reversal*



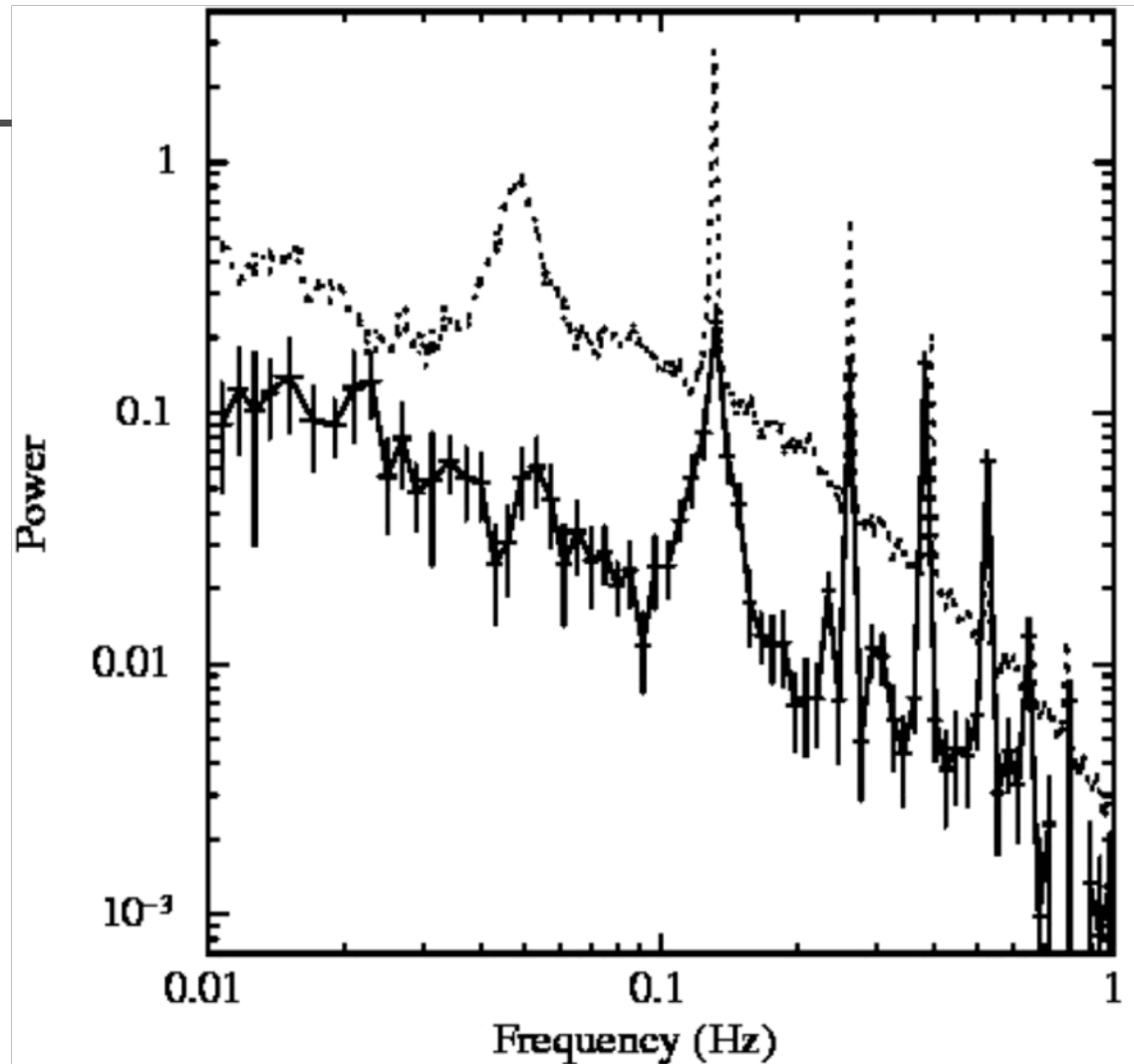
# *4U 1626-67 : A New Reversal*



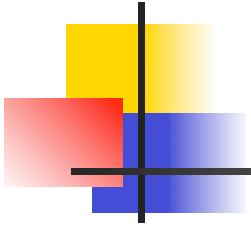
# *4U 1626-67 : A New Reversal*



# *4U 1626-67 : A New Reversal*



# *4U 1626-67 : A New Reversal*





# *Orbital Evolution of X-ray Pulsars*

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## **HMXBs**

**LMC X-4**

**SMC X-1**

**Cen X-3**

**4U 1538-52**

## ● **Be-XRBs**

**4U 0115+63**

## ● **LMXBs**

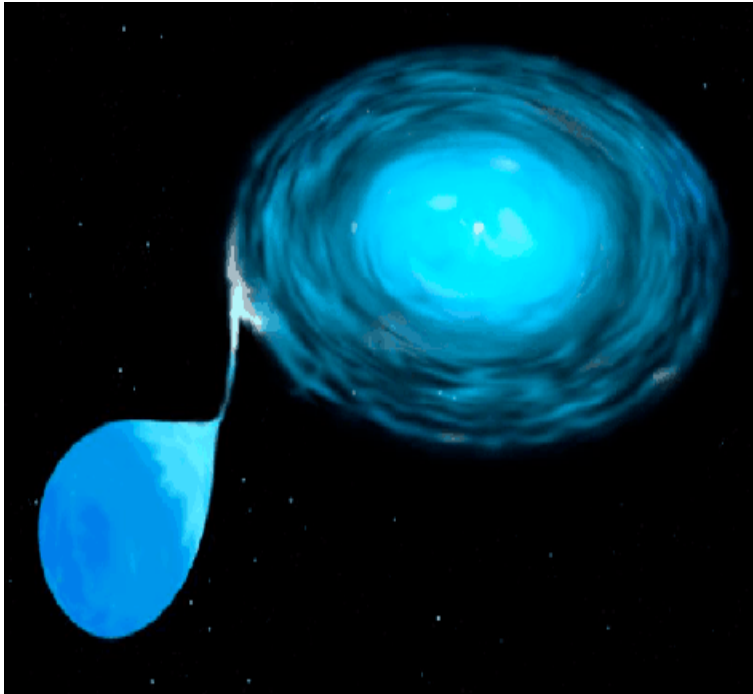
**Her X-1**

**SAX J1808.4-3658**

**4U 1822-37,**

**XTE J1710-281**

# *Orbital evolution of X-ray binaries*



- *Conservative mass transfer*
- *Mass transfer + mass loss*
- *Tidal effect*
- *Magnetic cycling*
- *Gravitational wave radiation*



# *Why study orbital evolution*

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- *Single star evolution is different from binary evolution*
- *End products are interesting (Gravitational wave, GRBs)*
- *Stellar physics!!*



# Measurement Techniques

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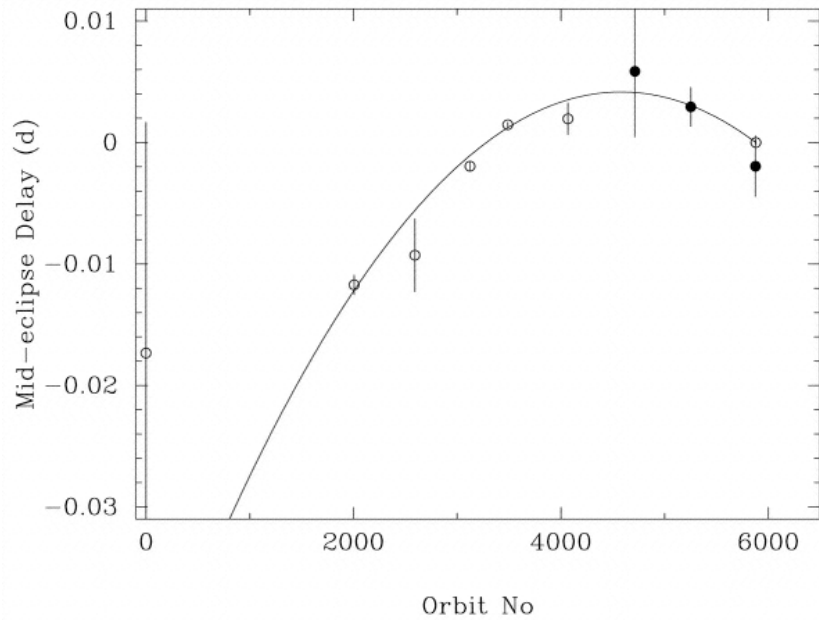
- *Pulse timing*  
(*Broad pulse, jitters, absorption, statistics*)
- *Eclipse timing*  
(*Pre-eclipse dips*)
- *Orbital modulation*  
(*Stability of modulation pattern*)
- *Spectroscopic*  
(*HMXB ? X-ray Irradiation ?*)



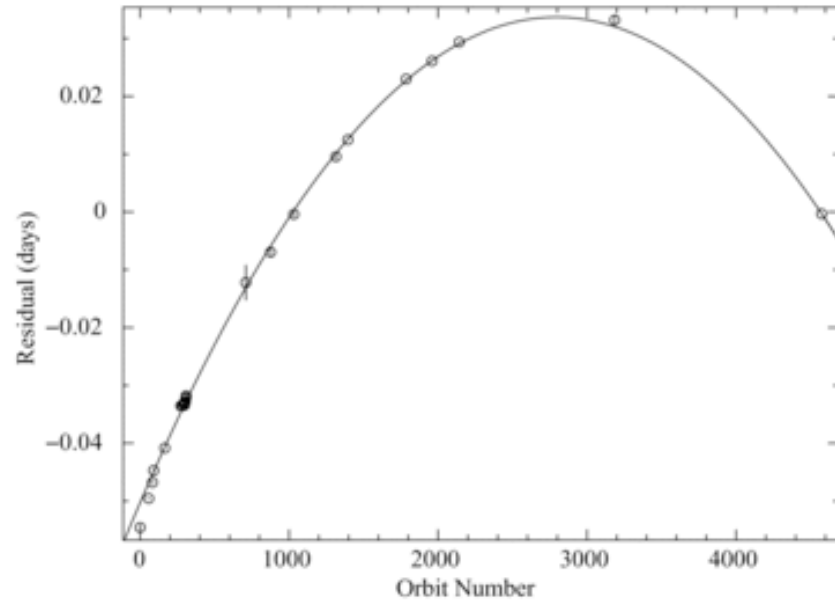
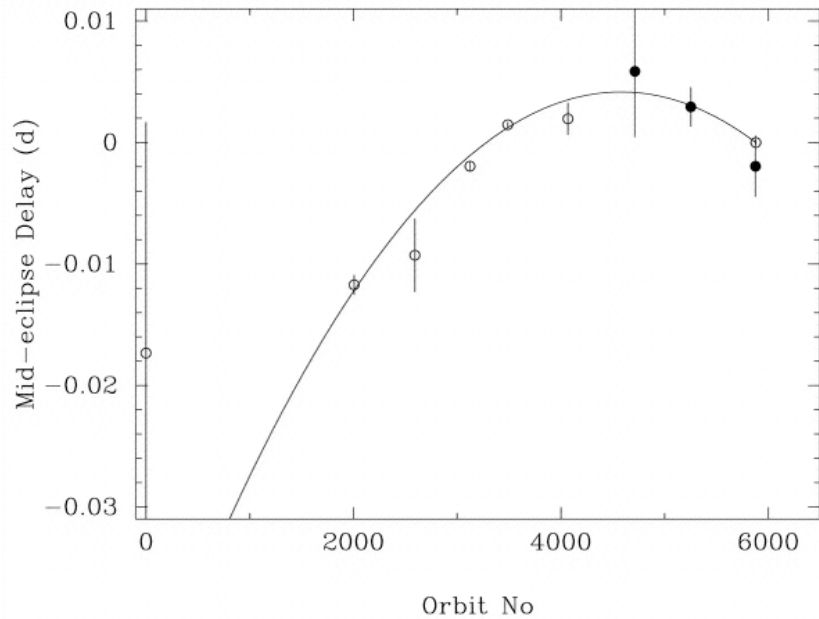
# *Orbital Evolution of HMXB Pulsars*

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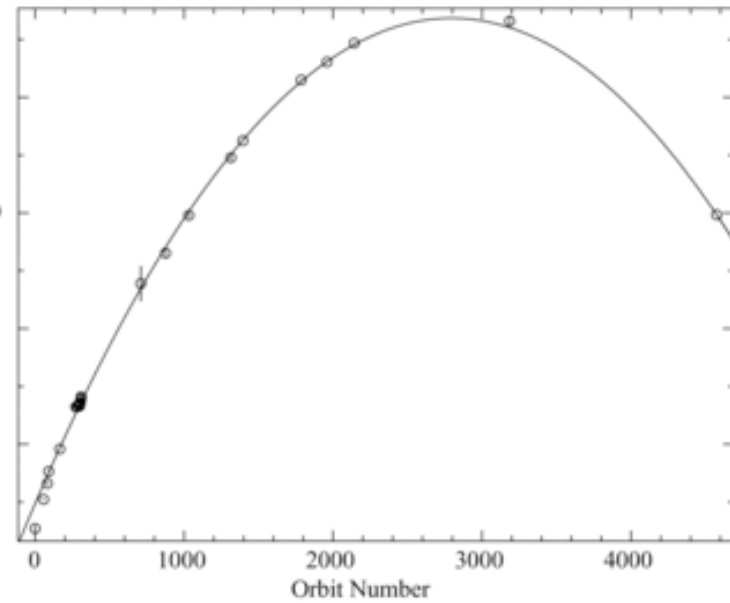
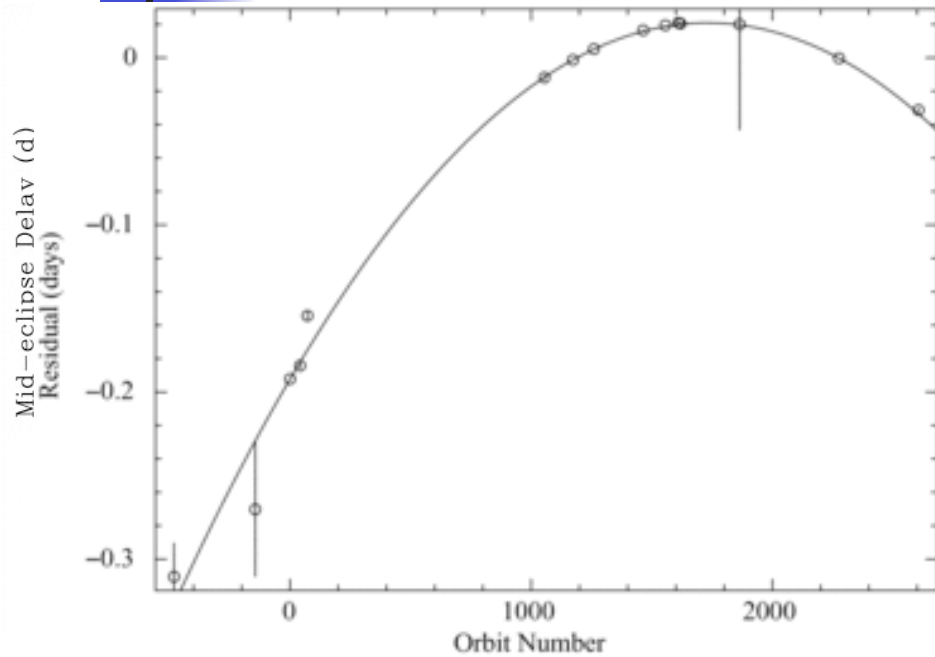
# *Orbital Evolution of HMXB Pulsars*



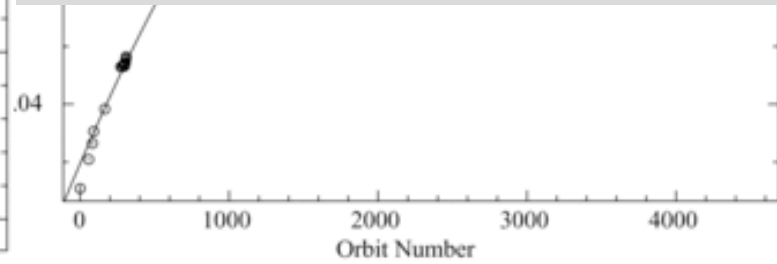
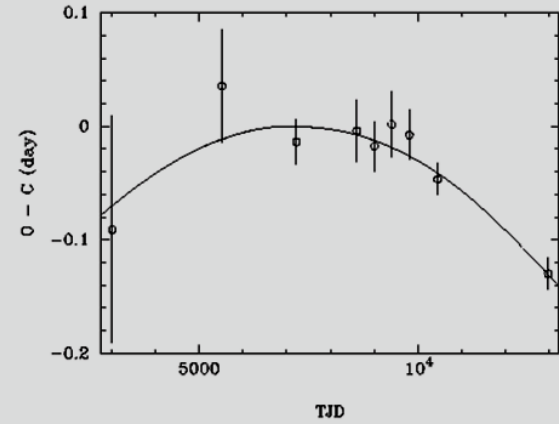
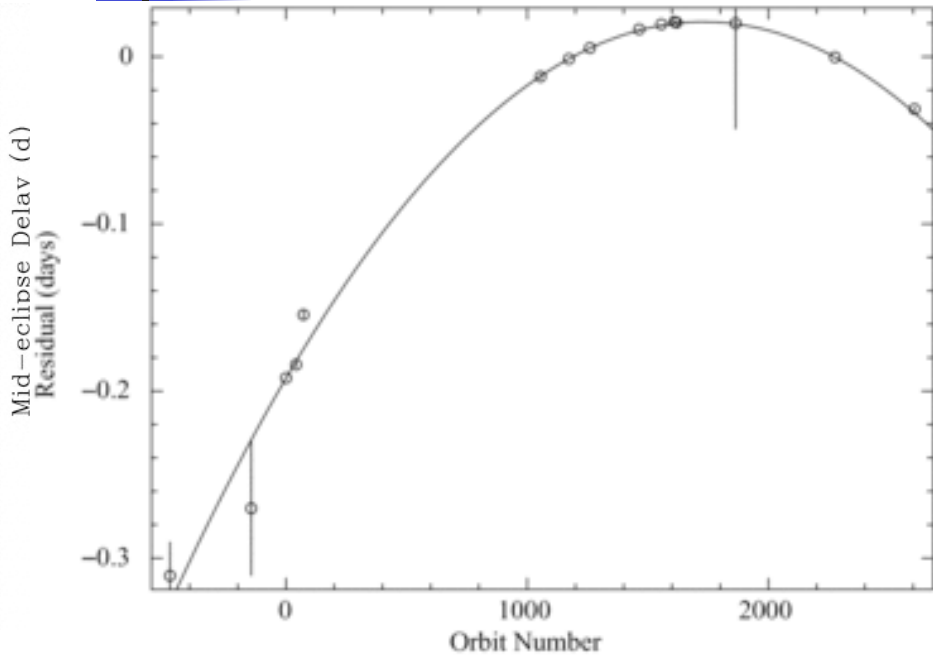
# Orbital Evolution of HMXB Pulsars



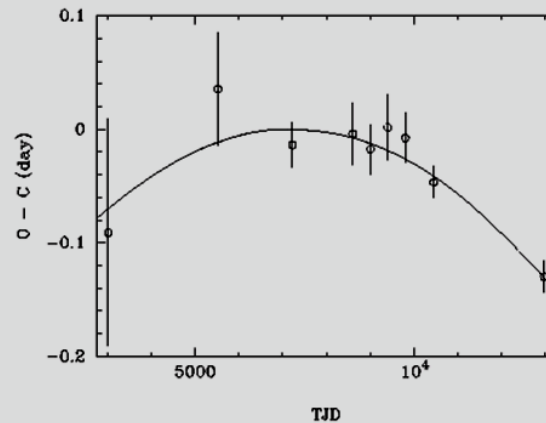
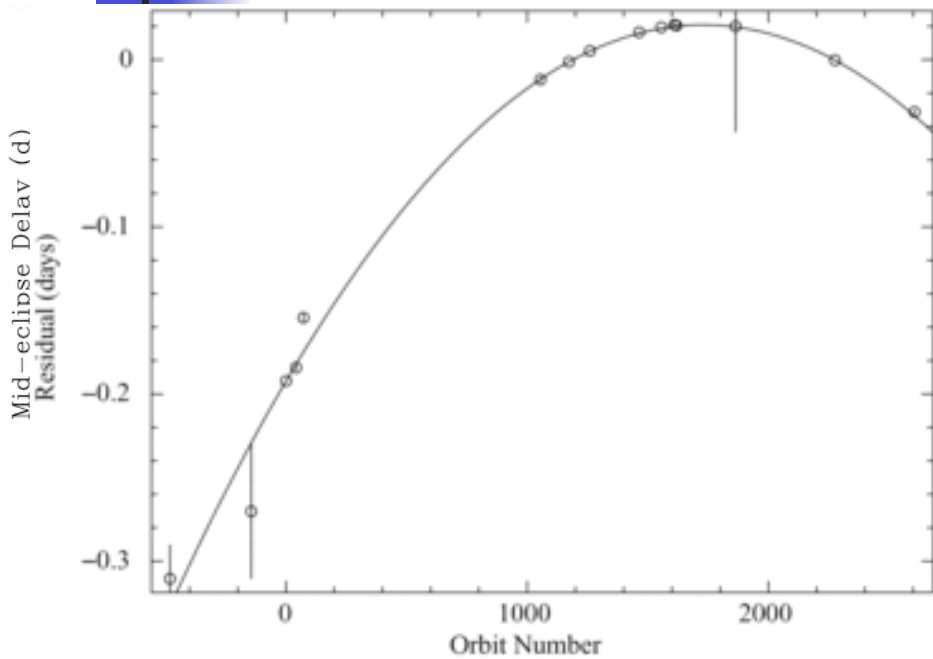
# Orbital Evolution of HMXB Pulsars



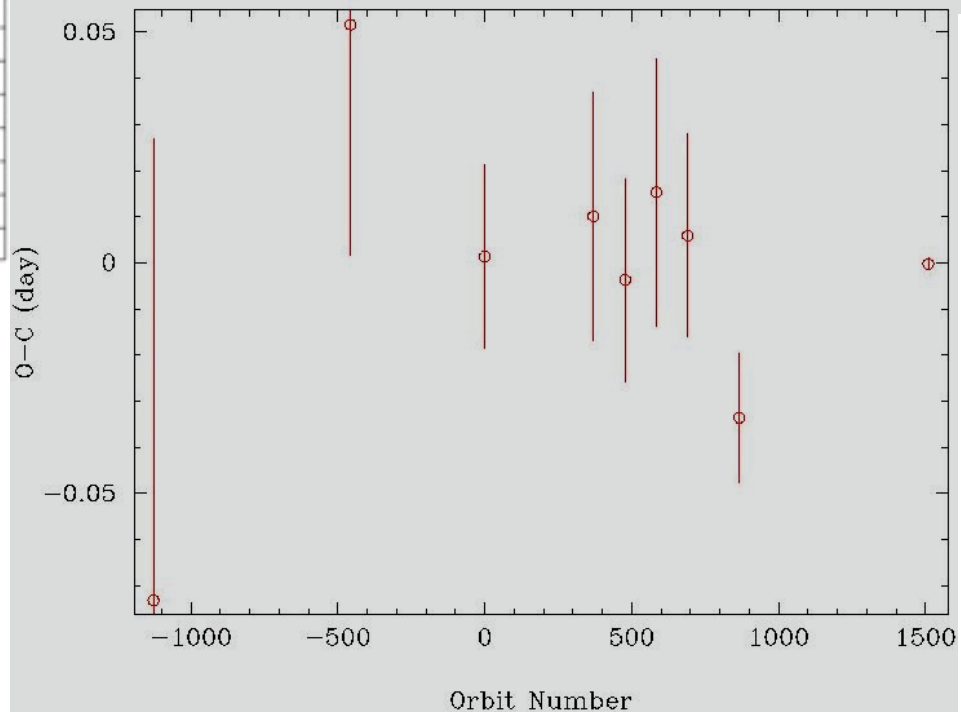
# Orbital Evolution



# Orbital Evolution



4U 1538-52: Orbital Evolution

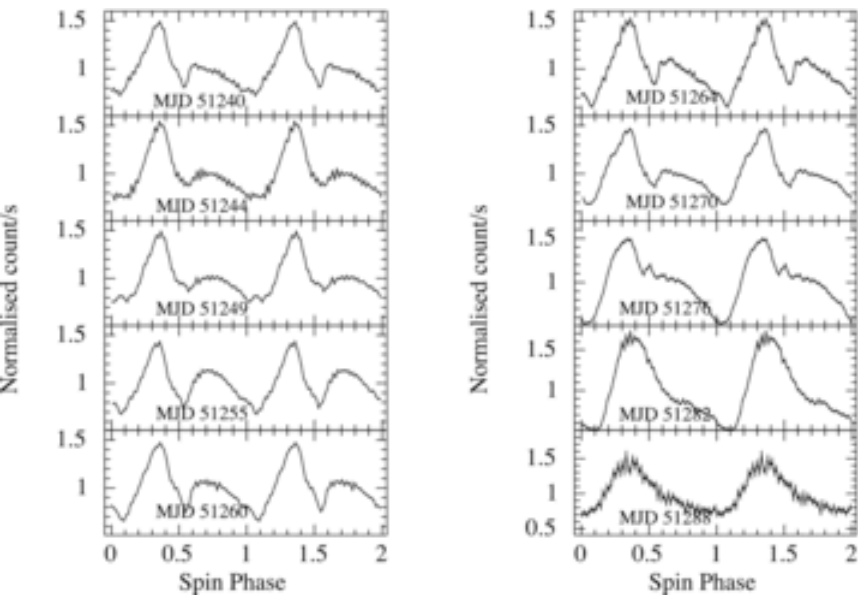




*Apsidal advance in 4U 0115+63*

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# *Apsidal advance in 4U 0115+63*

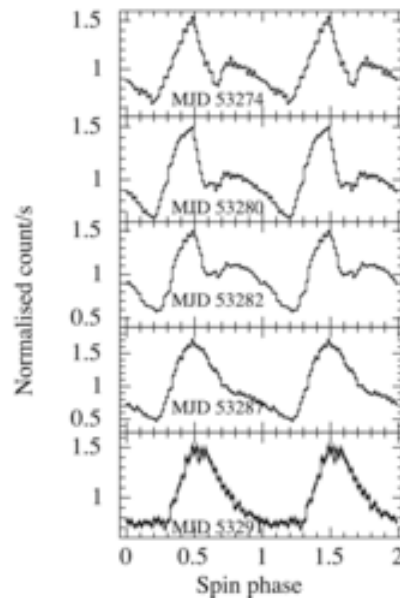
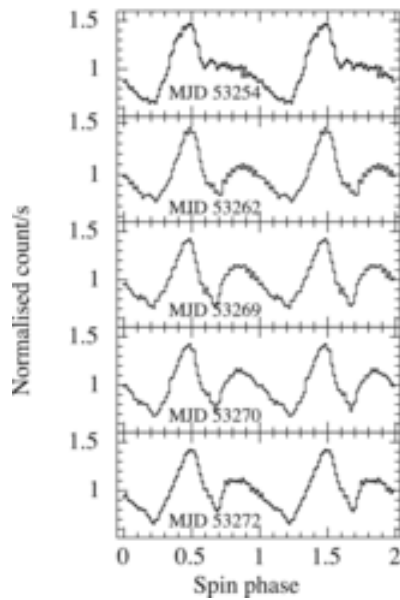




*Apsidal advance in 4U 0115+63*

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# *Apsidal advance in 4U 0115+63*

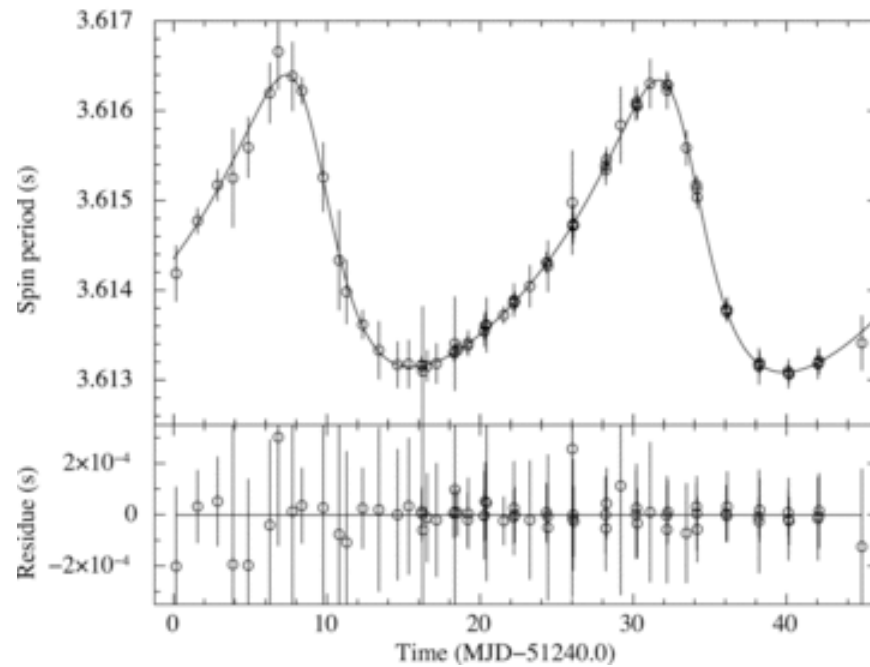




*Apsidal advance in 4U 0115+63*

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# *Apsidal advance in 4U 0115+63*

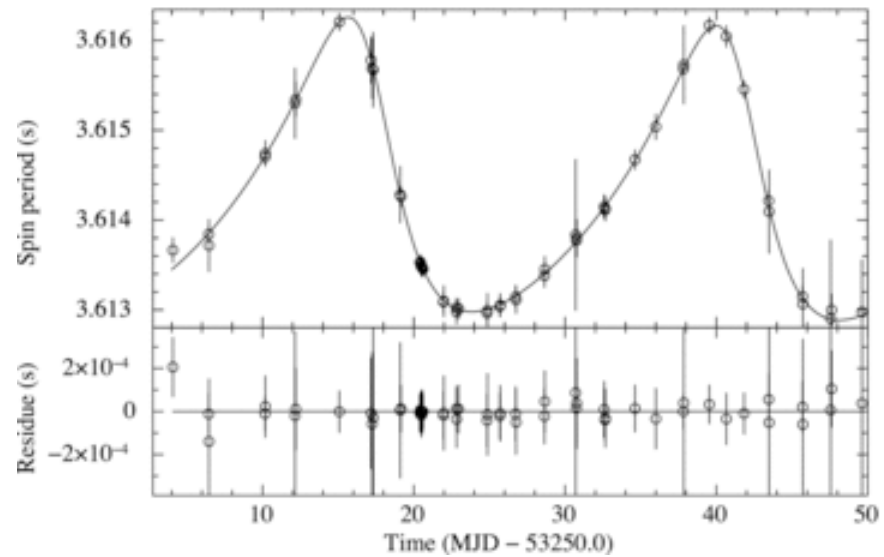




*Apsidal advance in 4U 0115+63*

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# *Apsidal advance in 4U 0115+63*

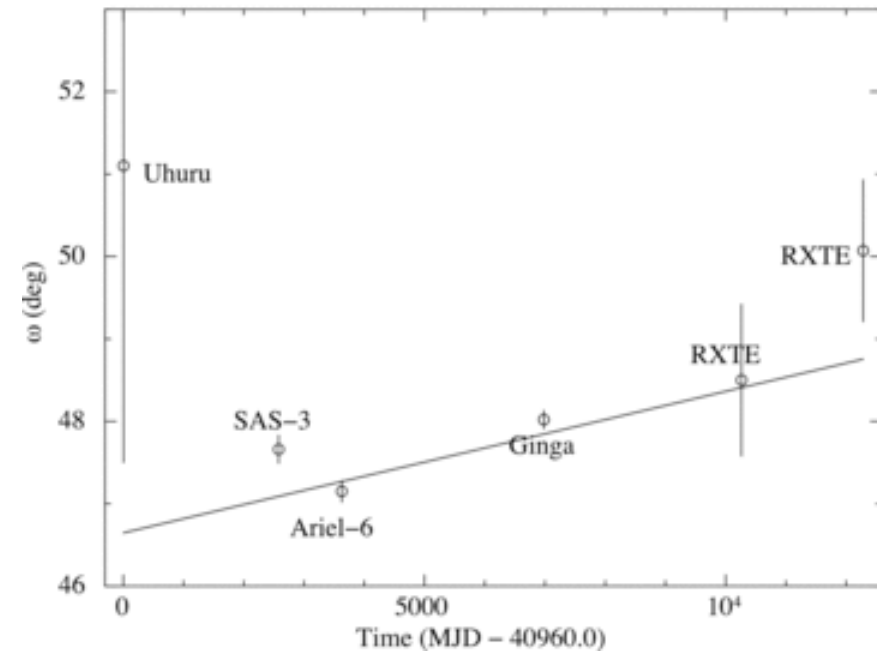




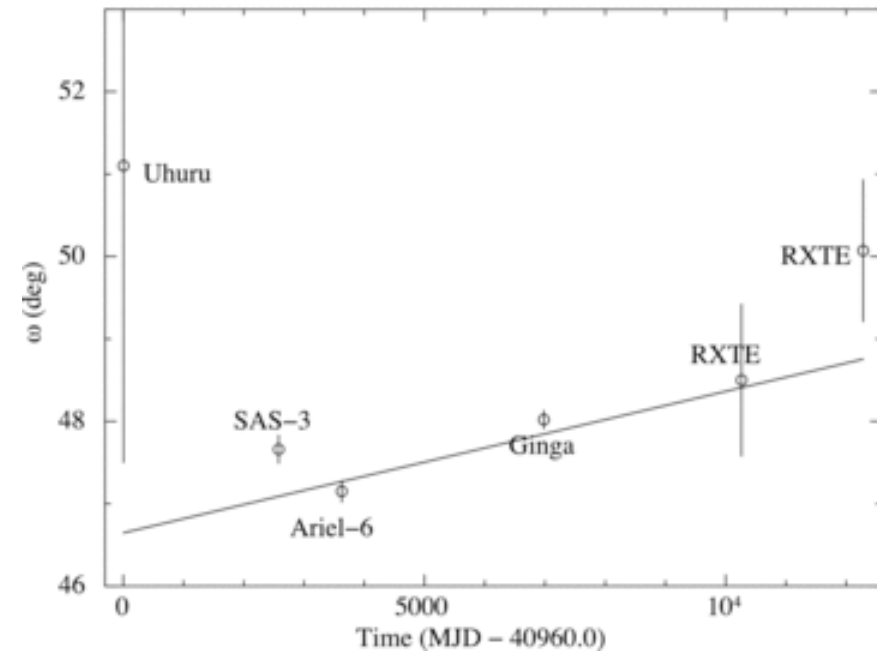
*Apsidal advance in 4U 0115+63*

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# *Apsidal advance in 4U 0115+63*



# *Apsidal advance in 4U 0115+63*

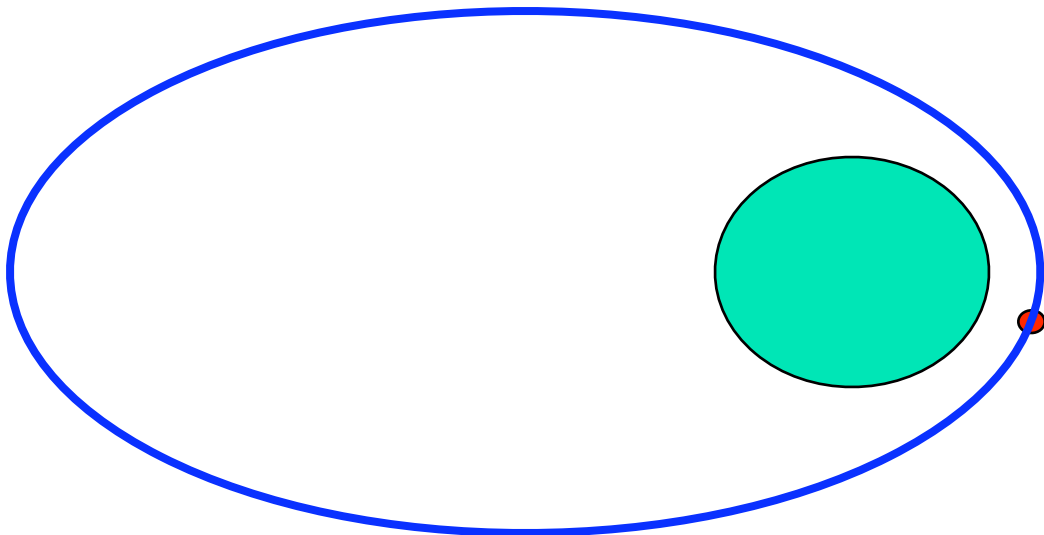
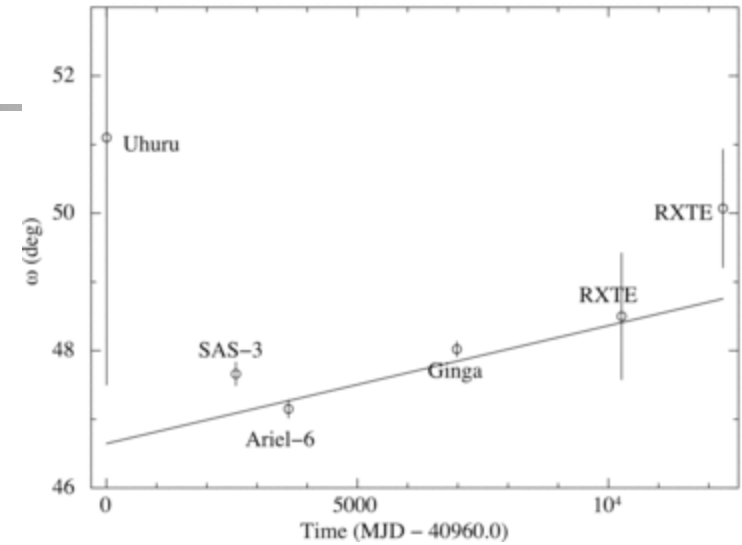


*4U 0115+63: 24.3 days*

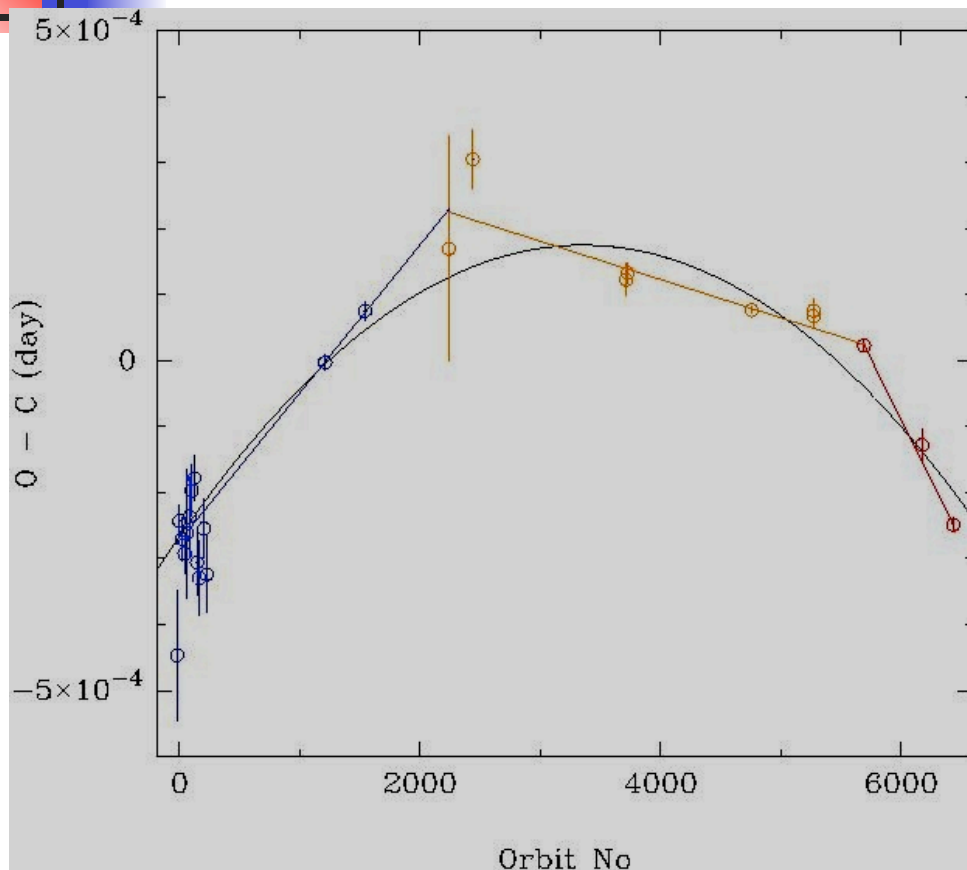
*Eccentricity: 0.34, apsidal rate: 0.06 $\pm$ 0.02*

*Raichur & Paul 2010b*

# Probing the Stellar Structure



# Her X-1: Orbital Evolution



$$P1 = 1.700167788(011) \text{ d}$$

$$\nabla P / P = 1.7 \times 10^{-7}$$

$$P2 = 1.700167506(009) \text{ d}$$

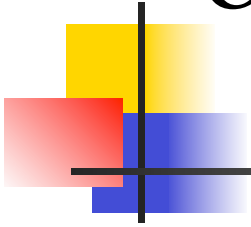
$$\nabla p / P = 2.4 \times 10^{-7}$$

$$P3 = 1.700167096(101) \text{ d}$$

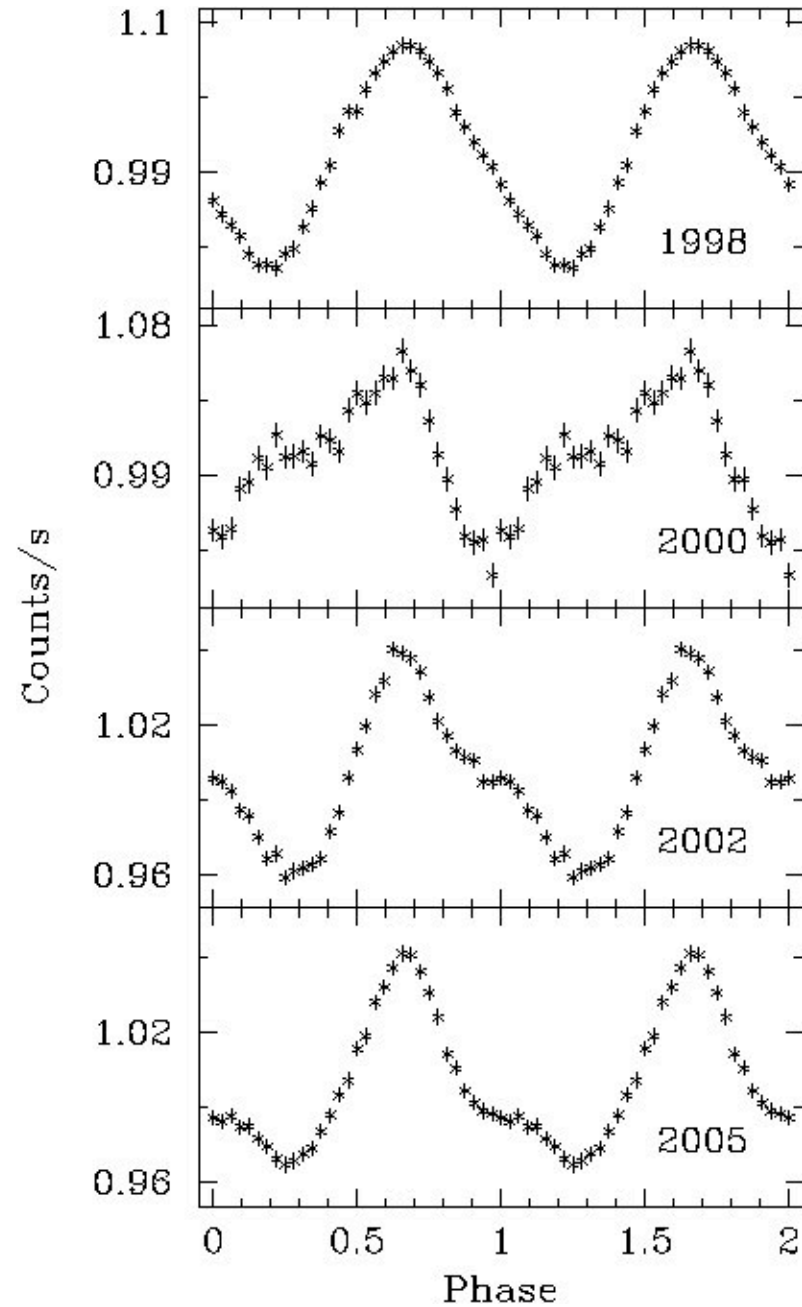
$$dP / dt = 1.7 \times 10^{-8} \text{ d yr}^{-1}$$

*Bhatt and Paul 2004*

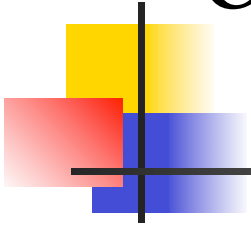
# *Orbital evolution of SAX 1808*



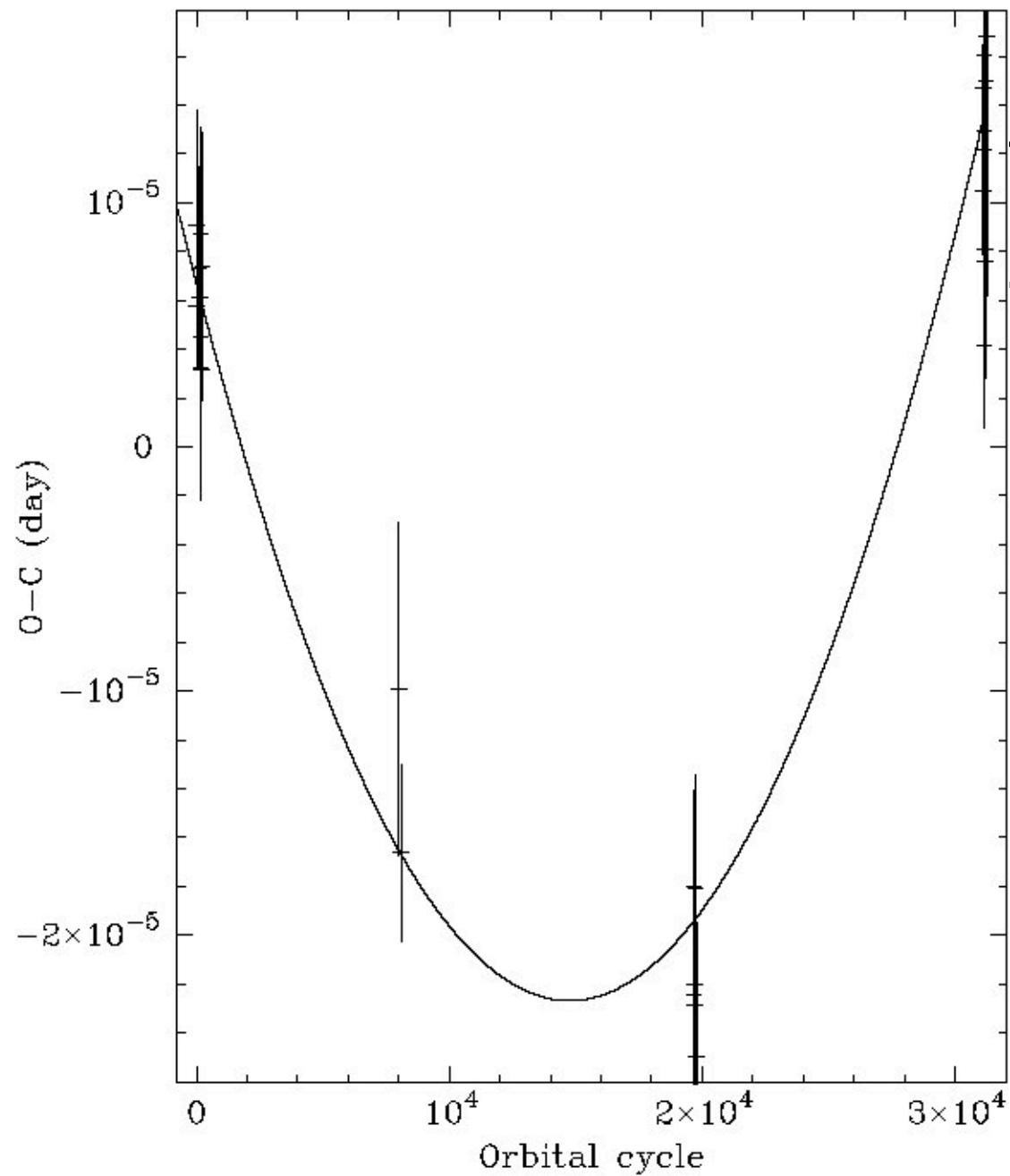
# *ion of SAX 1808*



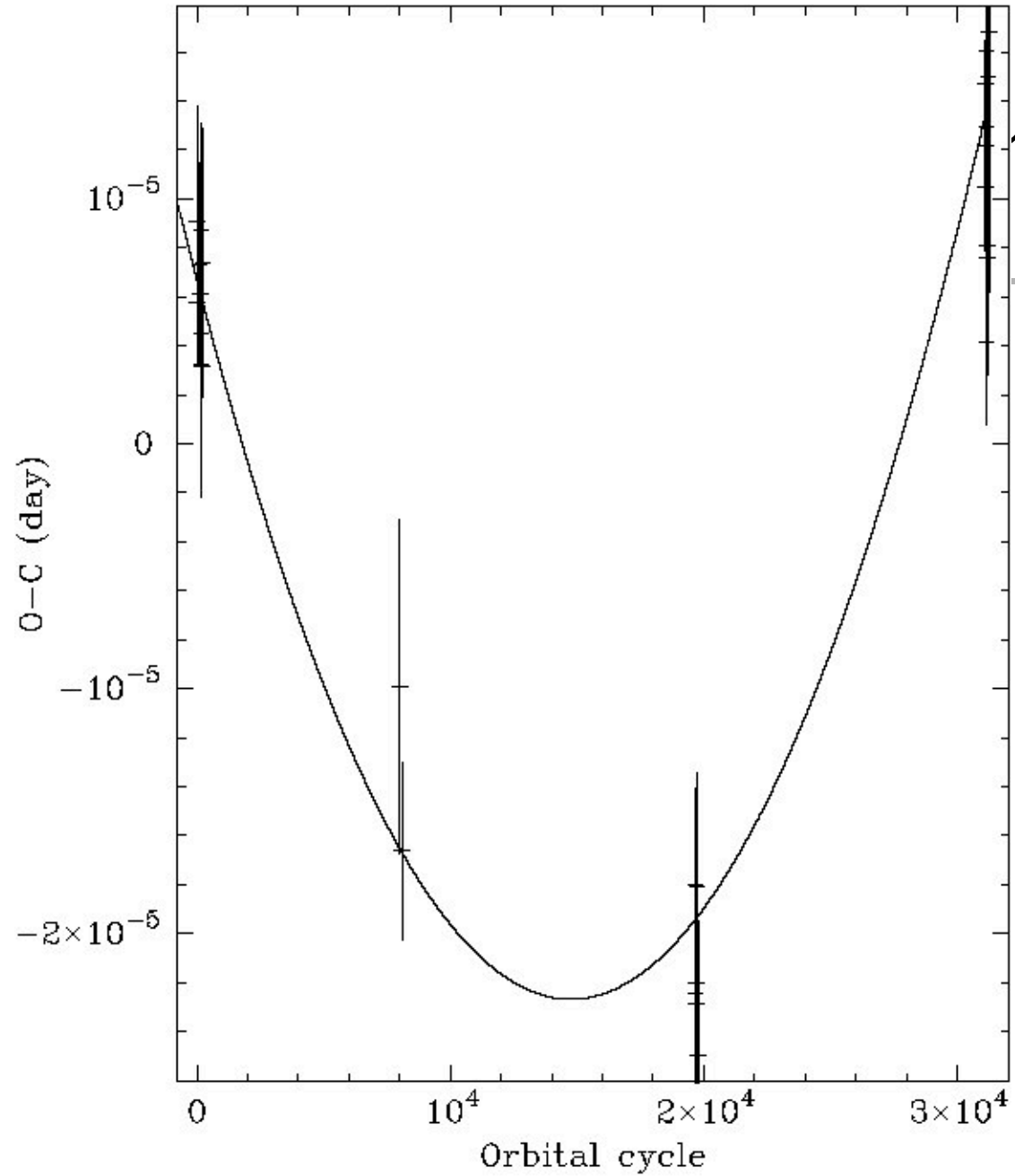
# *Orbital evolution of SAX 1808*



*AX 1808*



# *AX 1808*



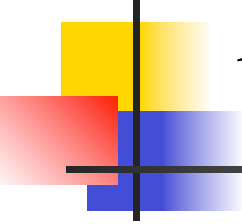
**Period derivative**

**$3.2 \pm 0.2 \cdot 10^{-12} \text{ s s}^{-1}$**

**Evolution time scale**

**73 MYr**

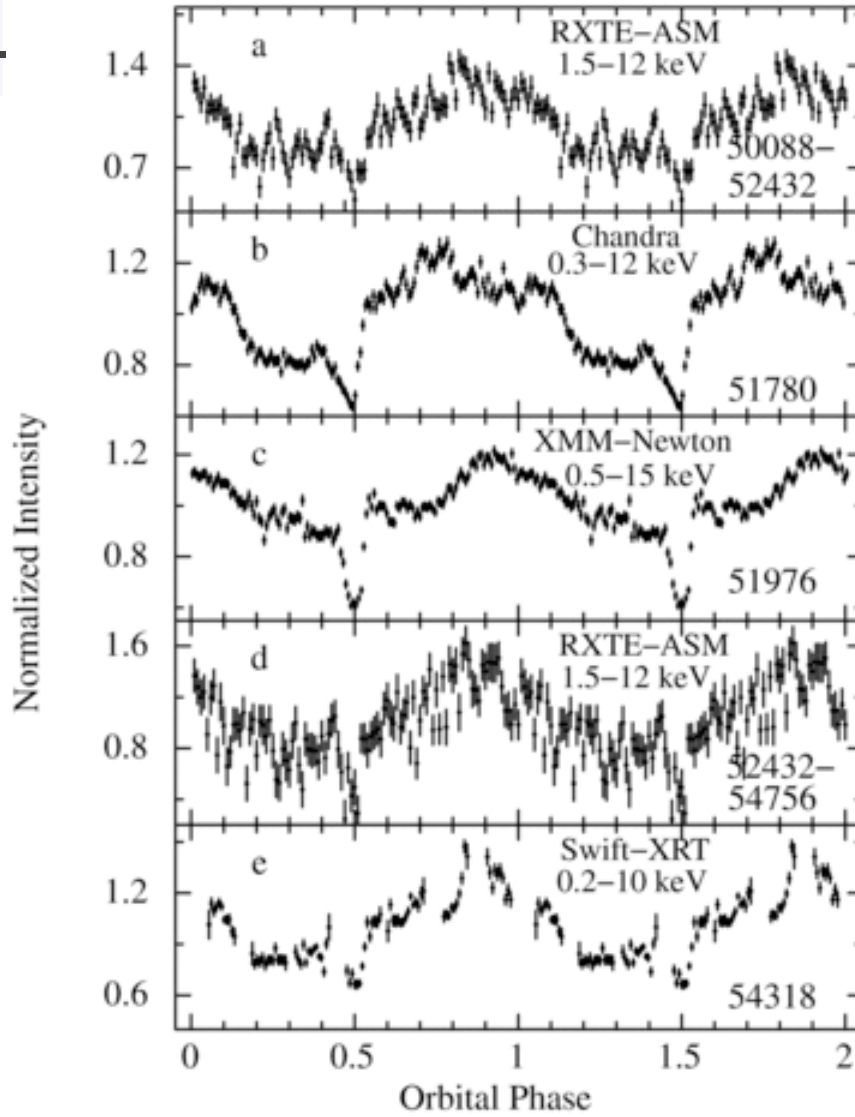
*Jain et al 2007*

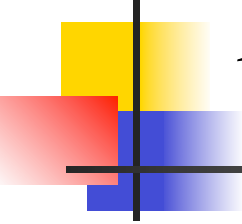


*LMXB orbital evolution by eclipse timing: 4U 1822-37*

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*LMXB orbital evolution by eclipse timing: 4U 1822-37*

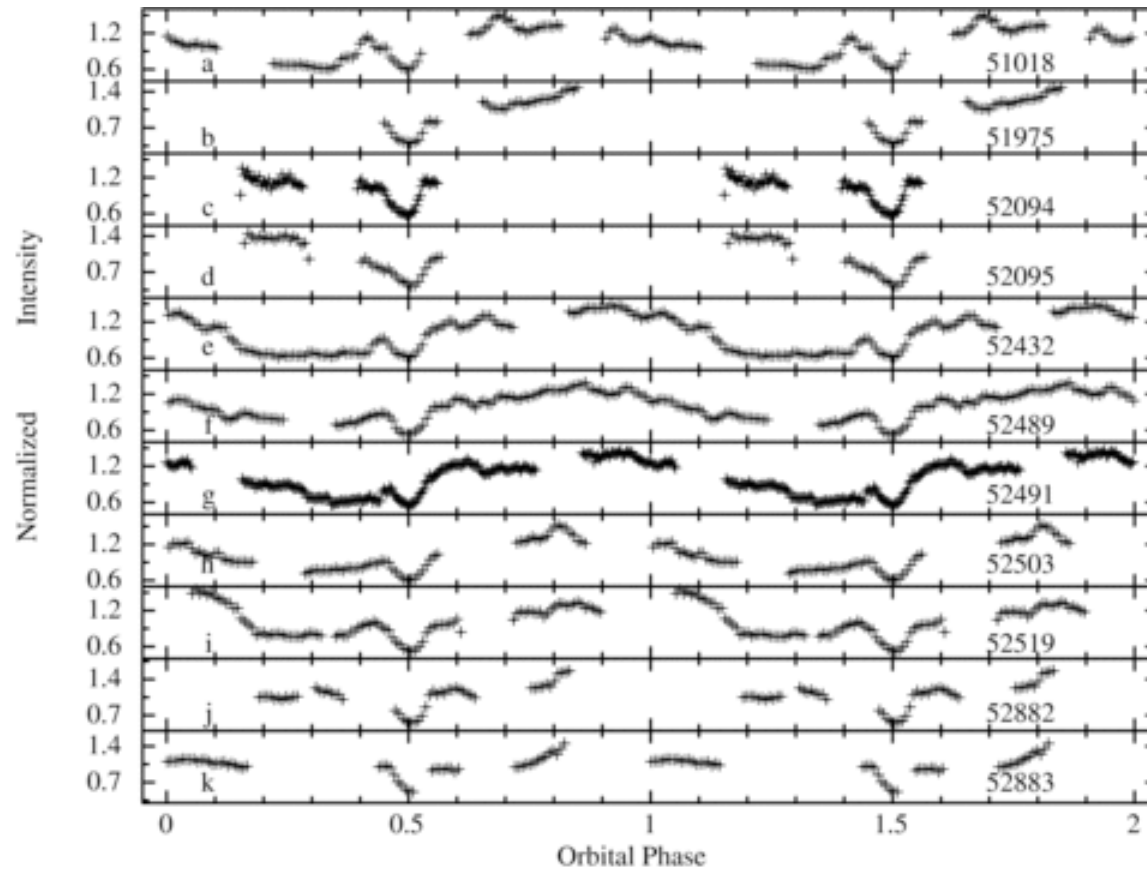


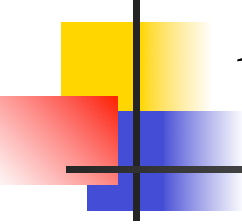


*LMXB orbital evolution by eclipse timing: 4U 1822-37*

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*LMXB orbital evolution by eclipse timing: 4U 1822-37*

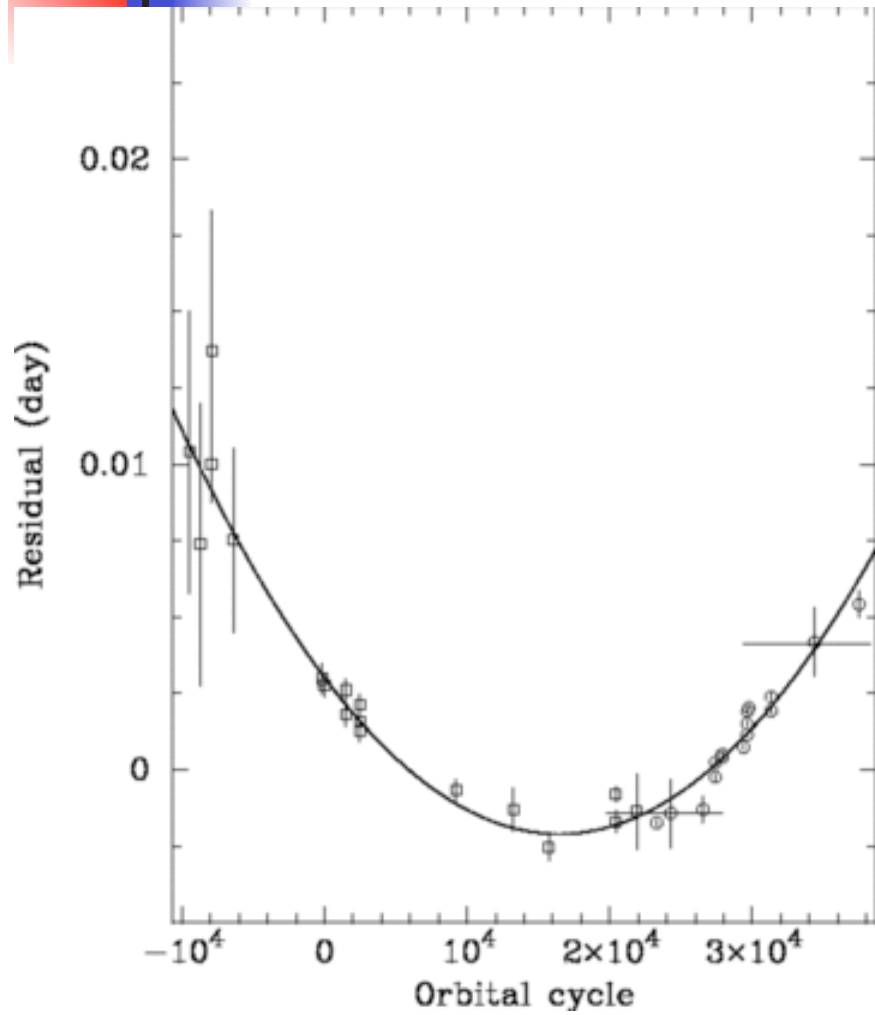




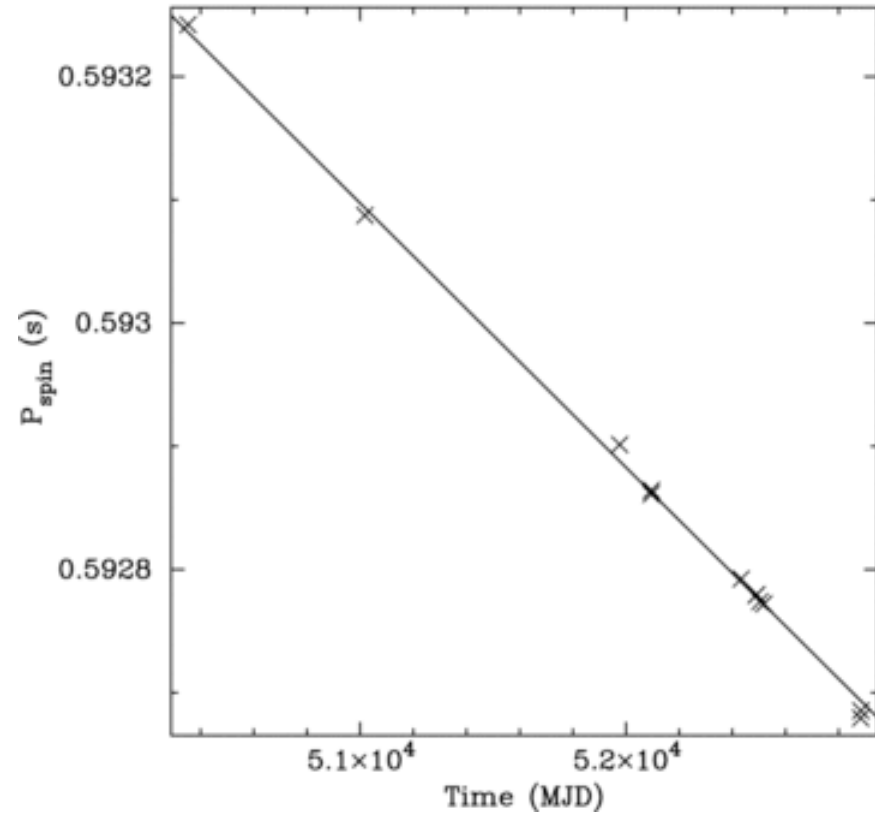
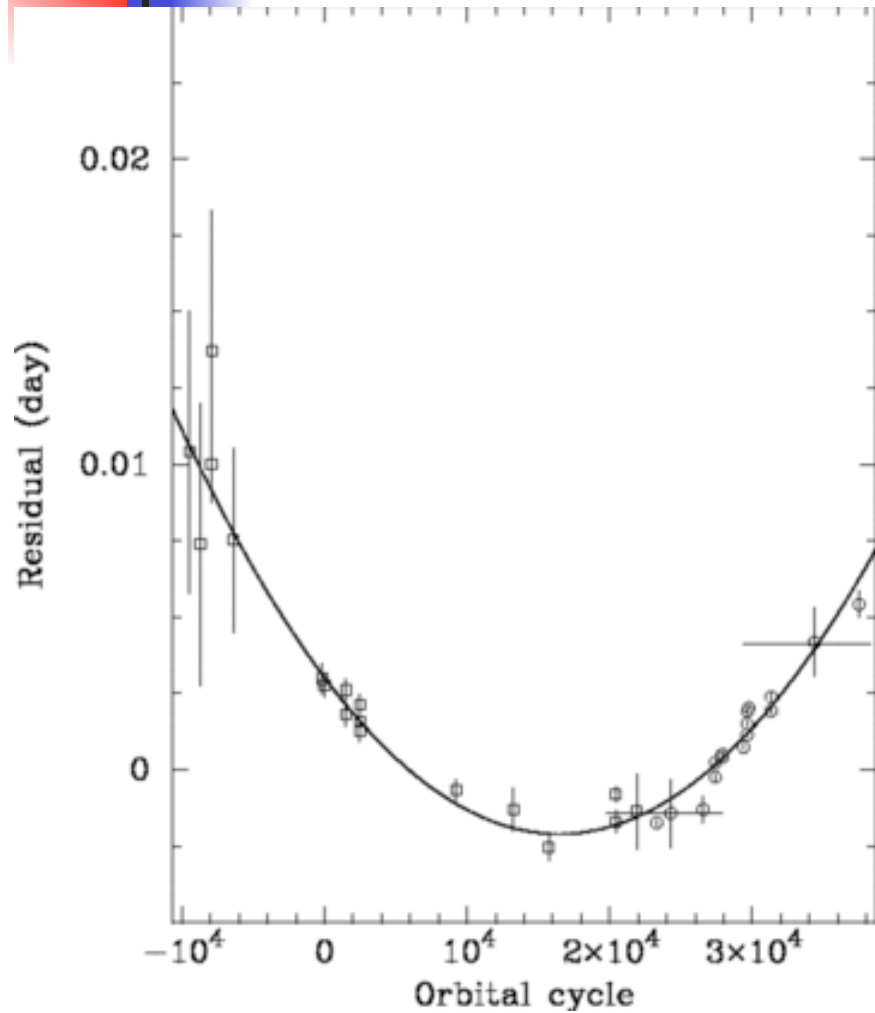
*LMXB orbital evolution by eclipse timing: 4U 1822-37*

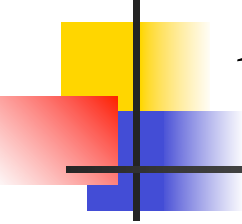
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*LMXB orbital evolution by eclipse timing: 4U 1822-37*



*LMXB orbital evolution by eclipse timing: 4U 1822-37*





## *LMXB orbital evolution by eclipse timing: 4U 1822-37*

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$$1.61 M_{\odot} \leq M_{\text{ns}} \leq 2.32 M_{\odot}$$

$$0.44 M_{\odot} \leq M_c \leq 0.56 M_{\odot}$$

$$0.24 \leq q \leq 0.27.$$

$$J = M_c M_{\text{ns}} \left( \frac{Ga}{M} \right)^{1/2},$$

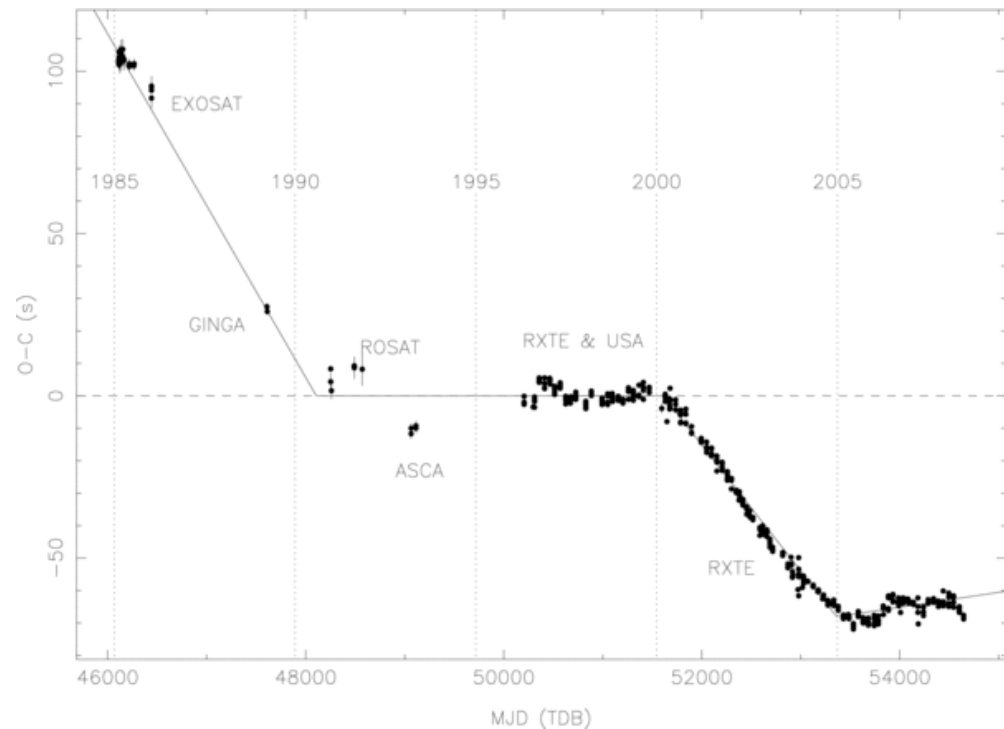
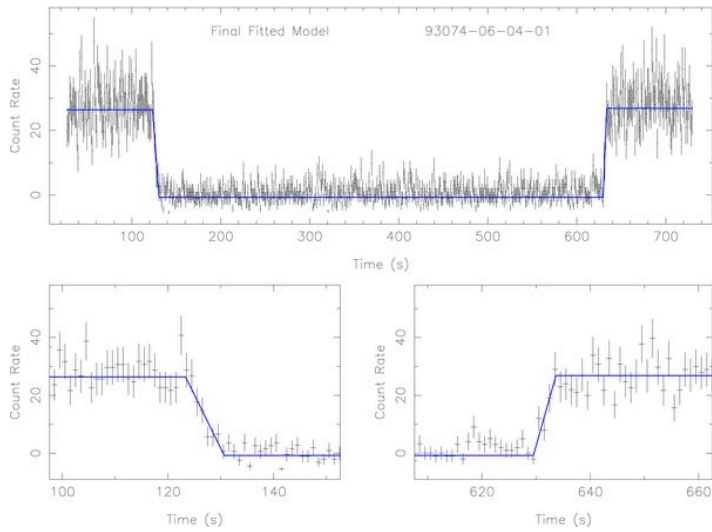
$$\dot{M}_{\text{ns}} = \frac{1}{3} M_c \frac{\dot{P}_{\text{orb}}}{P_{\text{orb}}} \left( 1 - \frac{M_c}{M_{\text{ns}}} \right)^{-1}.$$

$$\dot{v} \simeq 0.47 \times 10^{-12} m_1^{3/7} m_{1.6}^{6/7} \mu_{30}^{2/7} I_{45}^{-1} \text{ Hz s}^{-1},$$

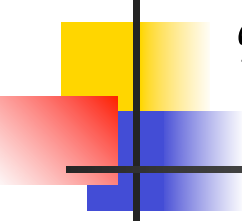
$\mathcal{B} = 1-3 \cdot 10^8 \text{ Gauss}$

*Jain, Paul and Dutta 2010*

# Eclipse timing: EXO 0748-676



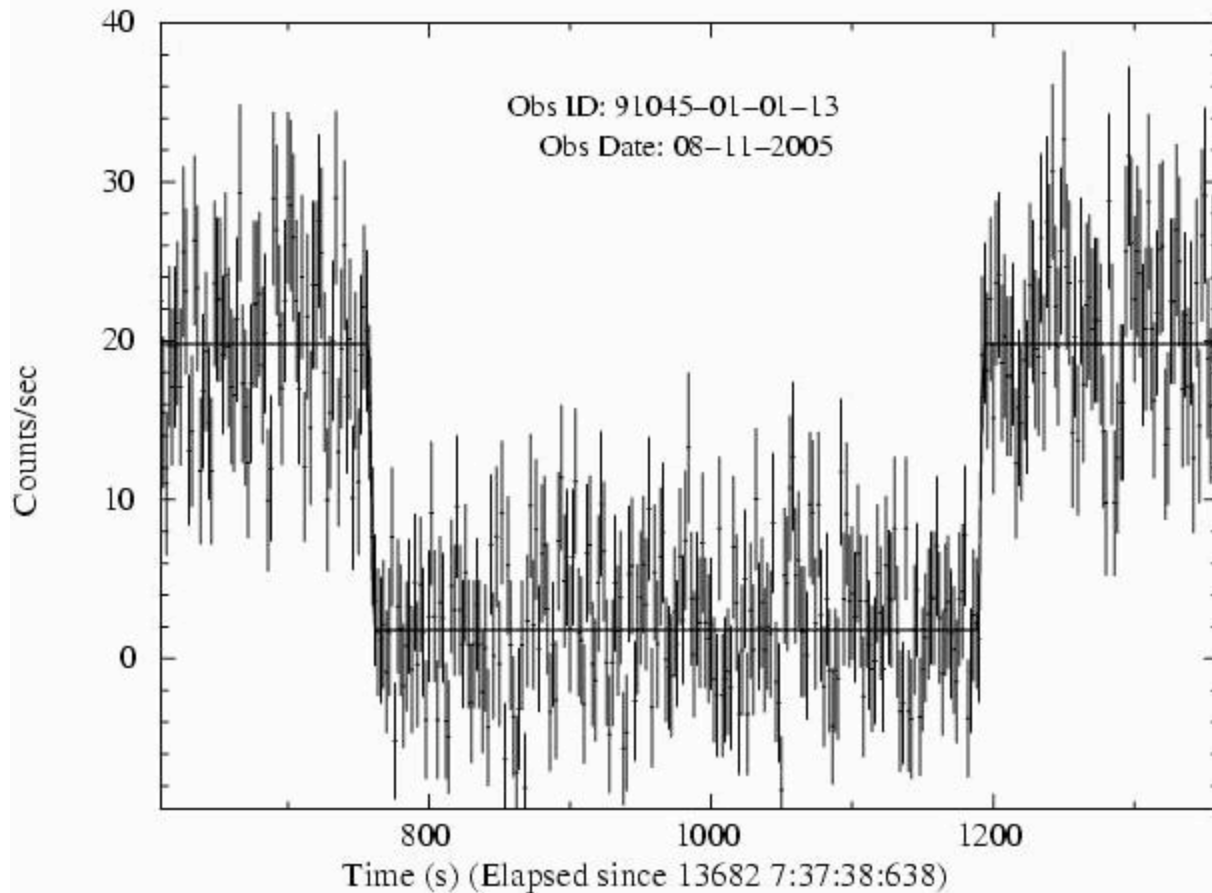
*Wolff et al. 2009*

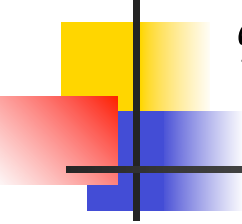


*Eclipse timing: XTE J1710-281*

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*Eclipse timing: XTE J1710-281*

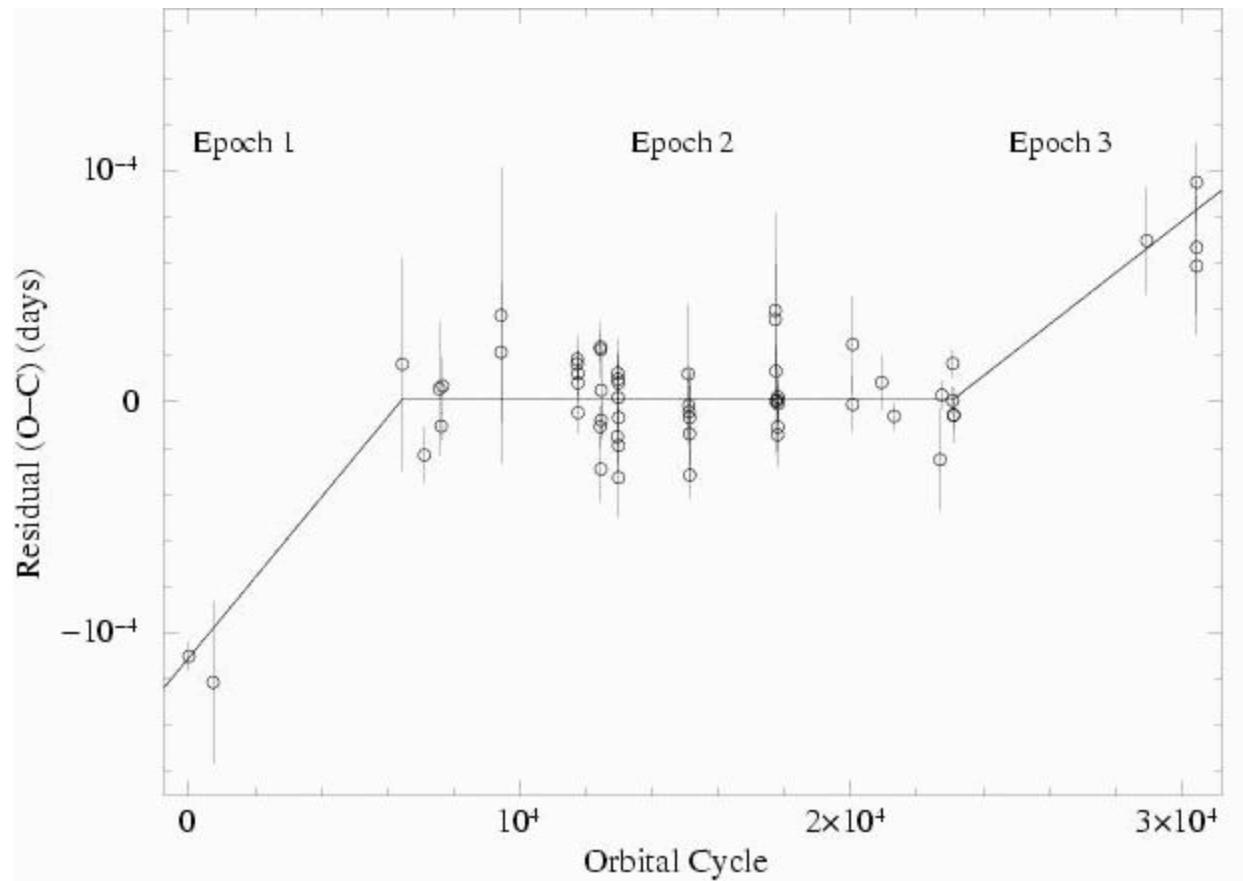


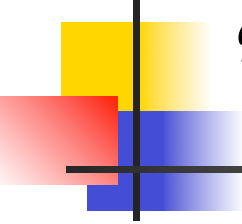


*Eclipse timing: XTE J1710-281*

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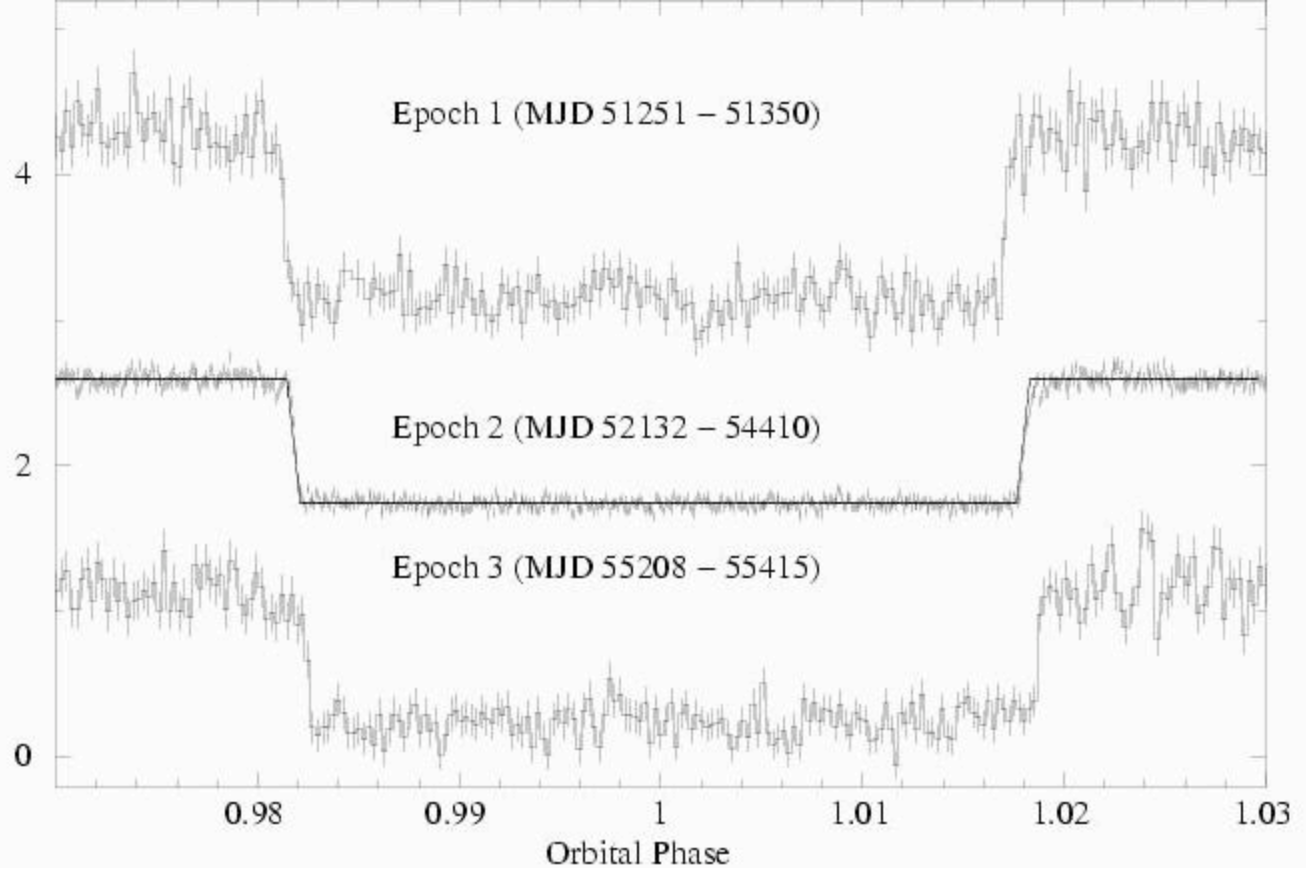
# Eclipse timing: XTE J1710-281

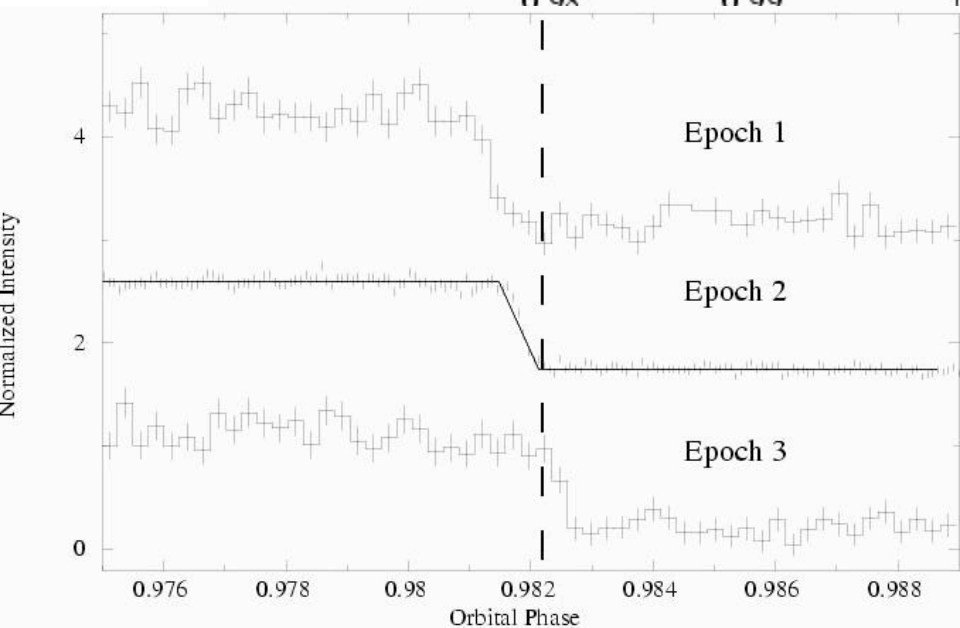
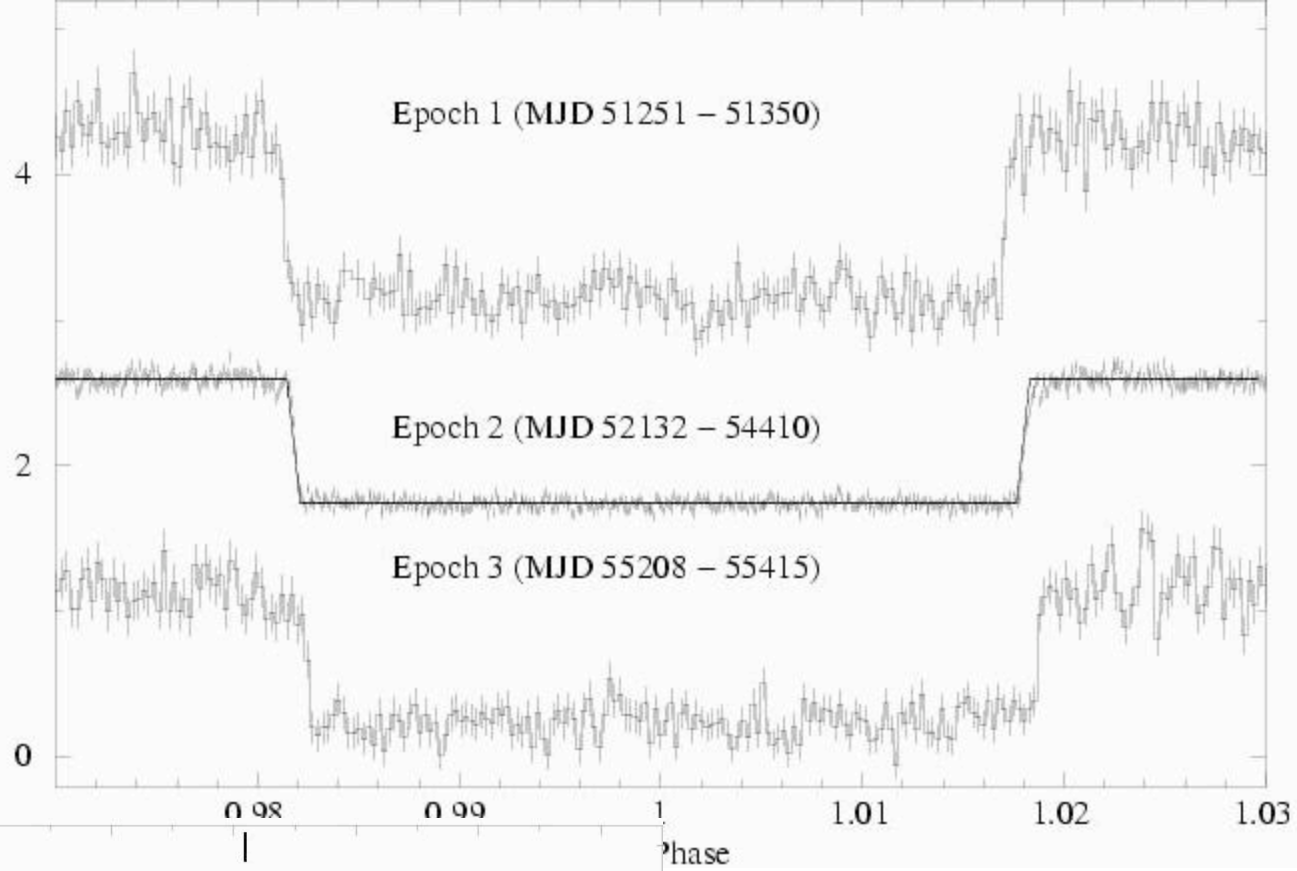


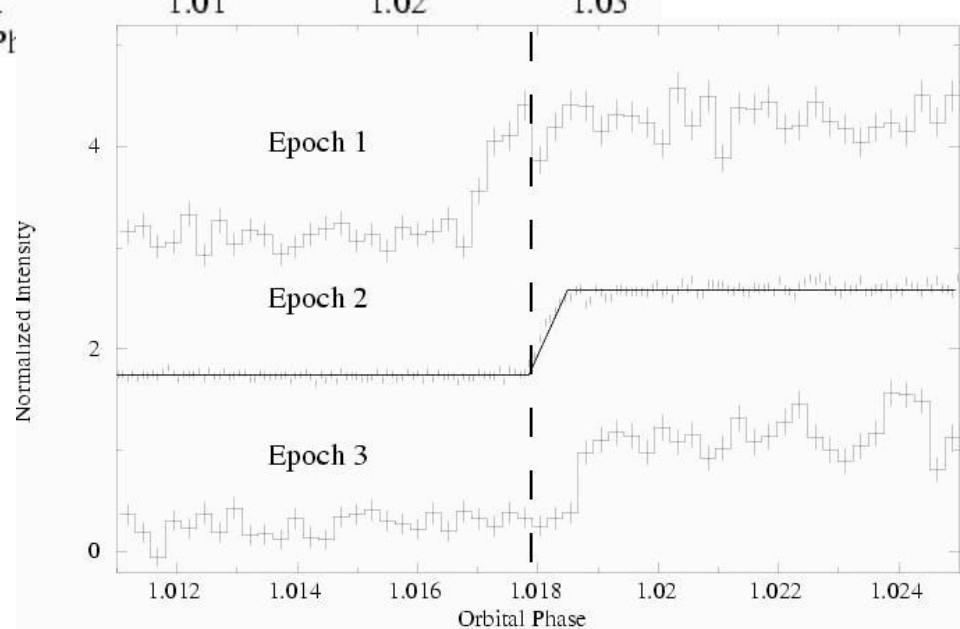
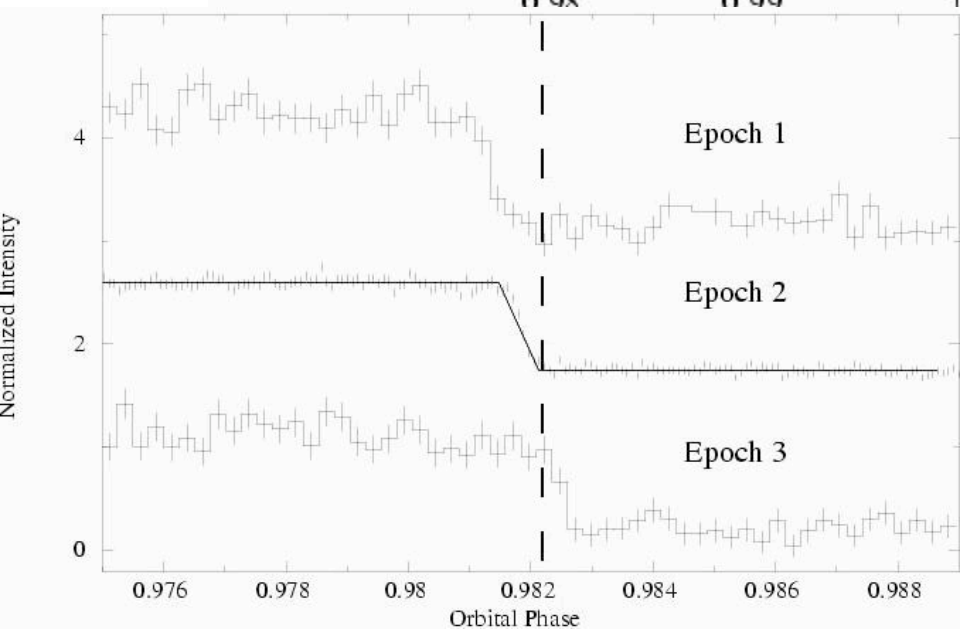
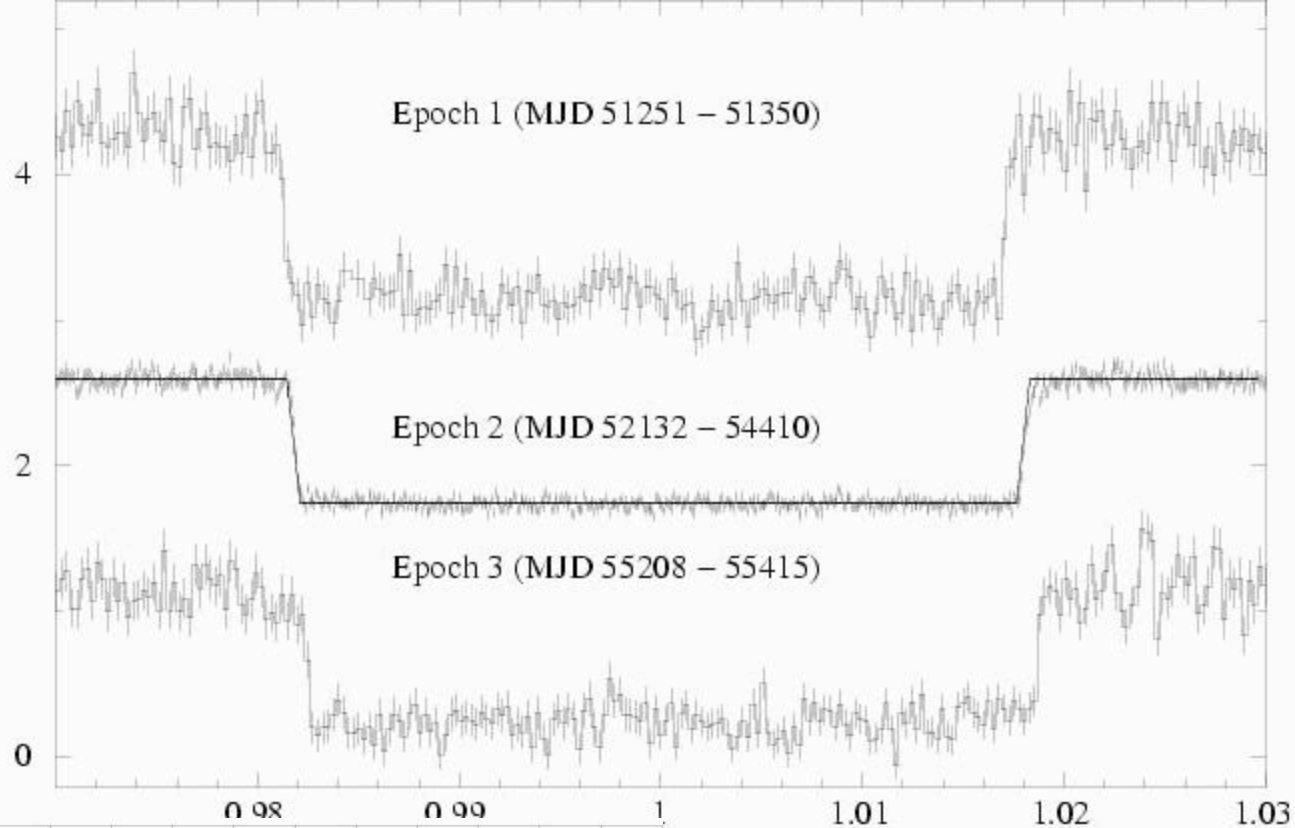


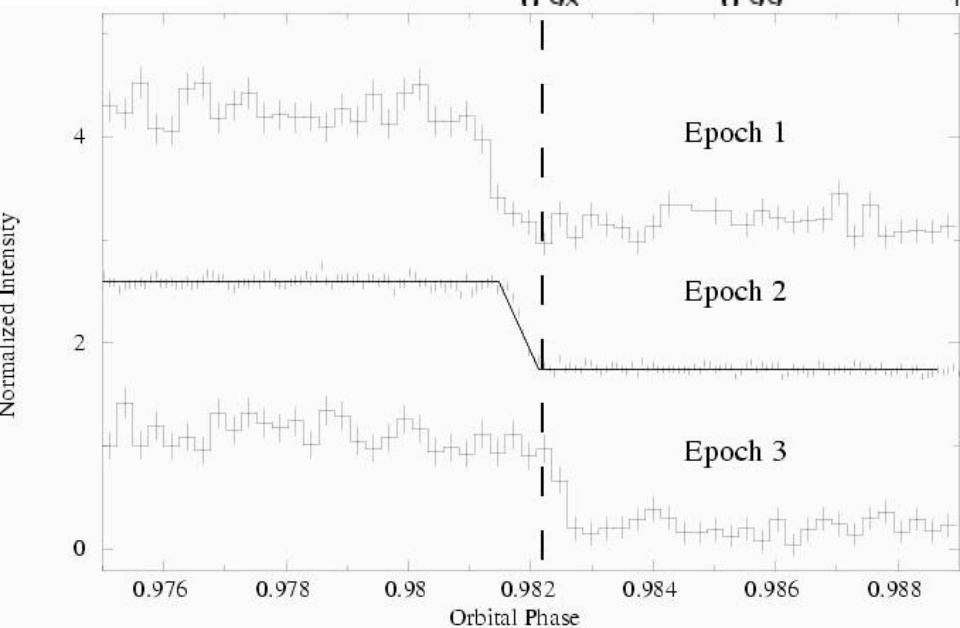
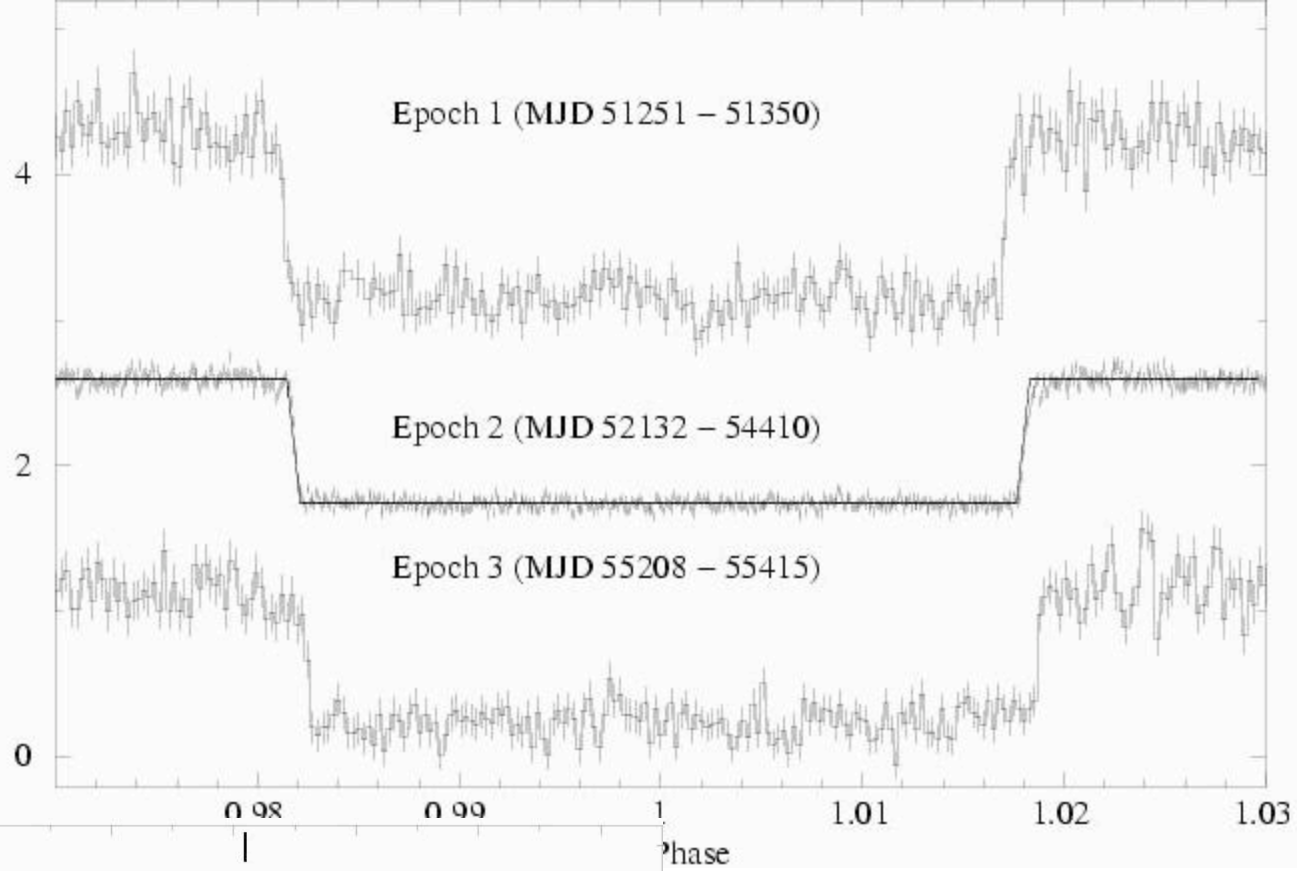
*Eclipse timing: XTE J1710-281*

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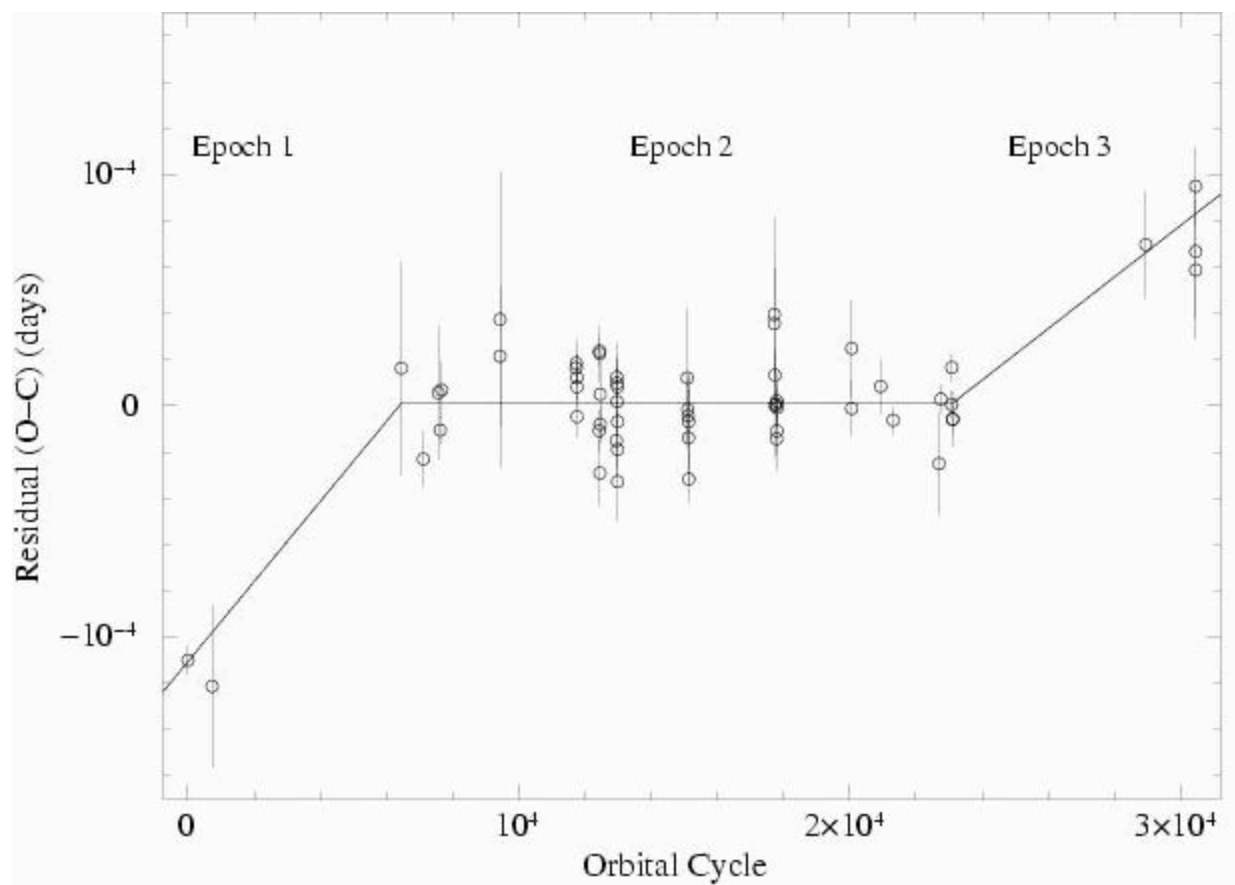


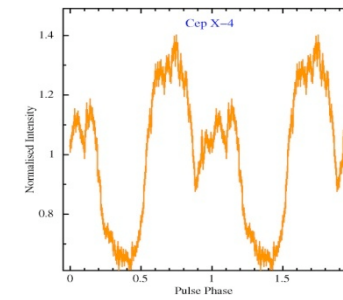
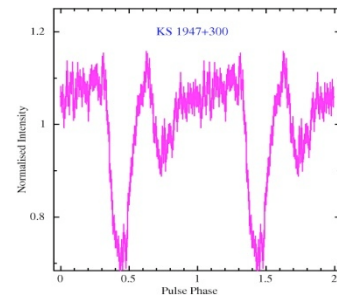
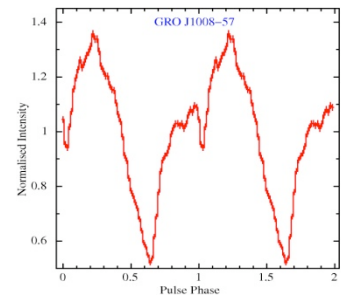
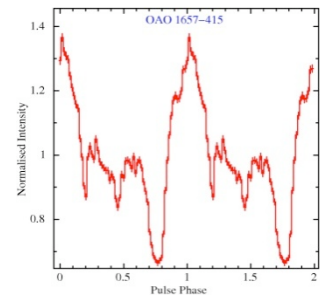
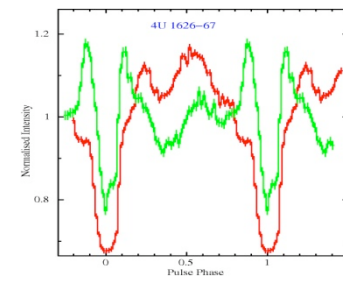
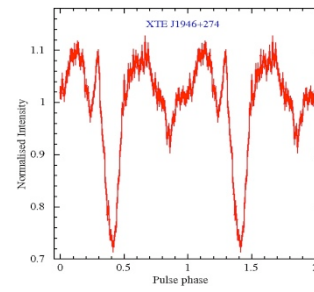
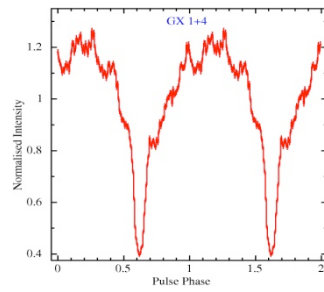
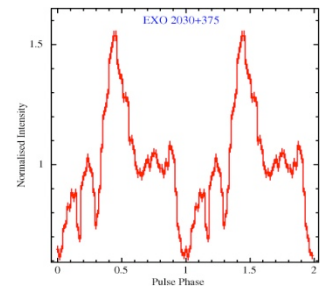
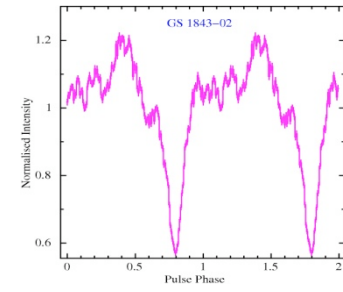
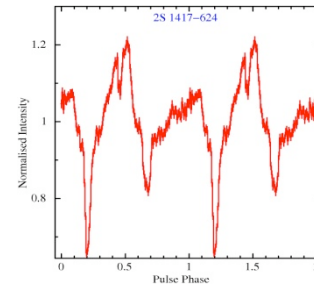
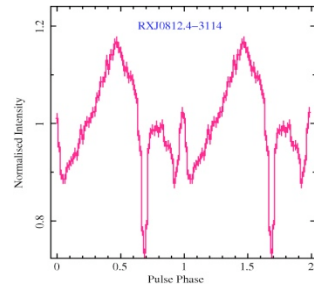
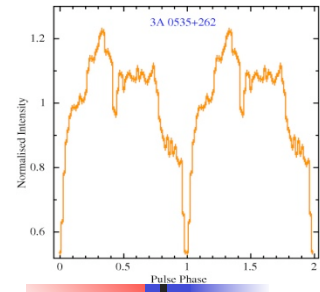




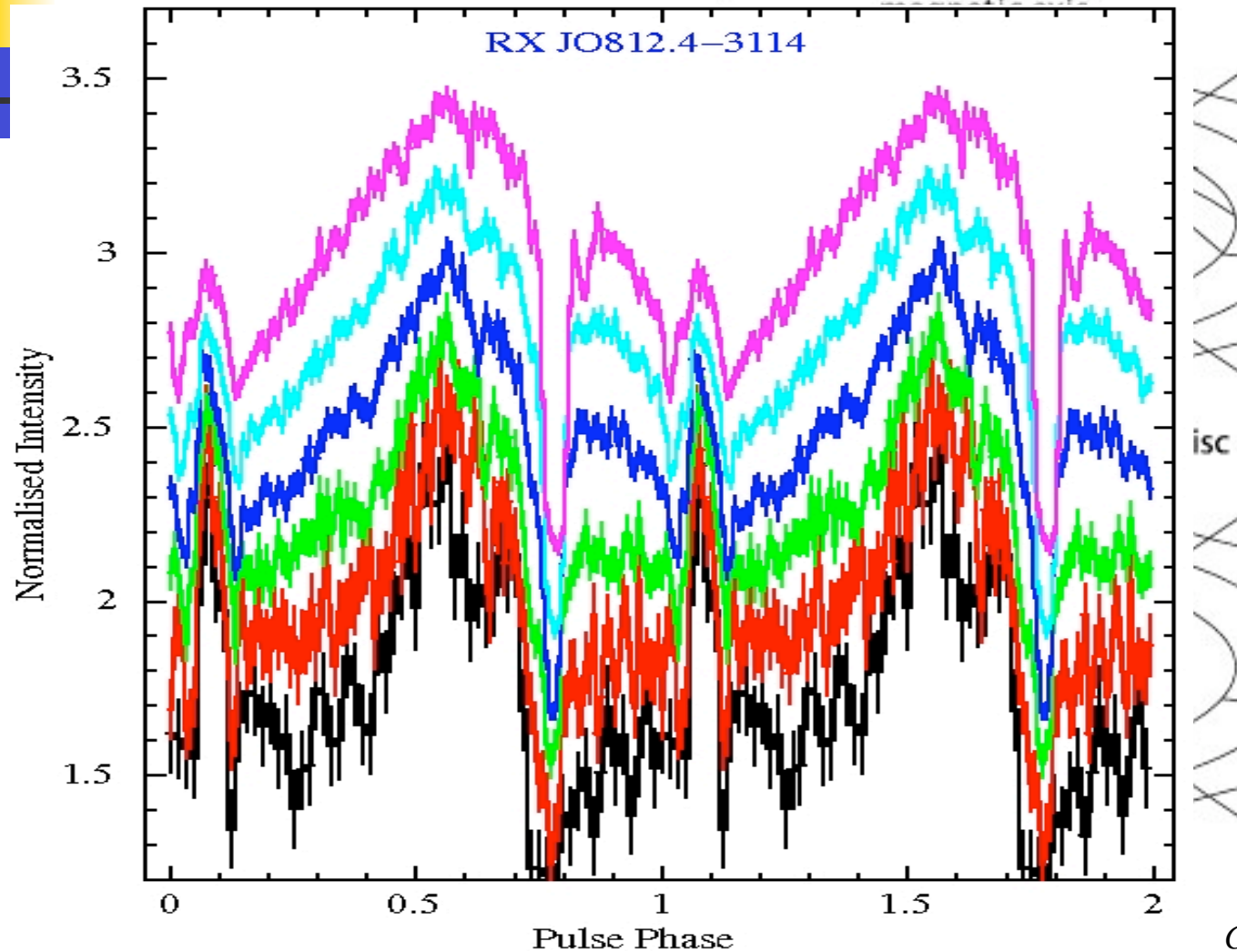


# Eclipse timing: XTE J1710-281





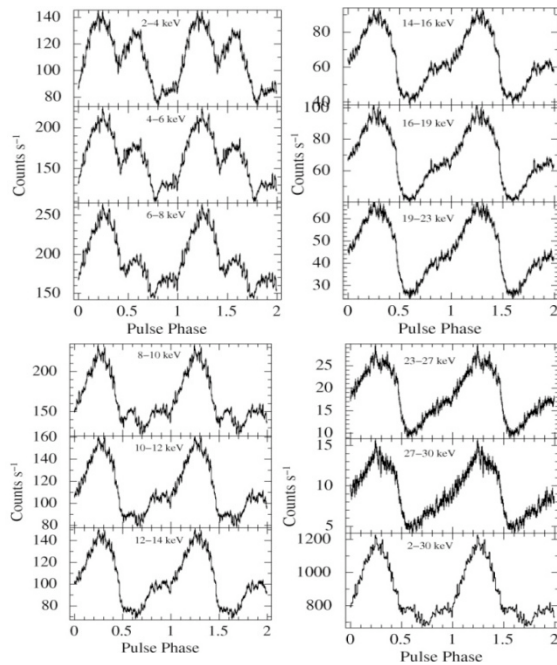
# Dips in X-ray Pulsars



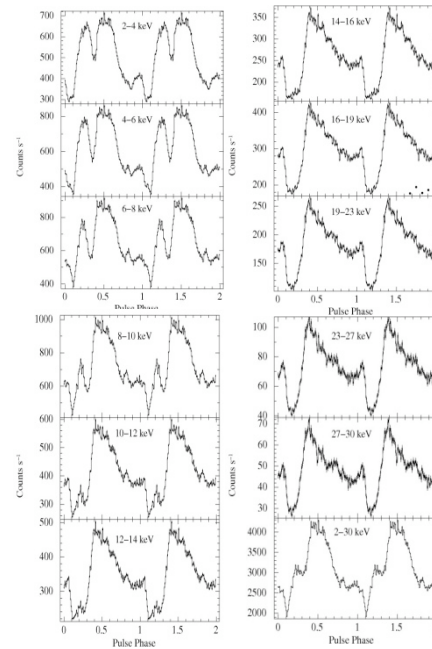
*Galloway et al. 2001*

*Devasia et al. 2011*

# Energy Dependent Pulse Profiles



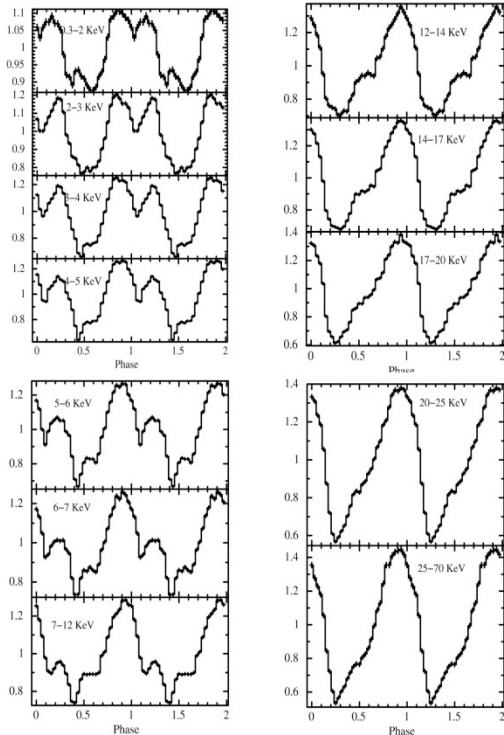
**1A 1118-61: RXTE-PCA**



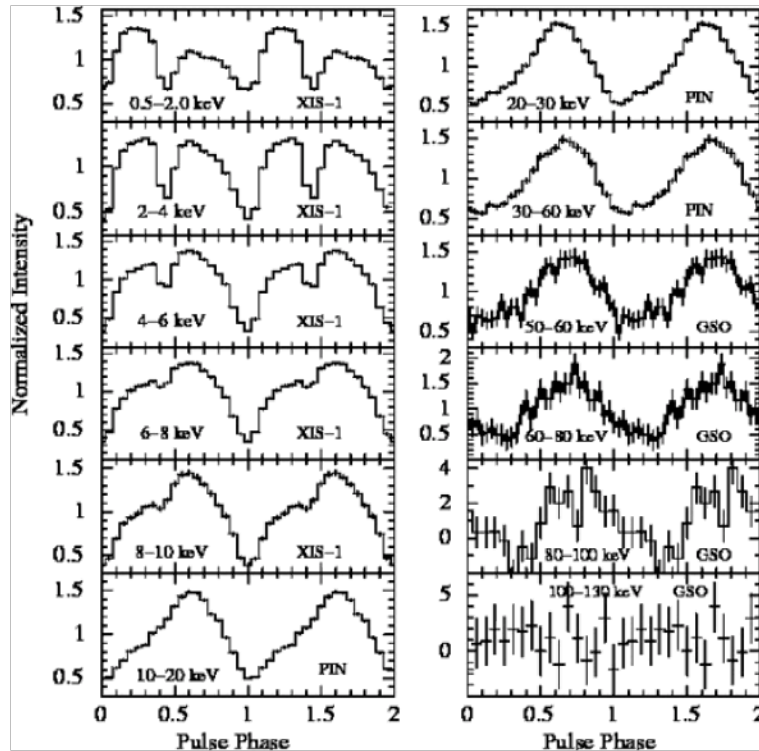
**GX 304-1: RXTE-PCA**

*Naiḳ et al. 2010*  
*Devasia et al. 2011a*  
*Devasia et al. 2011b*  
*Maitra et al. 2011*

# Energy Dependent Pulse Profiles



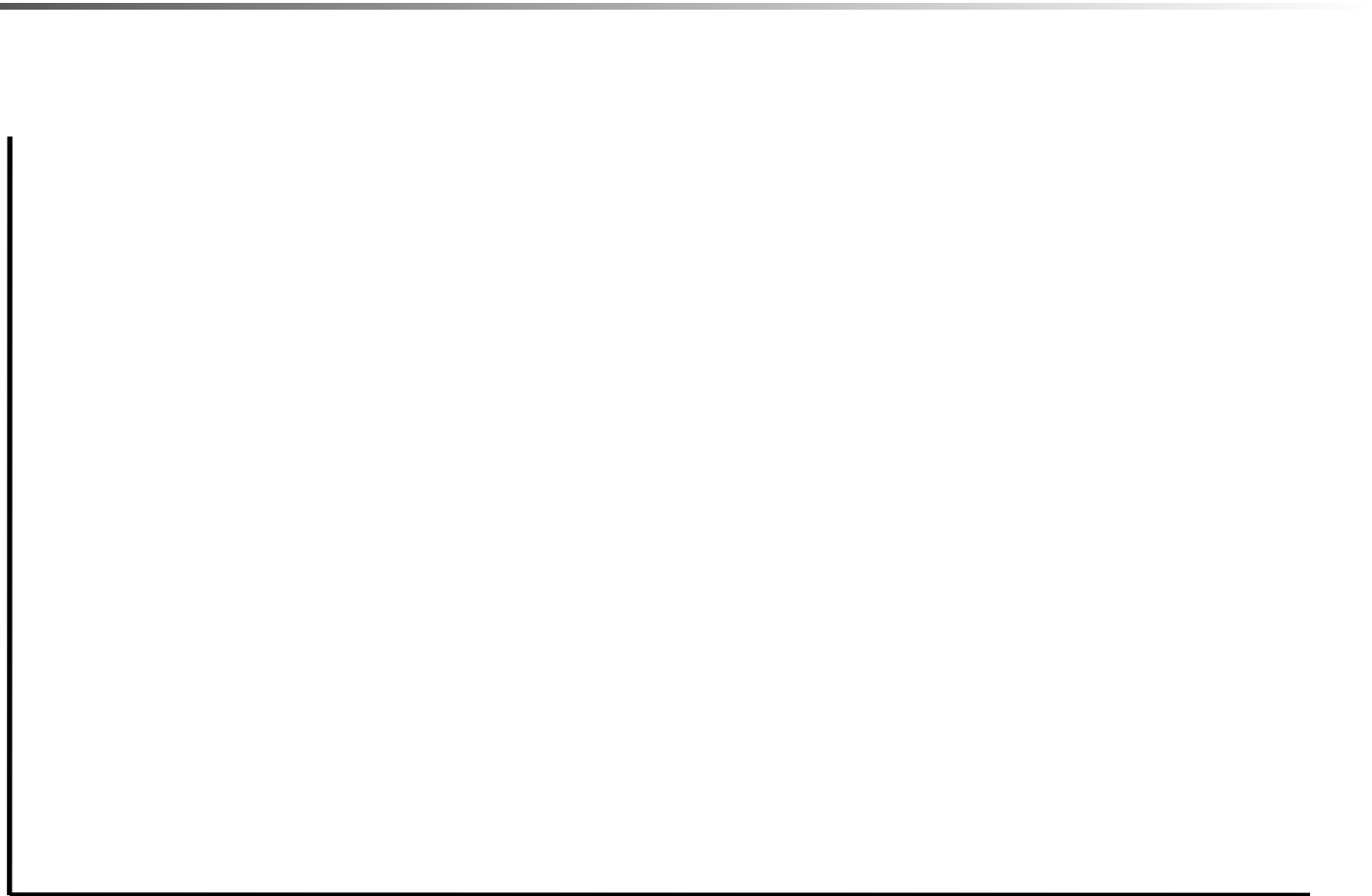
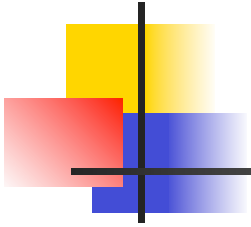
**1A 1118-61: Suzaku**



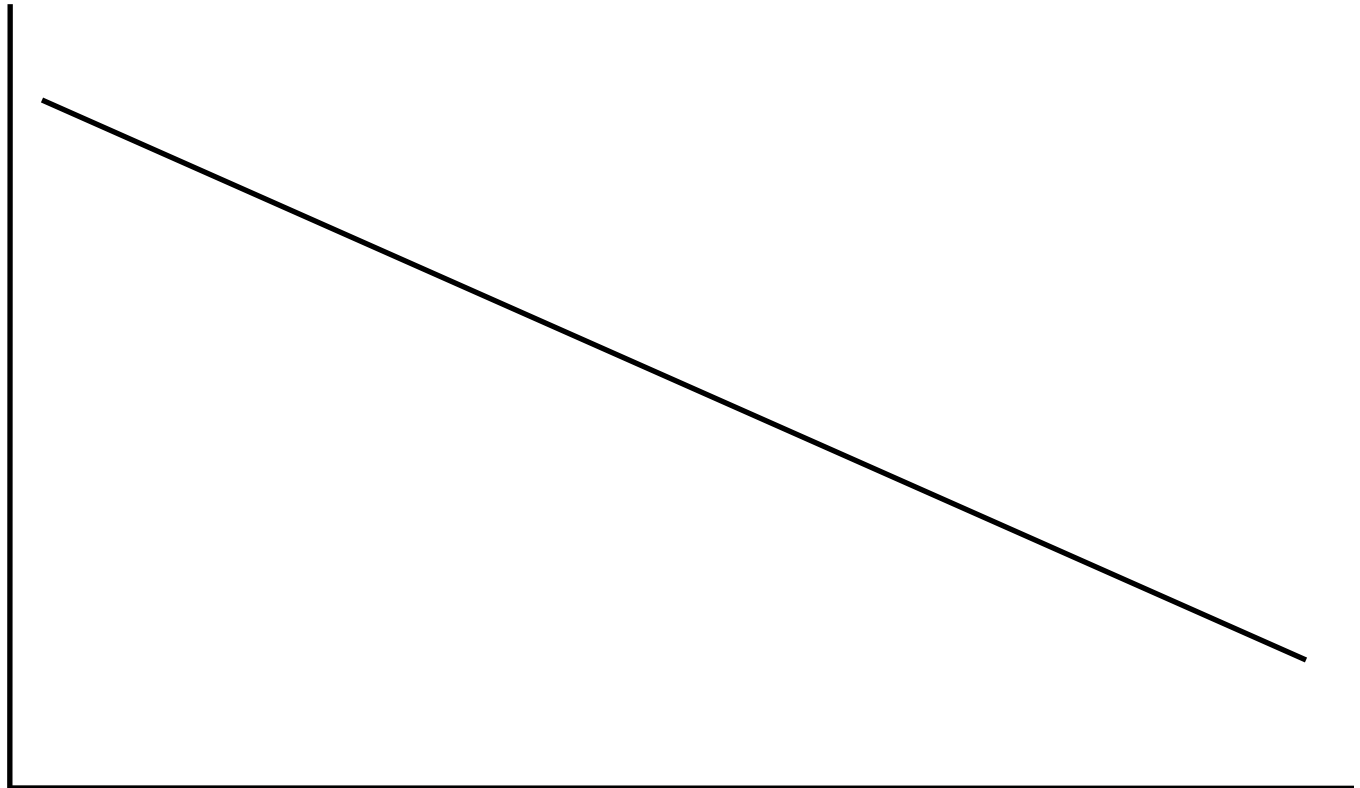
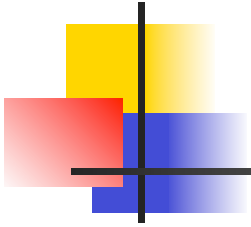
**GRO J1008-57: Suzaku**

*Naij et al. 2010*  
*Devasia et al. 2011a*  
*Devasia et al. 2011b*  
*Maitra et al. 2011*

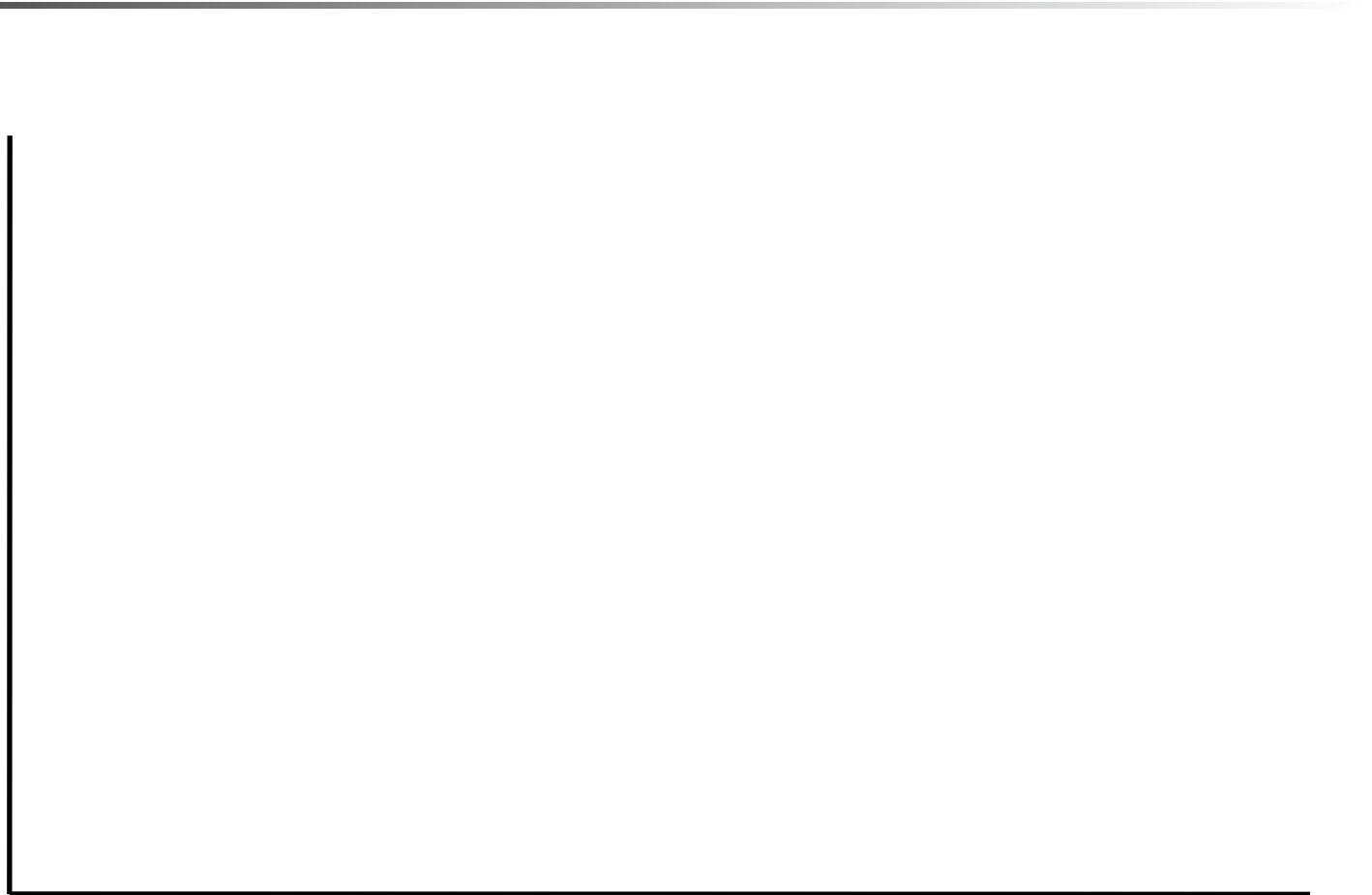
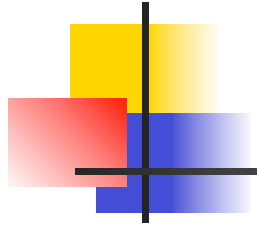
# *Energy Dependent Pulse Profiles*



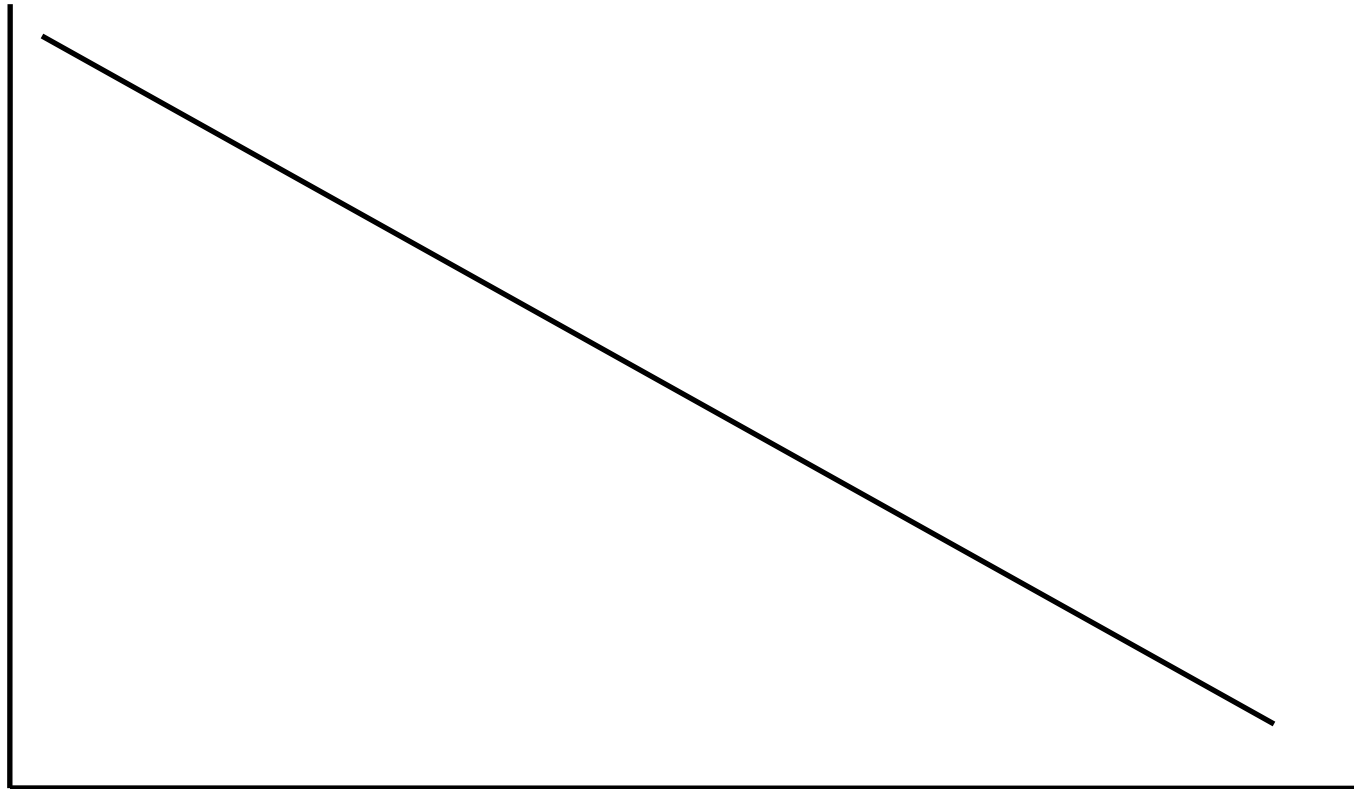
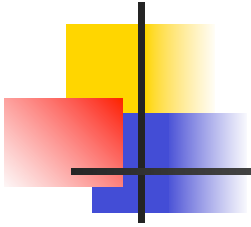
# *Energy Dependent Pulse Profiles*



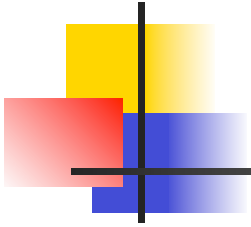
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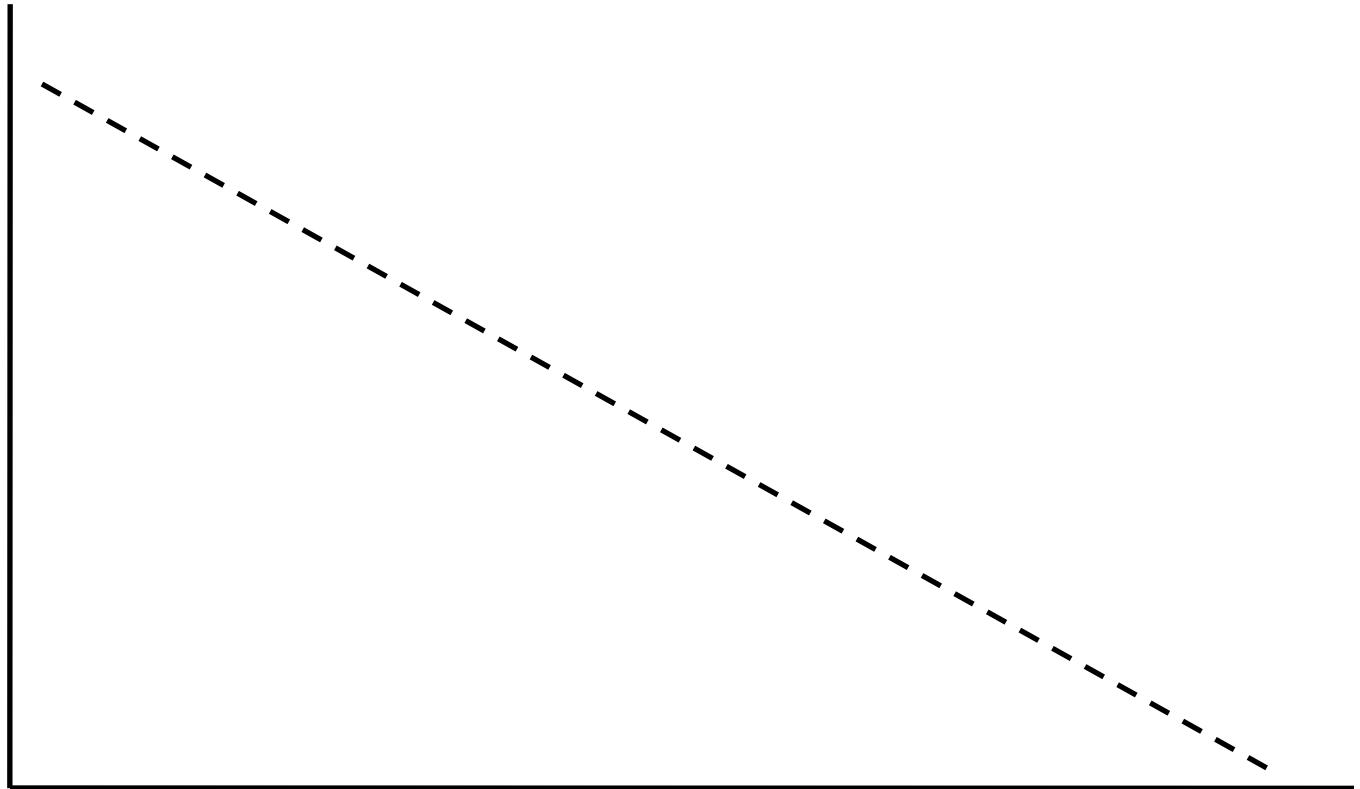
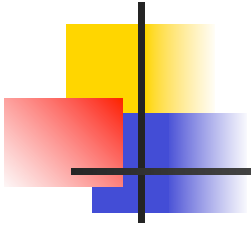
# *Energy Dependent Pulse Profiles*



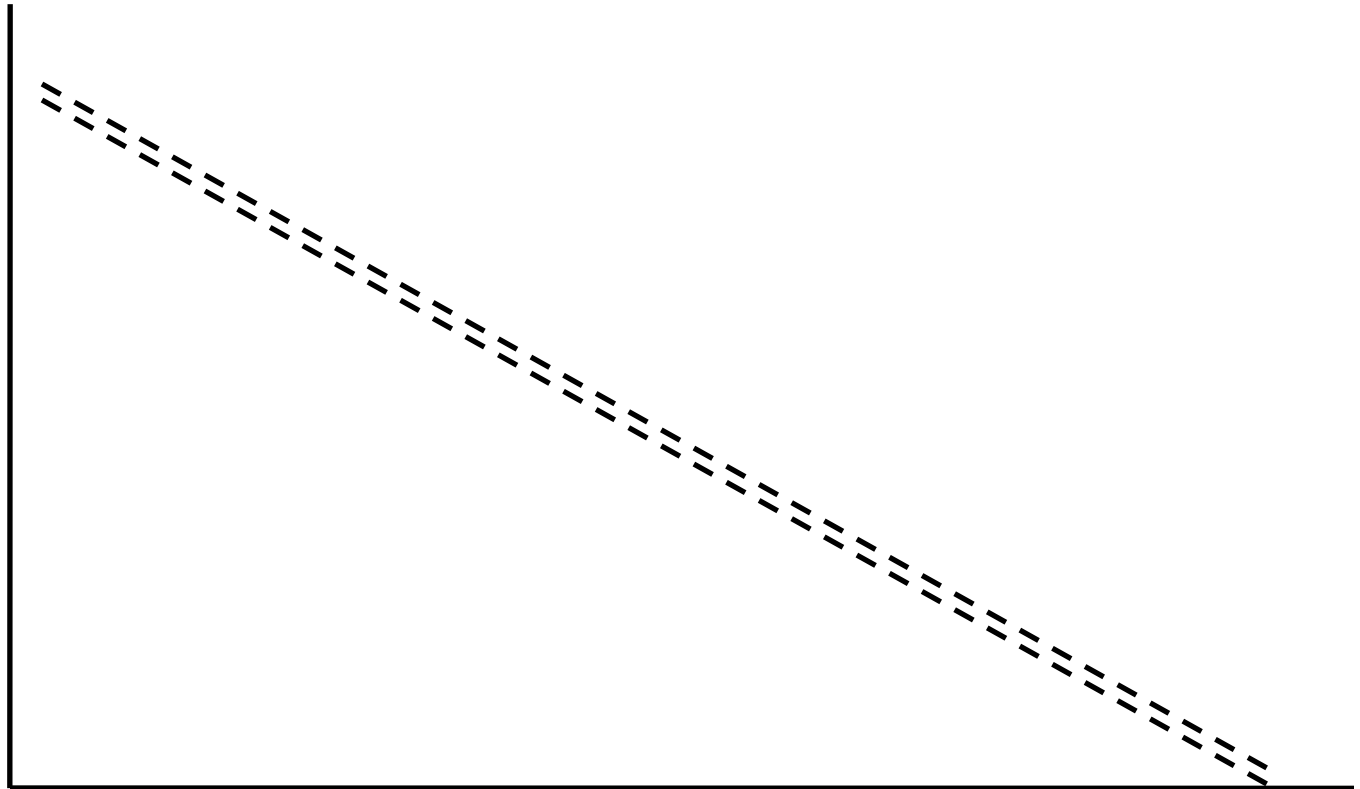
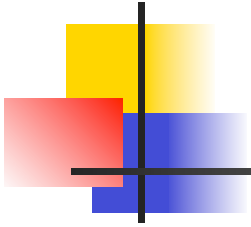
# *Energy Dependent Pulse Profiles*



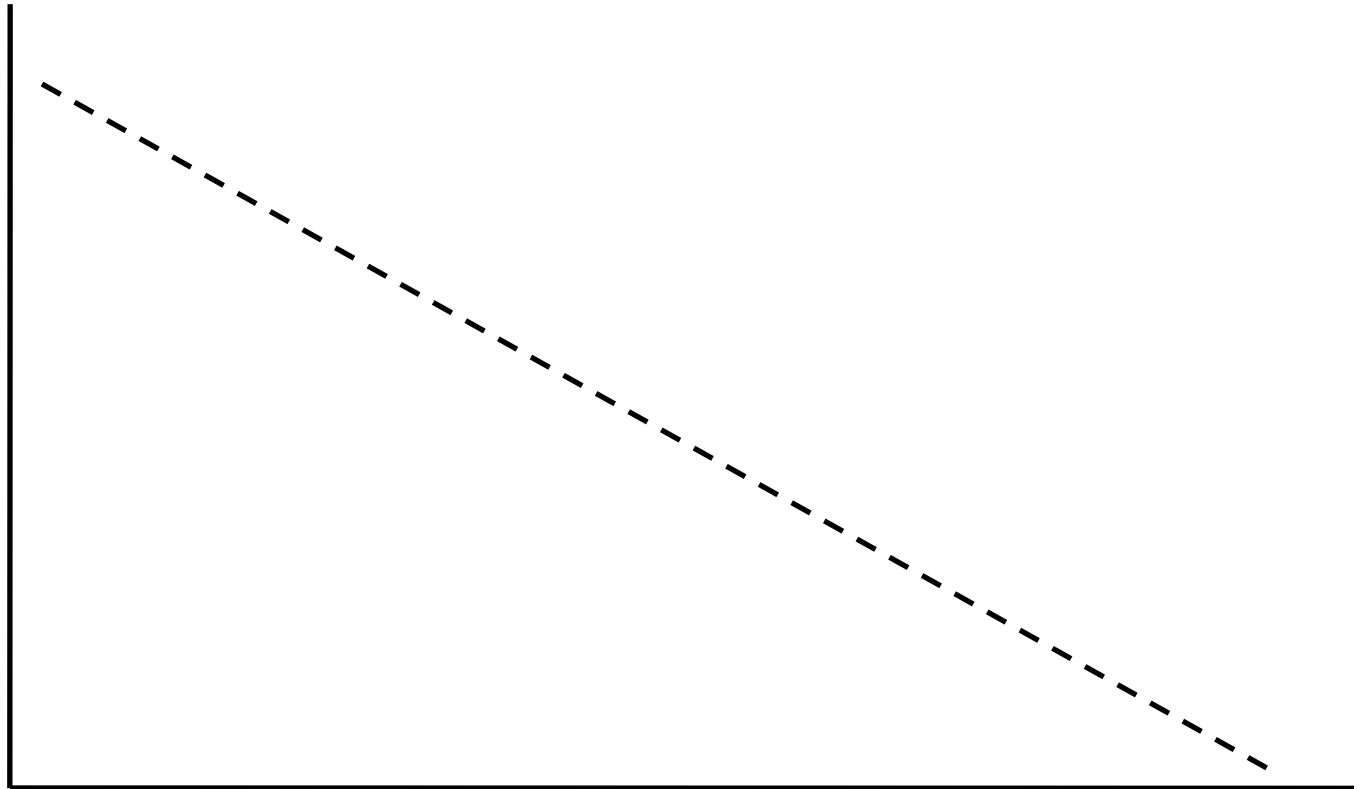
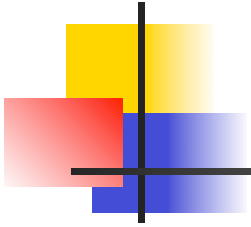
# *Energy Dependent Pulse Profiles*



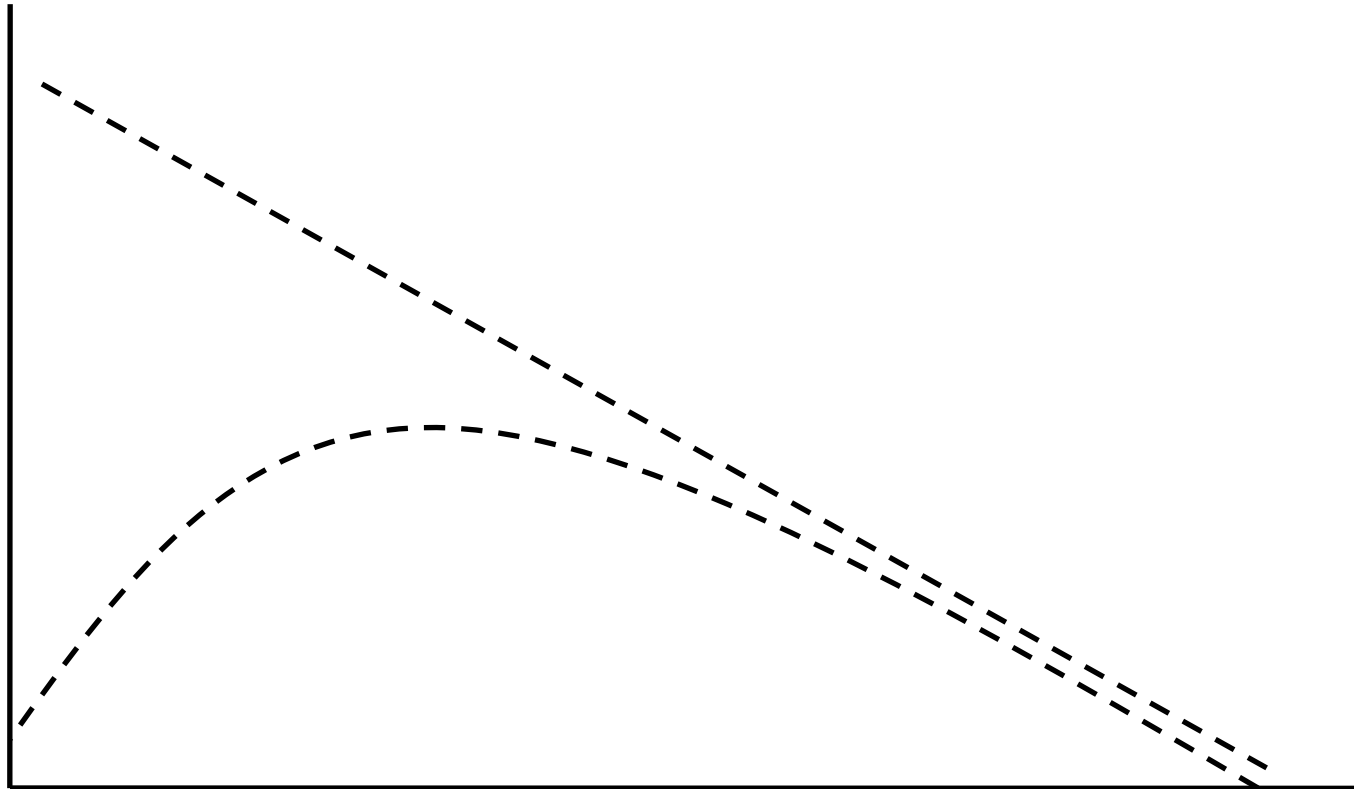
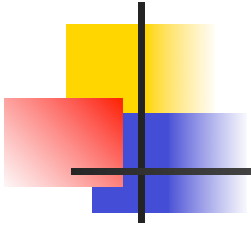
# *Energy Dependent Pulse Profiles*



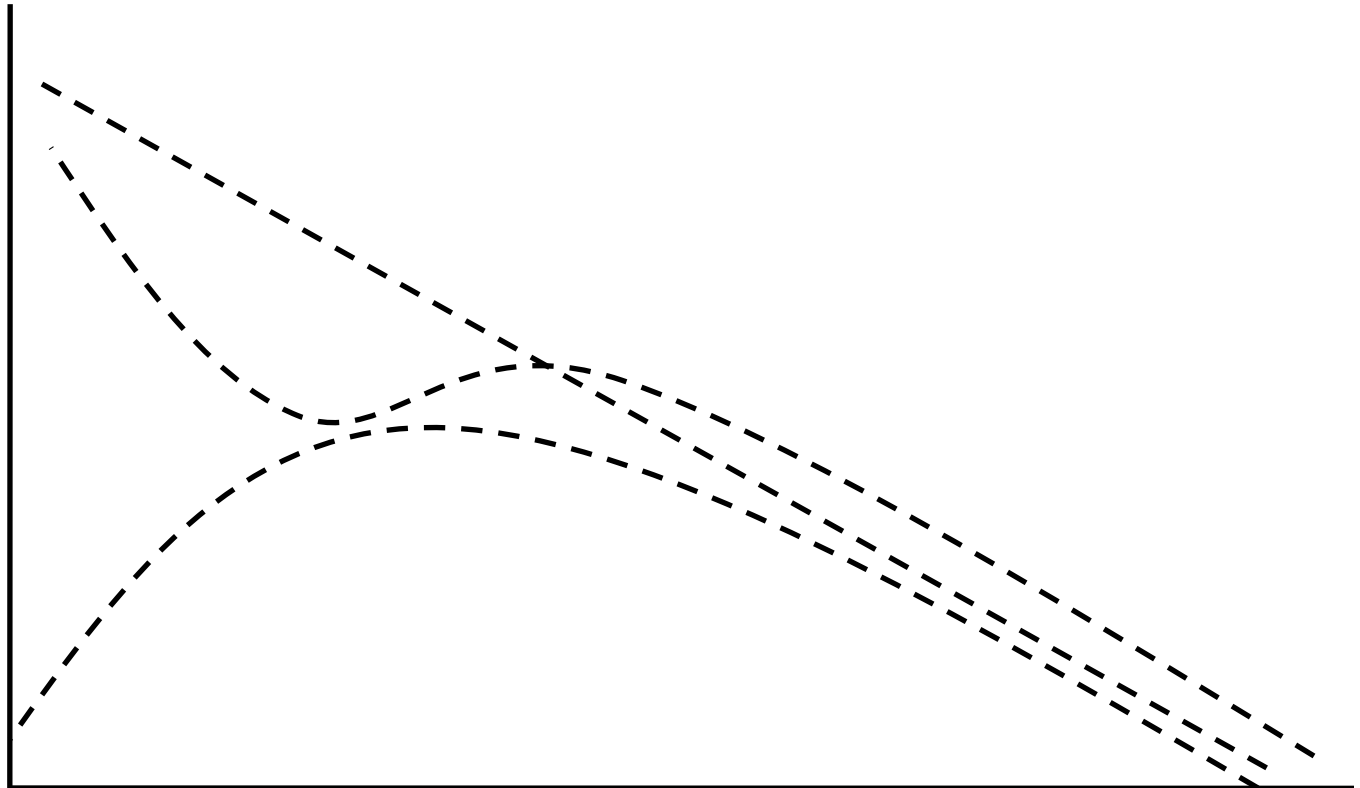
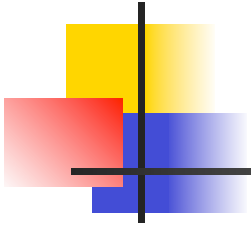
# *Energy Dependent Pulse Profiles*



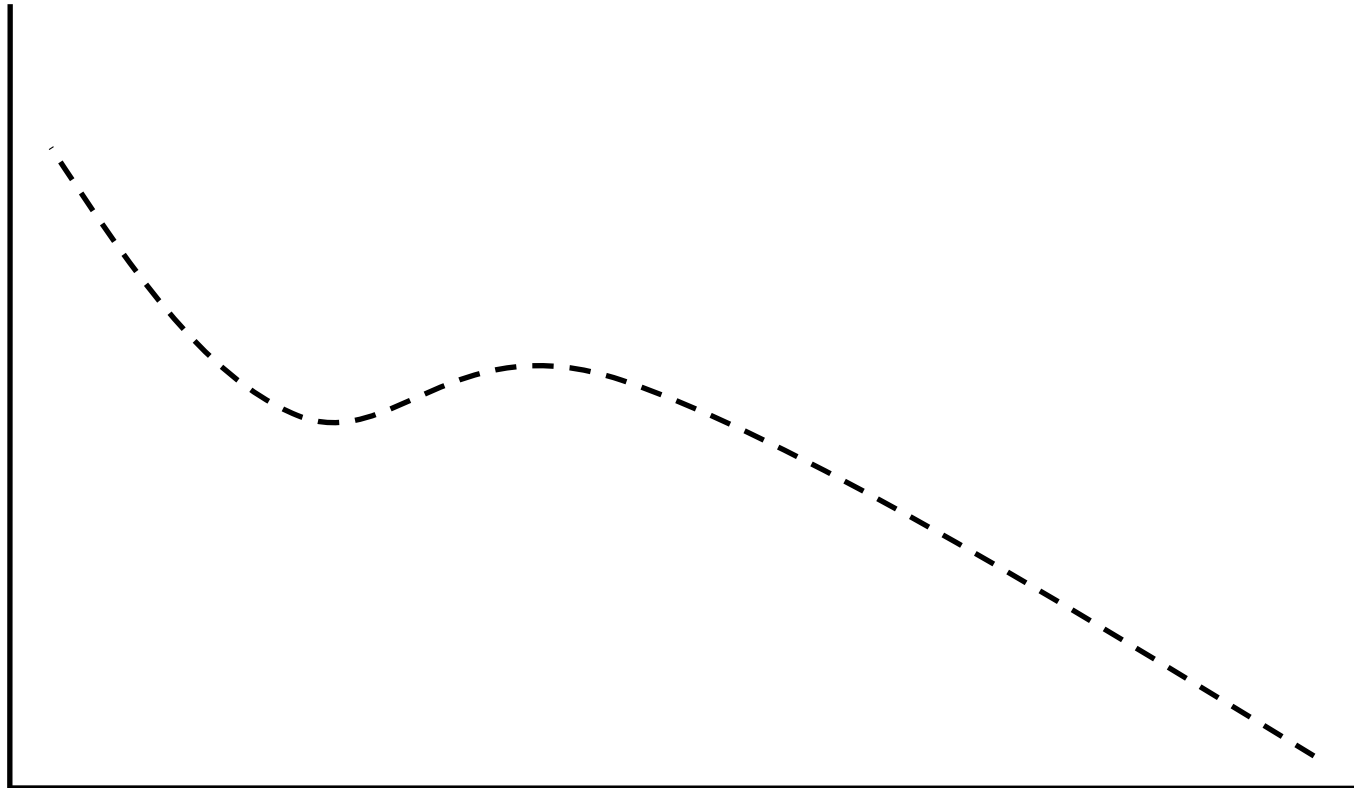
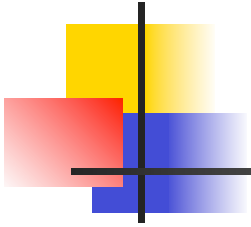
# *Energy Dependent Pulse Profiles*



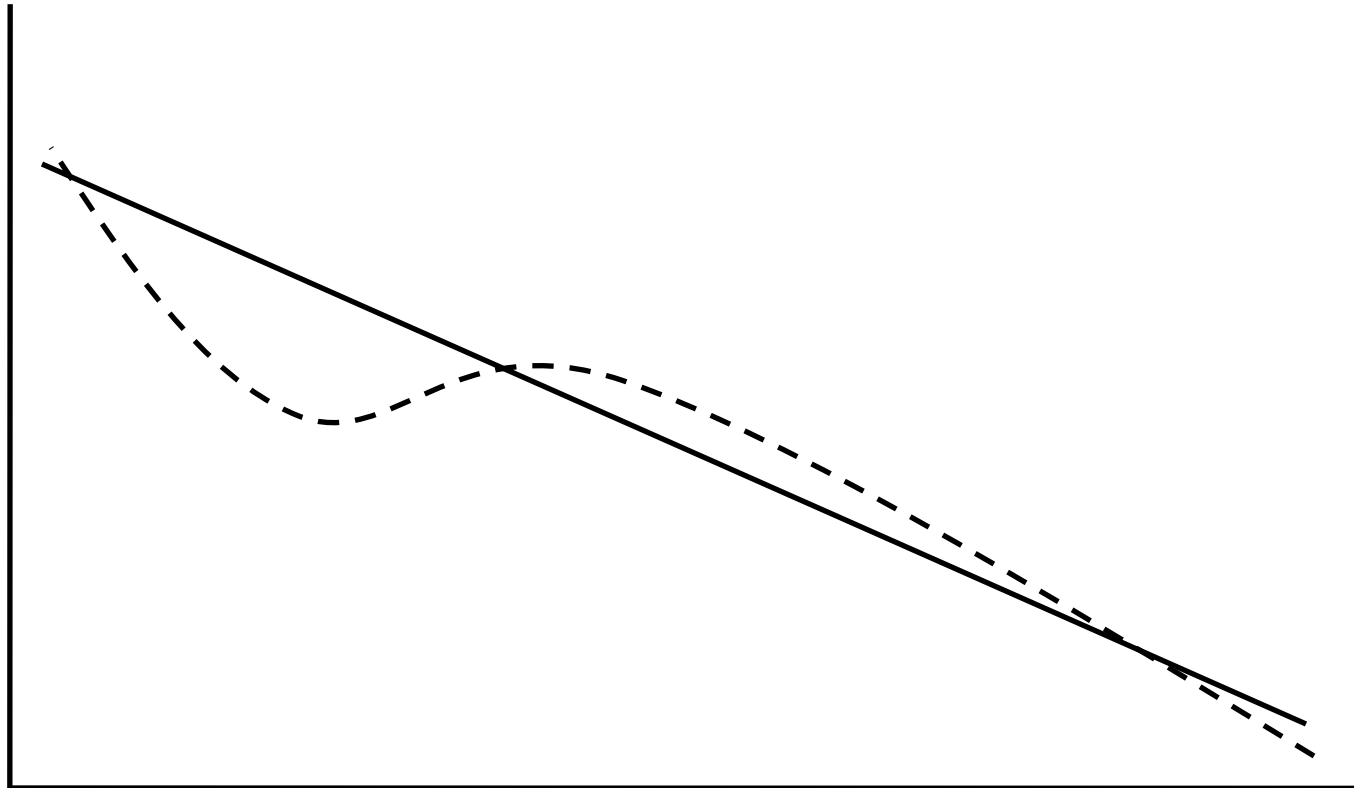
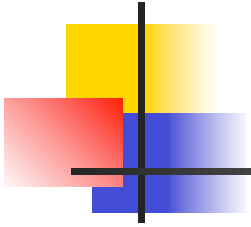
# *Energy Dependent Pulse Profiles*



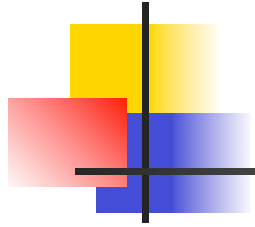
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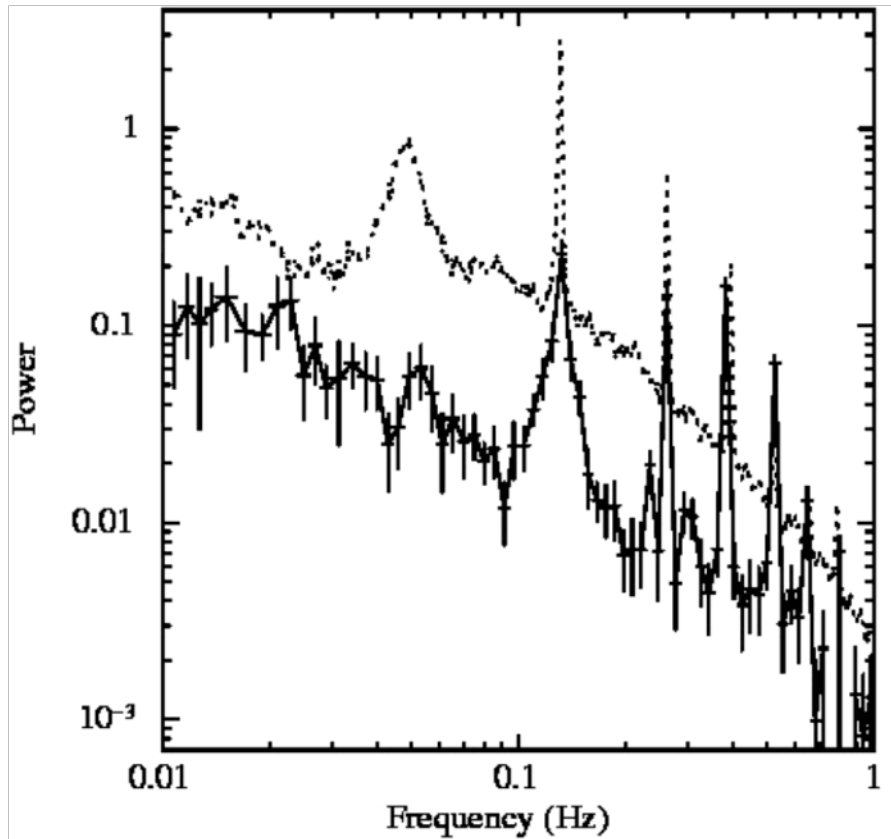
# *Energy Dependent Pulse Profiles*



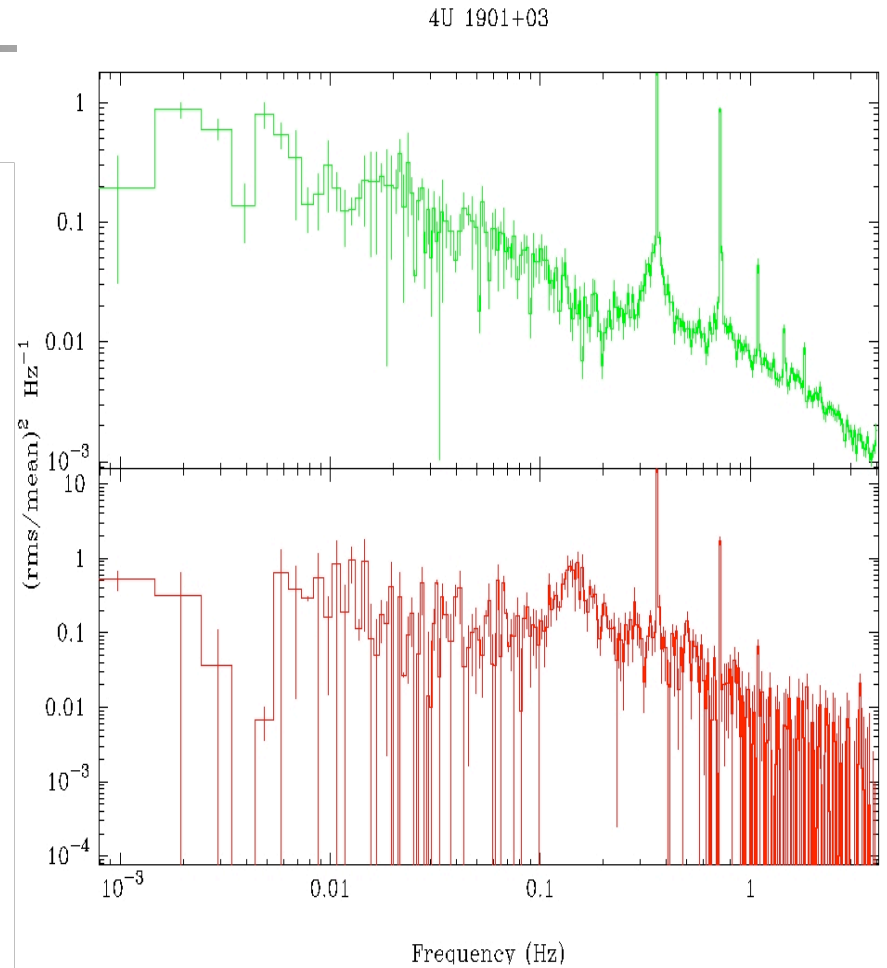
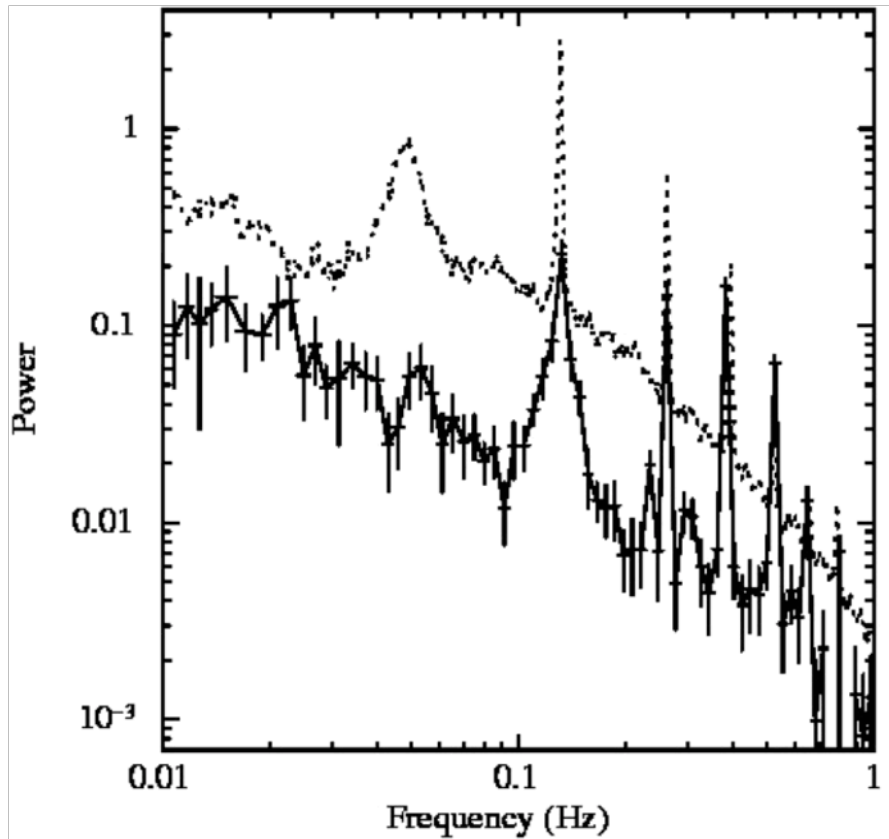
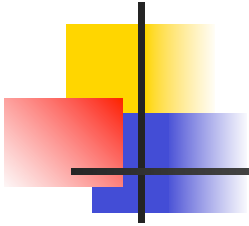
# *Broadening of Pulse Profiles in X-ray Pulsars*



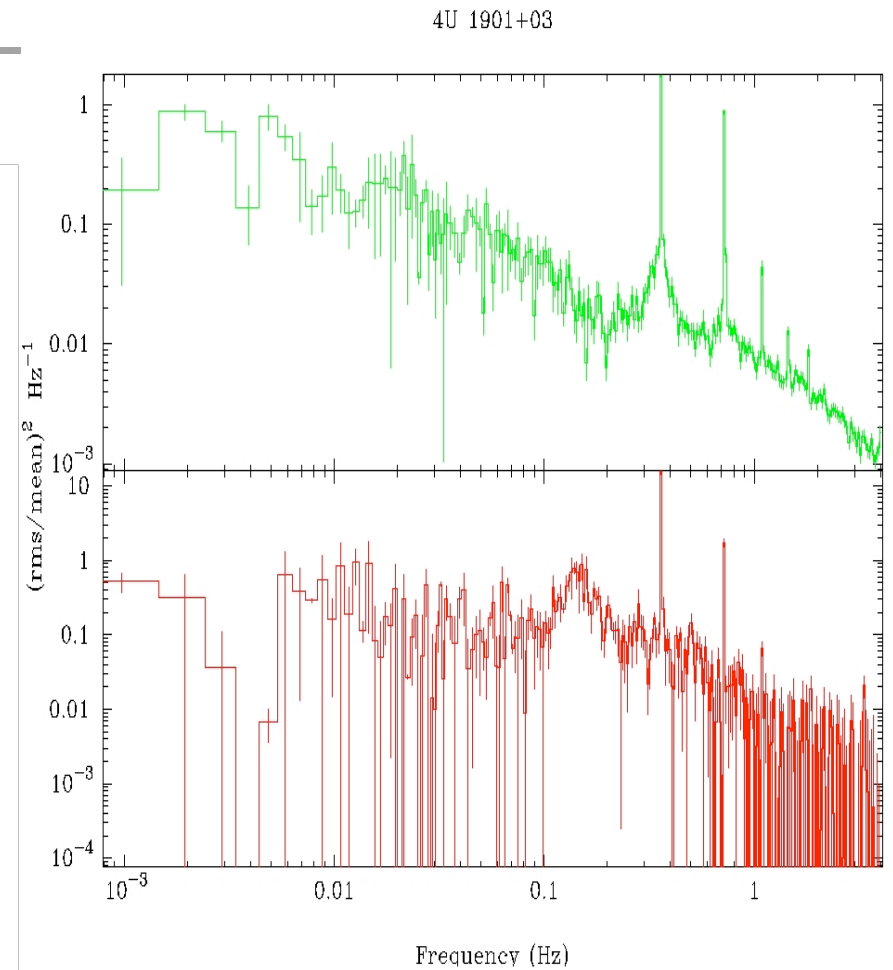
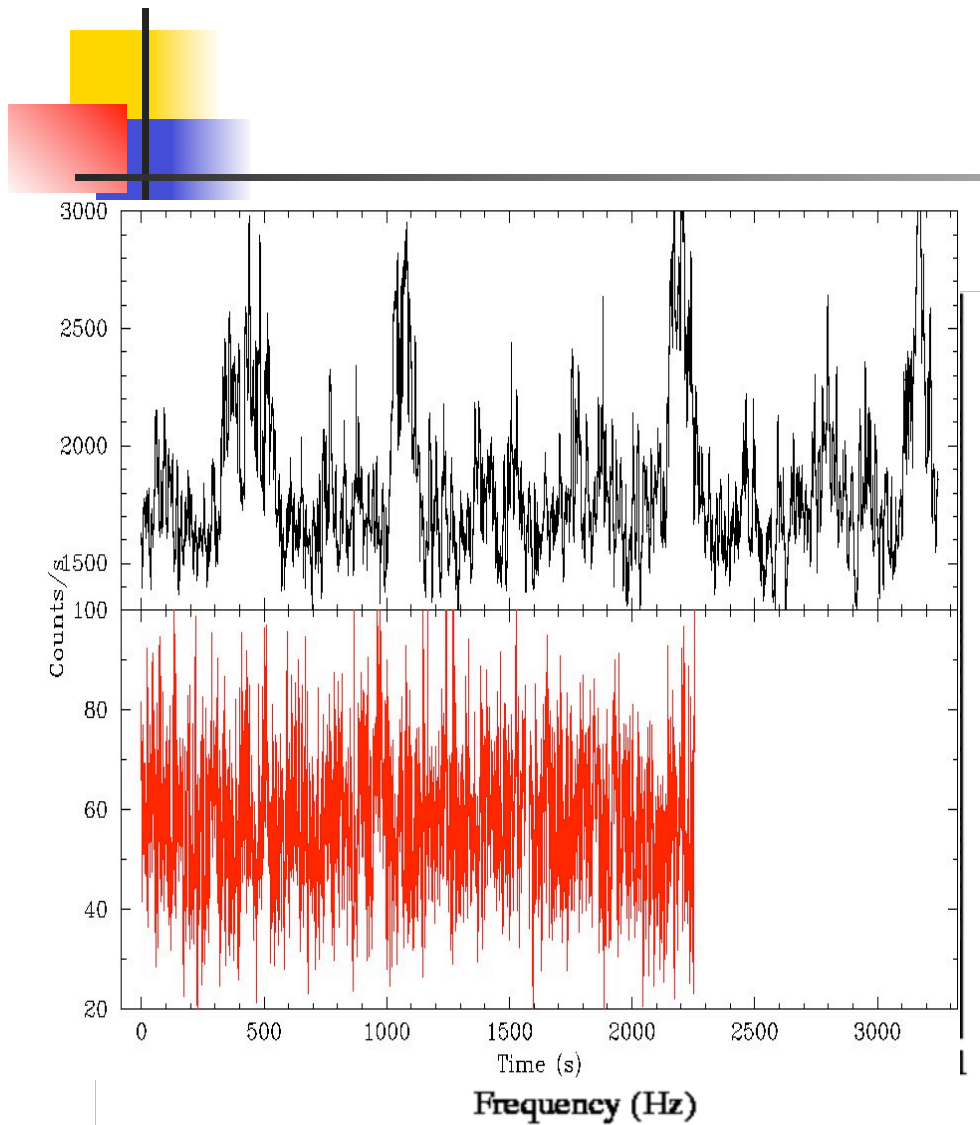
# *Broadening of Pulse Profiles in X-ray Pulsars*



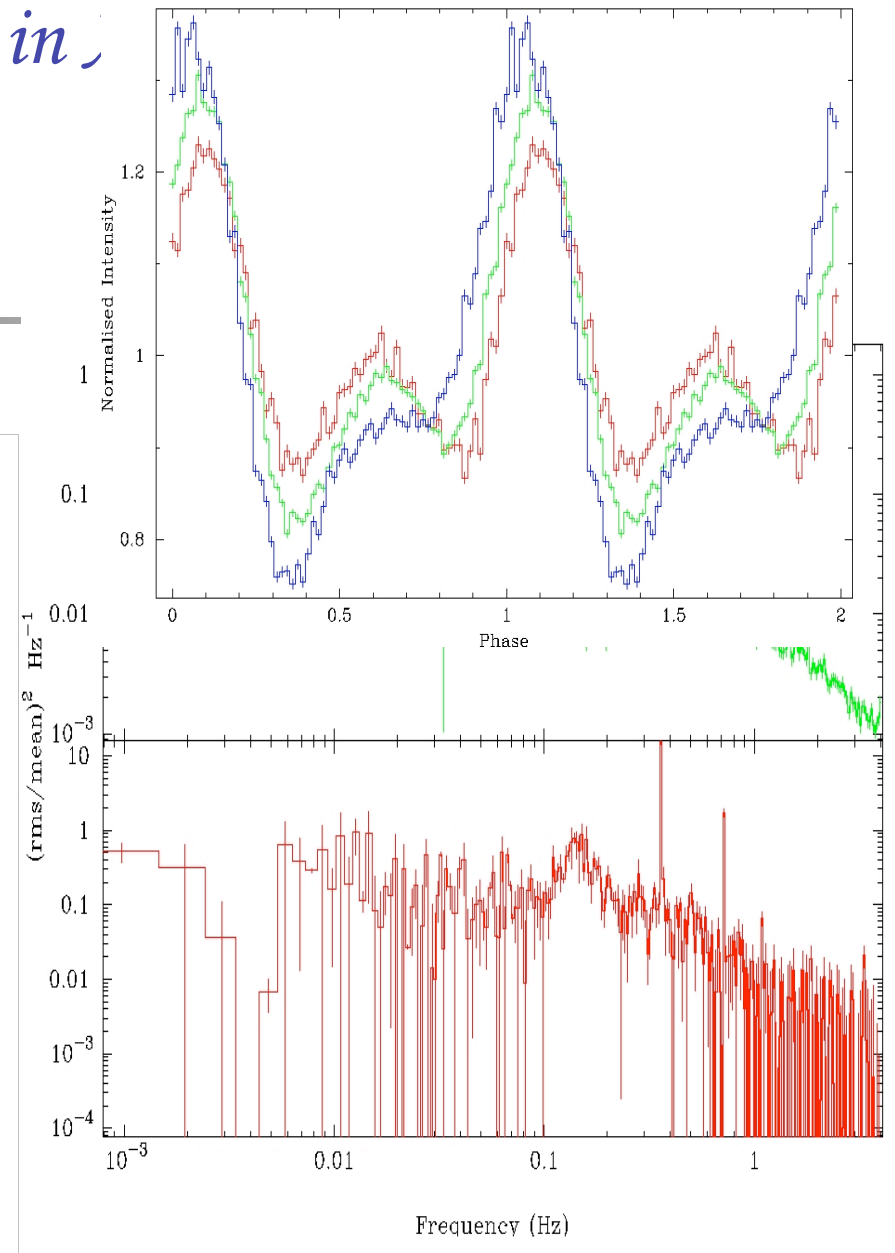
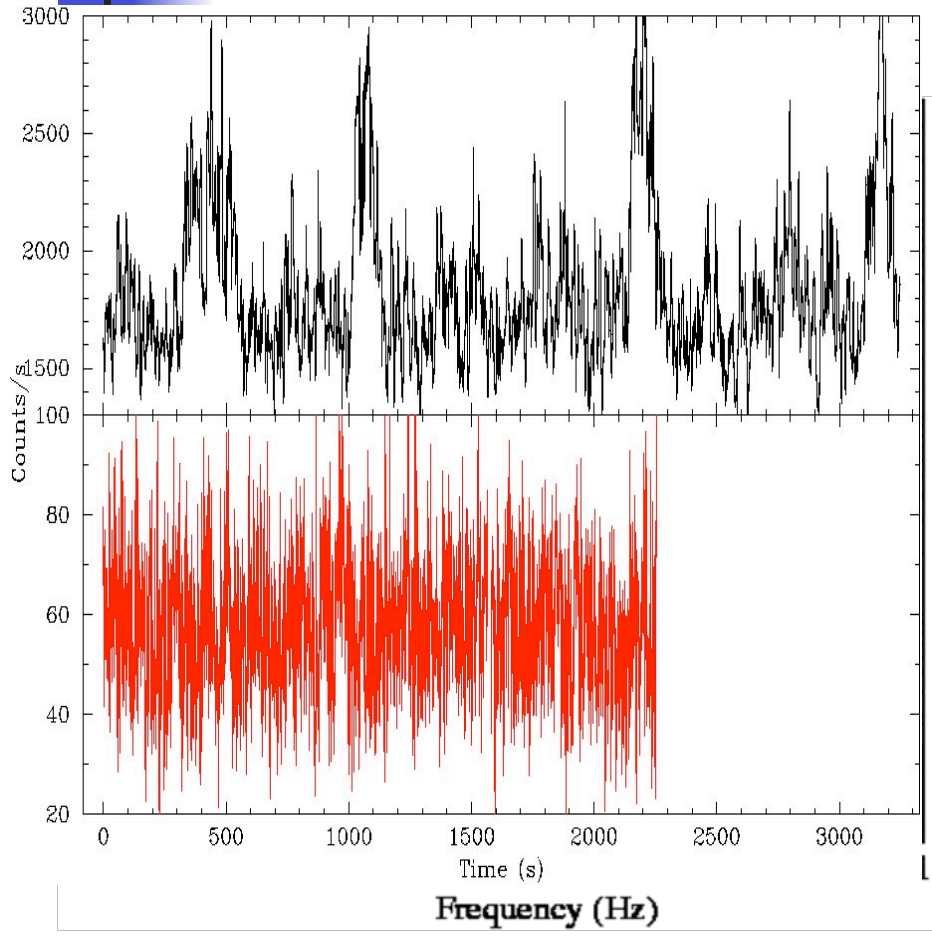
# Broadening of Pulse Profiles in X-ray Pulsars



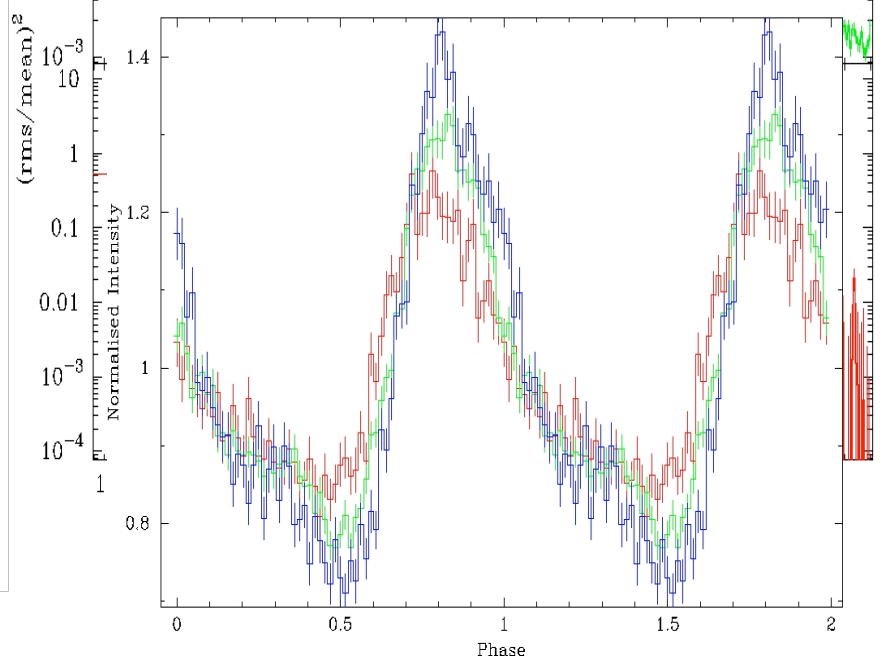
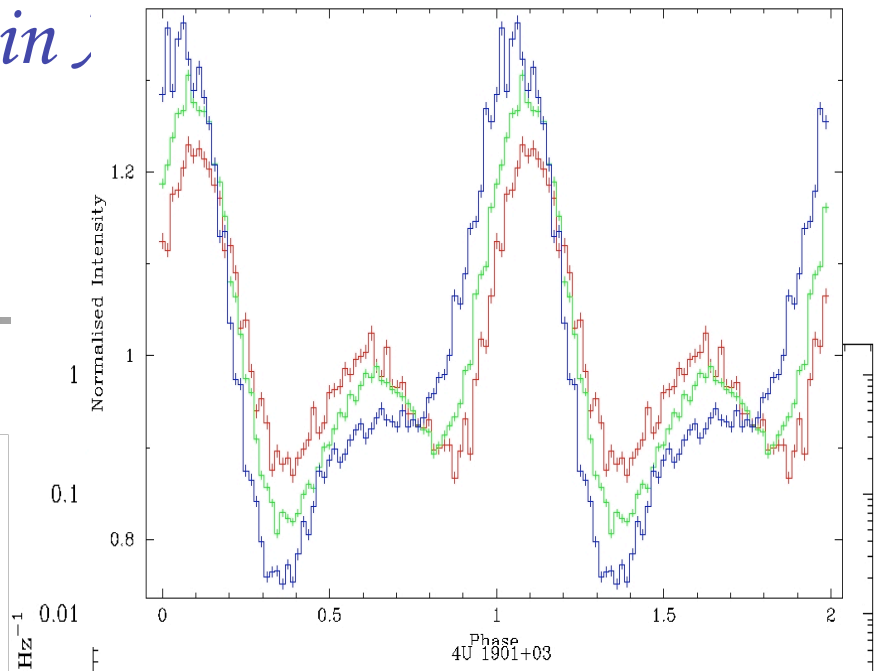
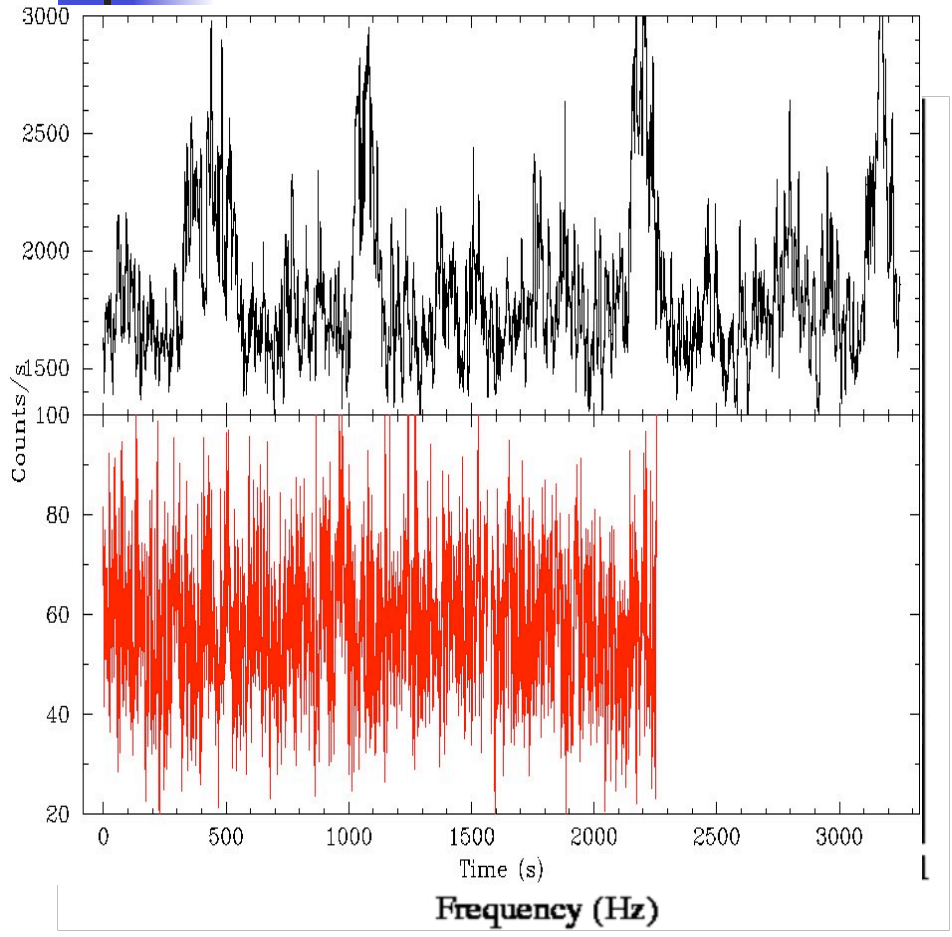
# Broadening of Pulse Profiles in X-ray Pulsars



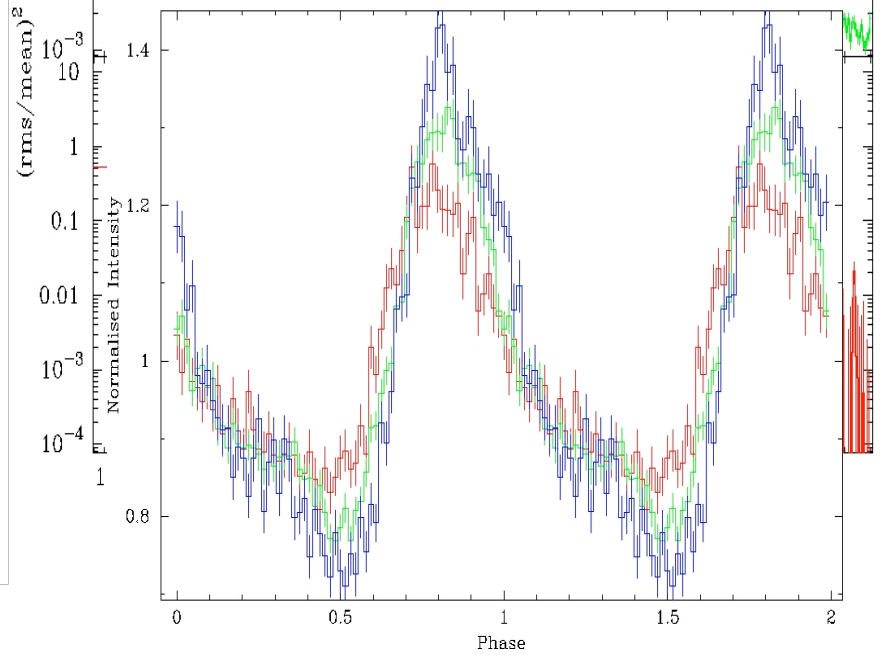
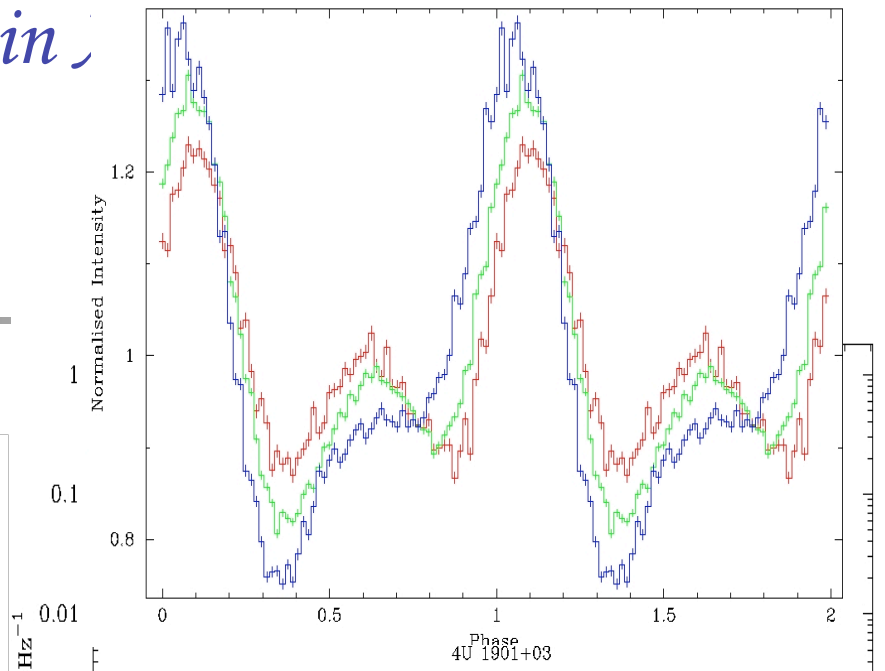
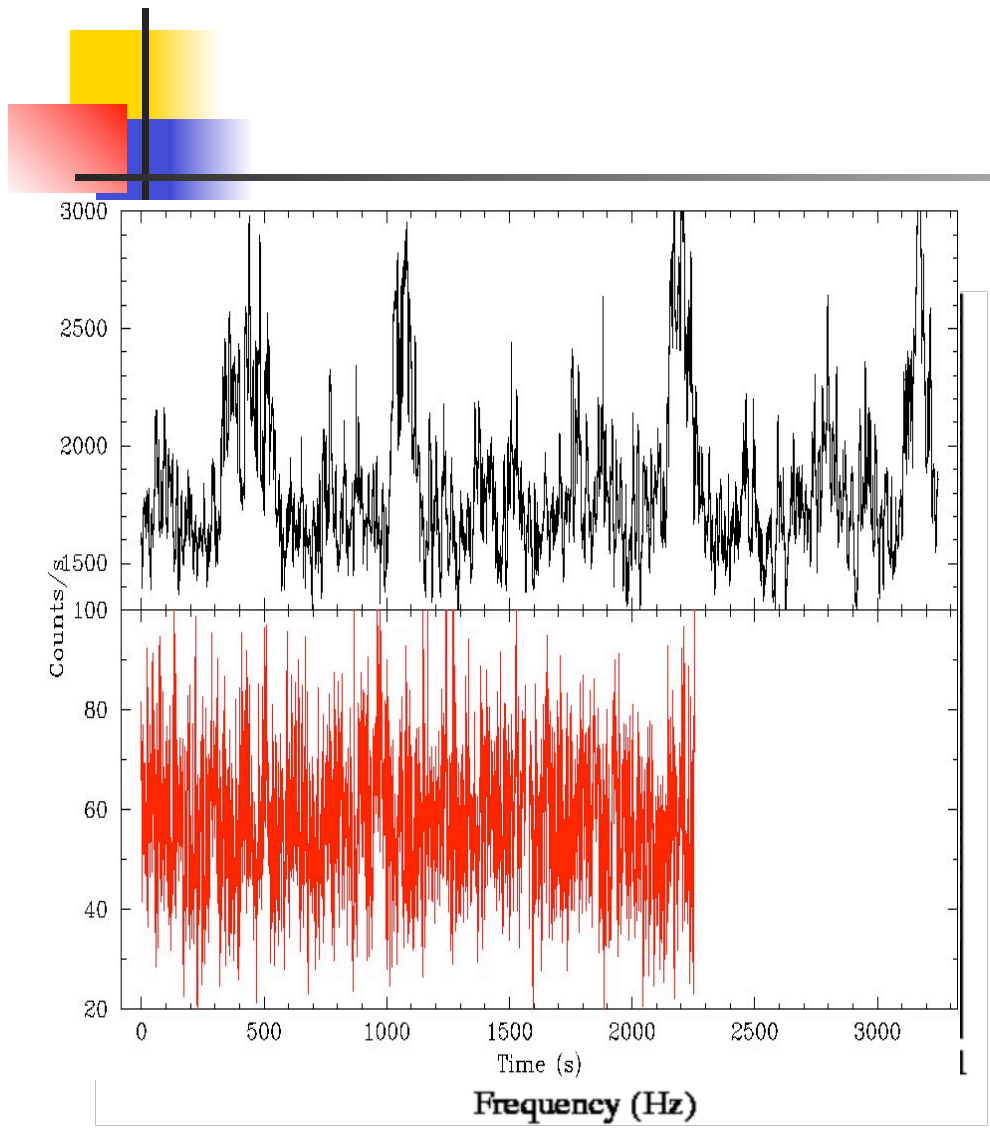
# Broadening of Pulse Profiles in



# Broadening of Pulse Profiles in

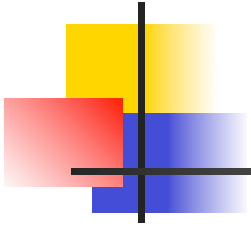


# Broadening of Pulse Profiles in

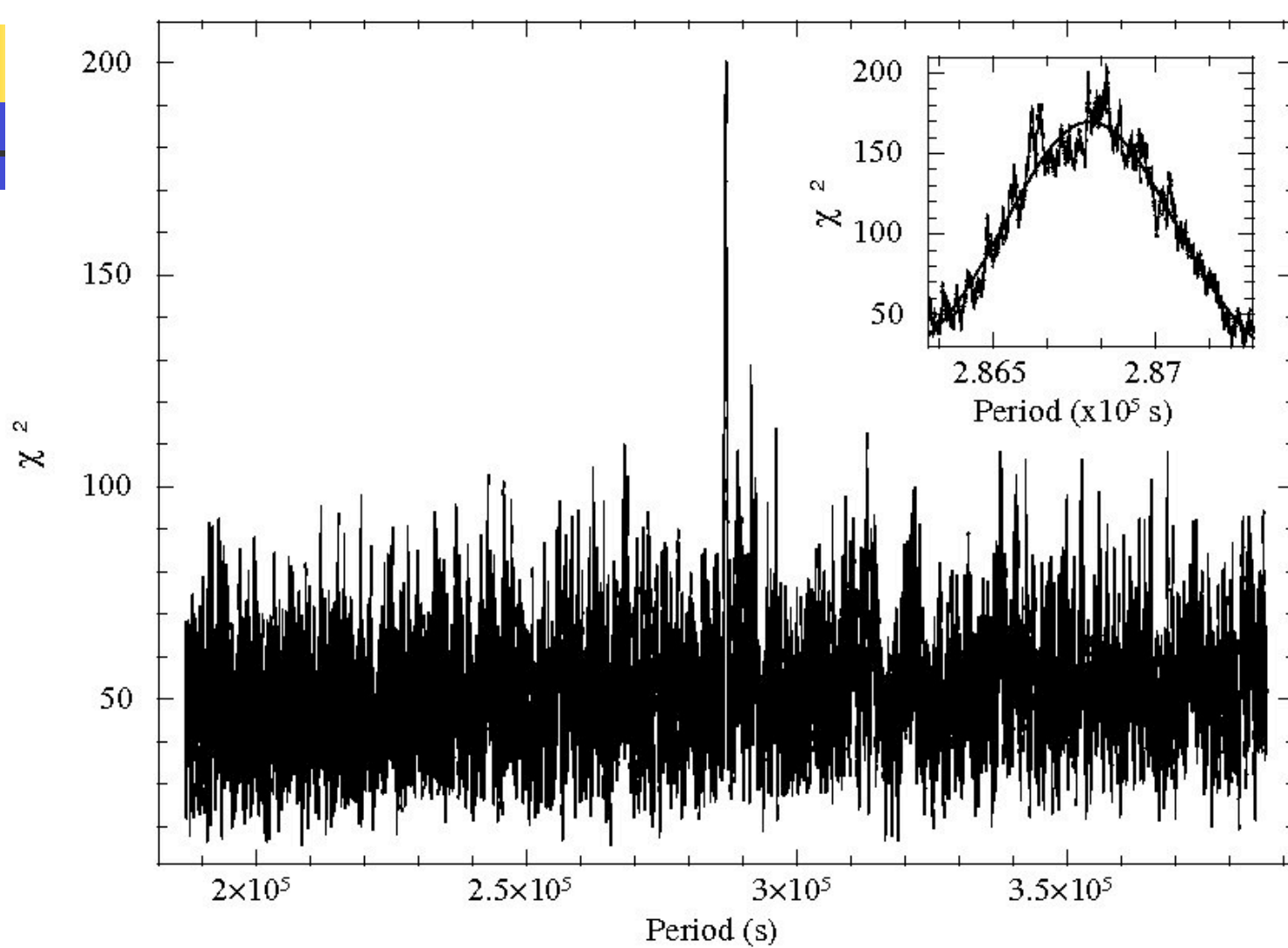


James et al. 2011

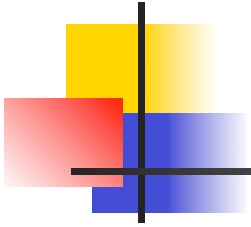
# *Supergiant Fast X-ray Transient: IGR J16479-4514*



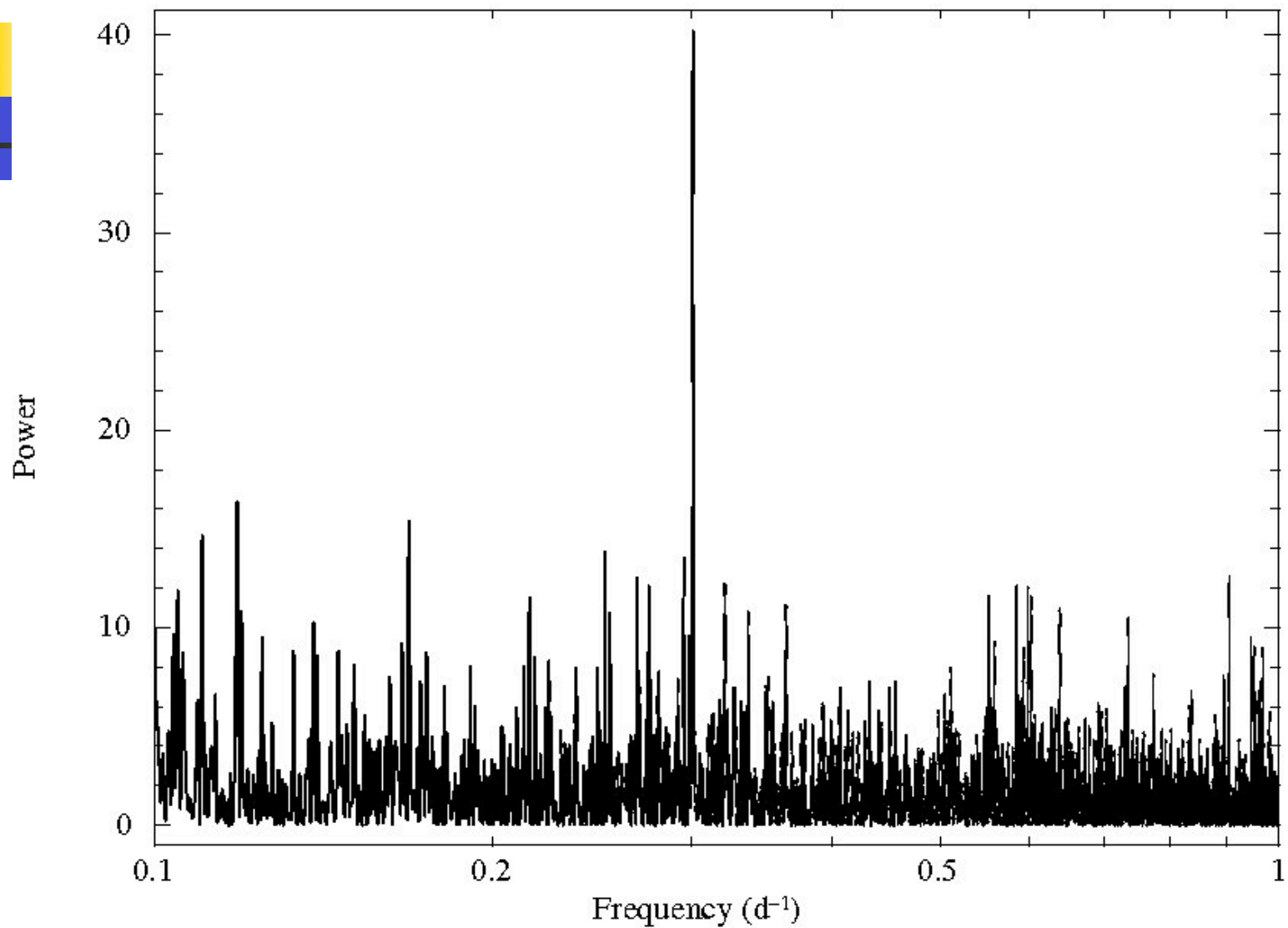
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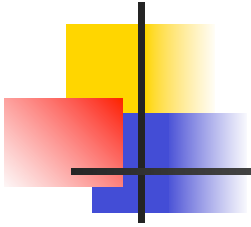
# *Supergiant Fast X-ray Transient: IGR J16479-4514*



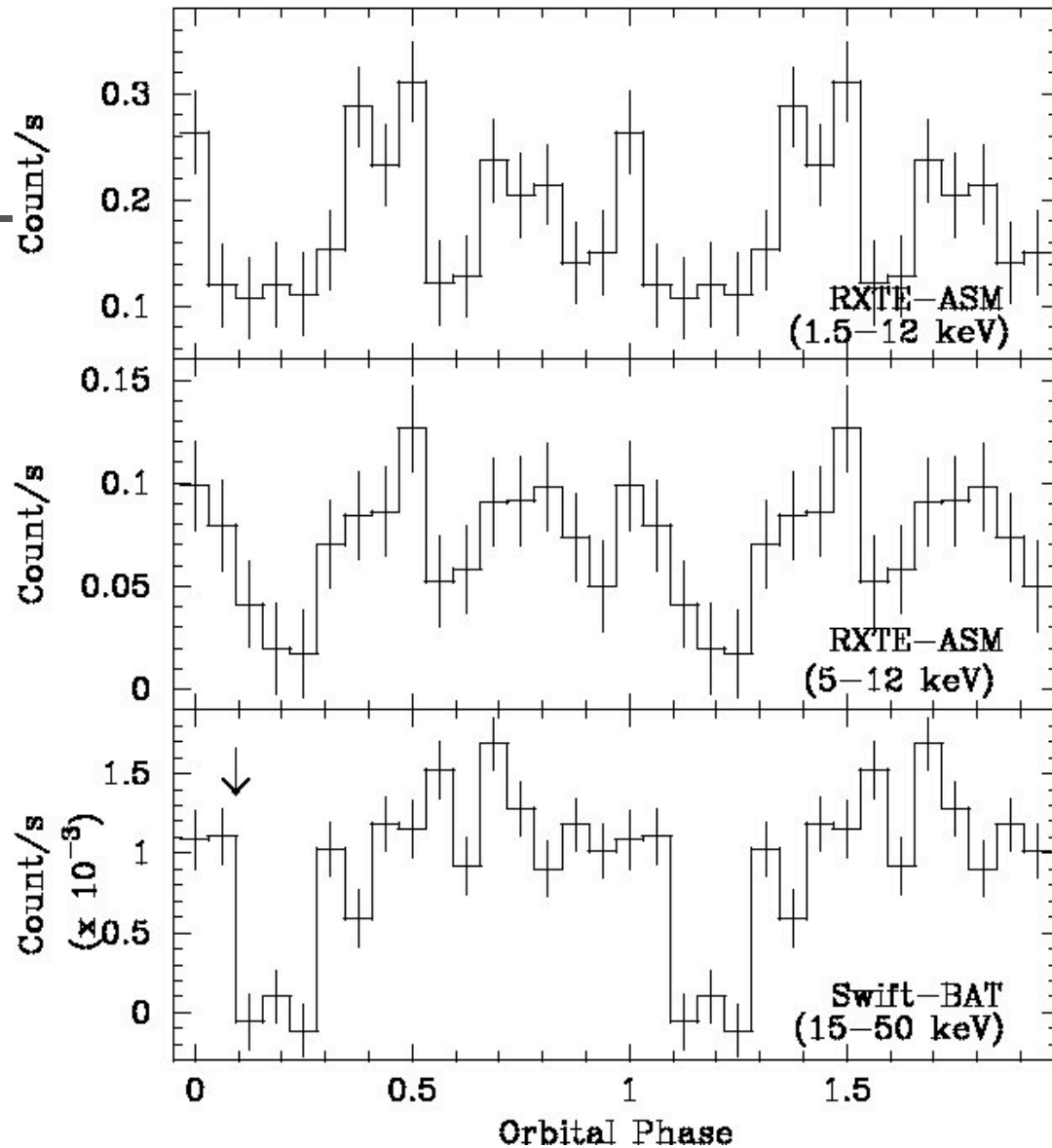
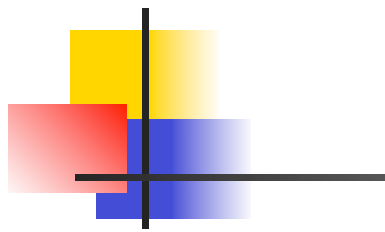
# *Supergiant Fast X-ray Transient: IGR J16479-4514*



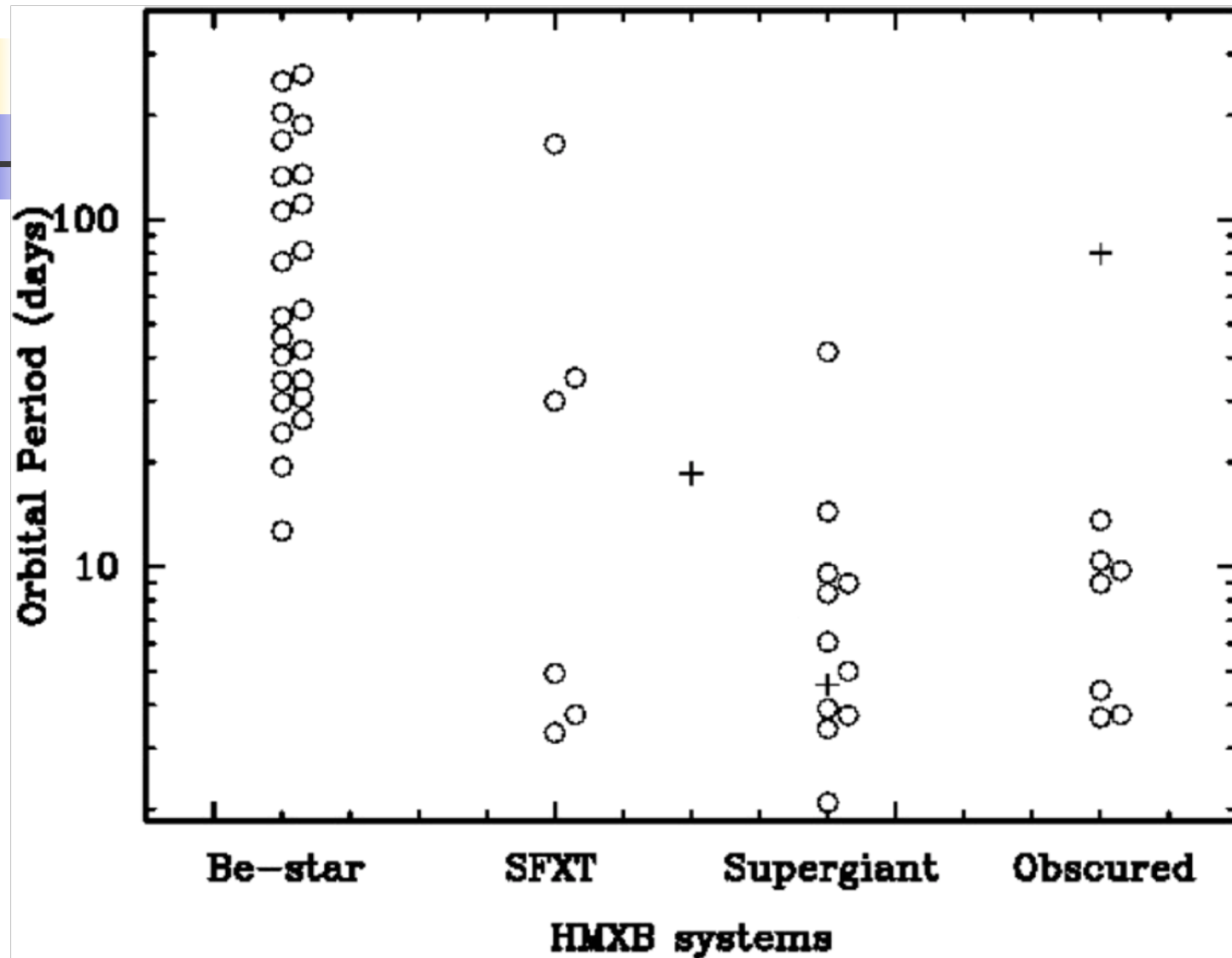
# *Supergiant Fast X-ray Transient: IGR J16479-4514*



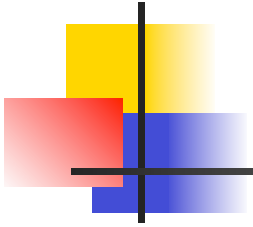
# Supergiant Fast X-ray Transient: IGR J16479-4514



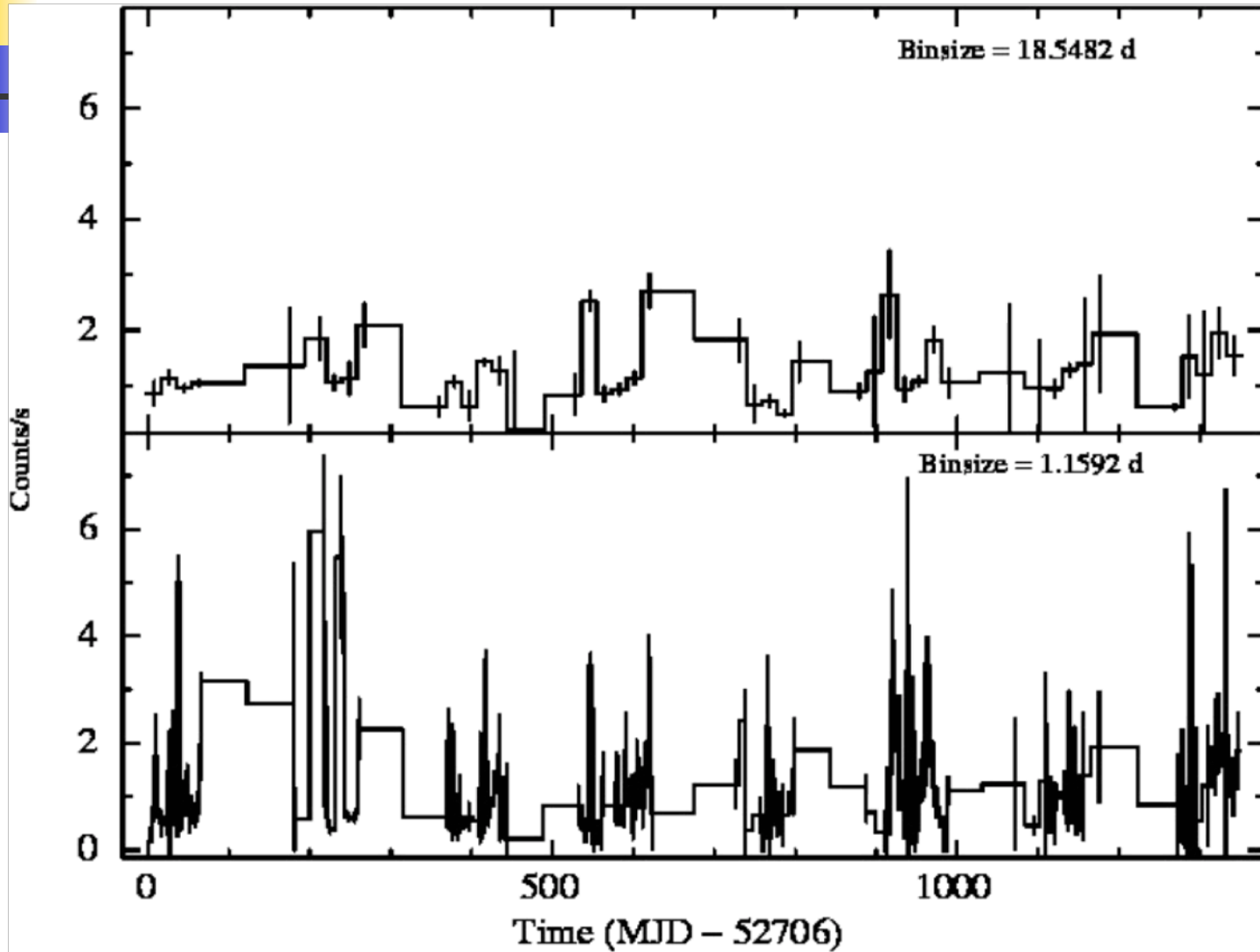
# Long term variability in HMXBs



# *Orbital phase locked flares*



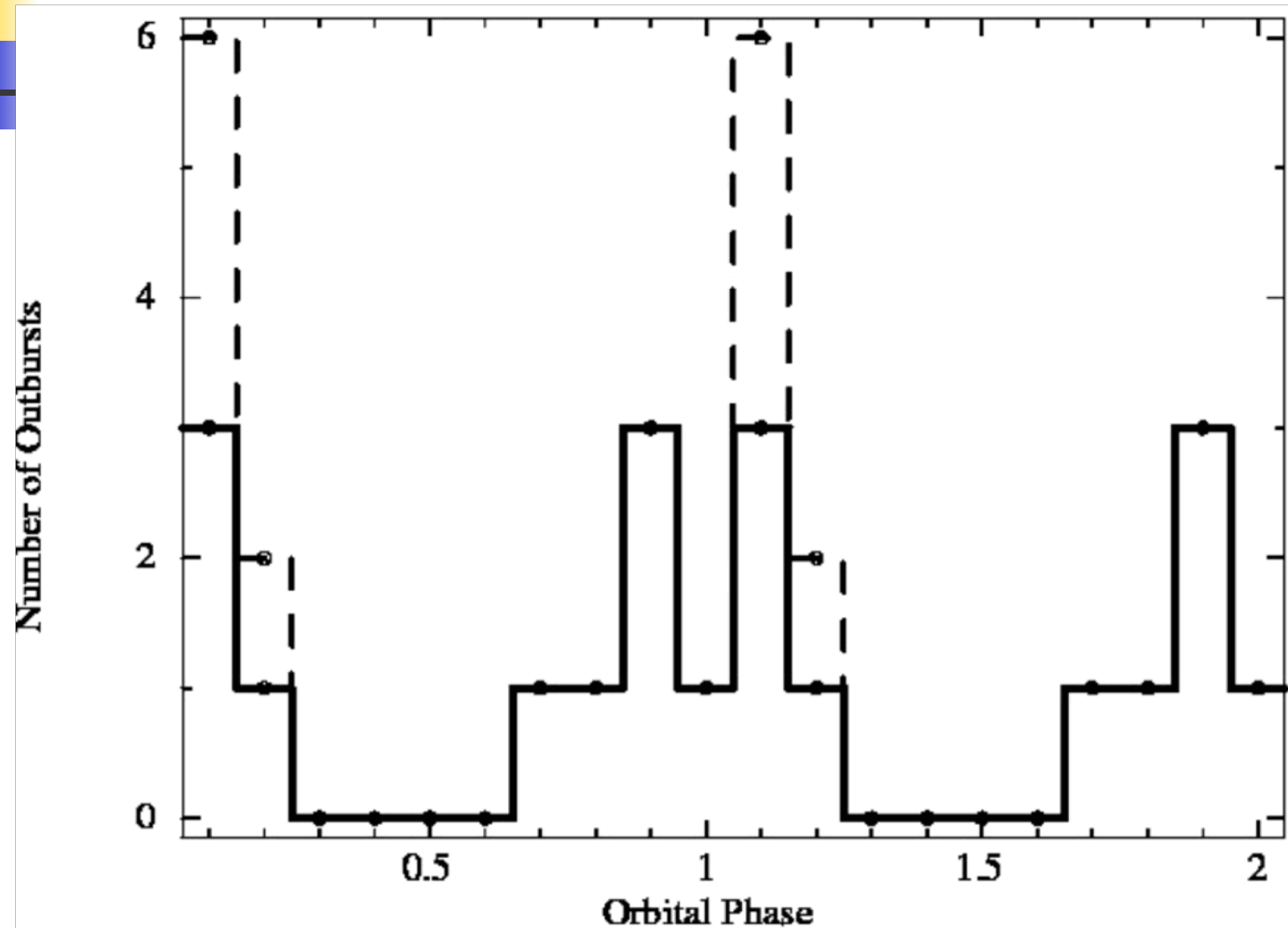
# *Orbital phase locked flares*



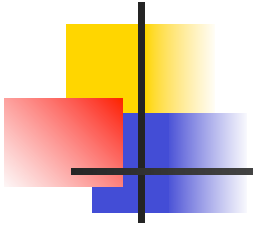
# *Orbital phase locked flares*



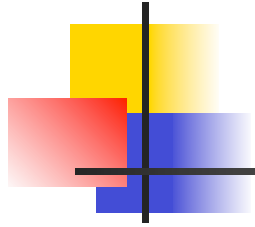
# *Orbital phase locked flares*



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# *Orbital phase locked flares*



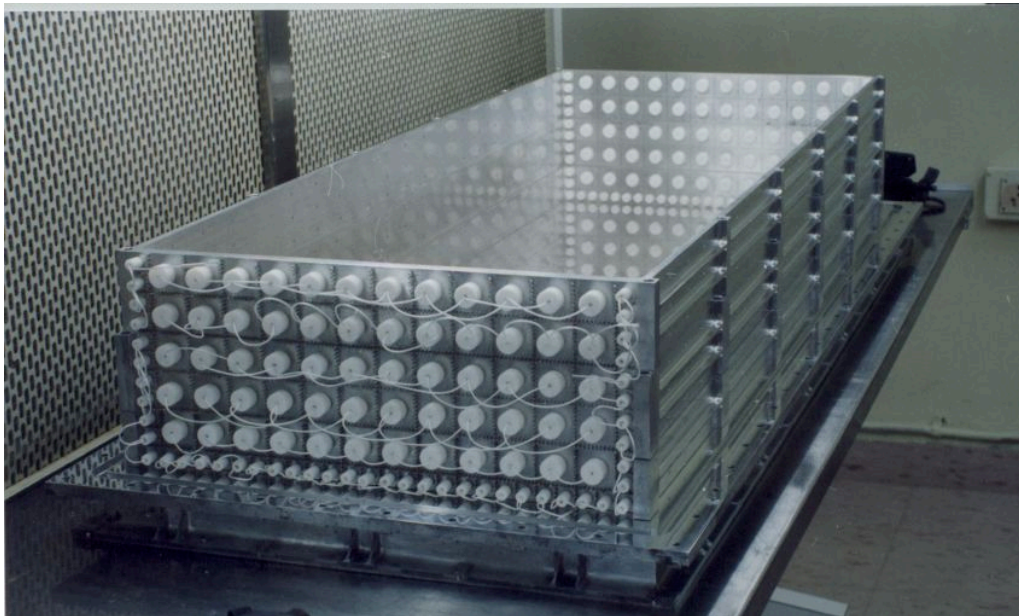
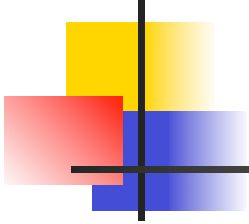
*IGR J18027-2016*

*IGR J18483-0311*

*IGR J16318-4848*

*Jain et al. 2010*

# *X-ray Polarimeter*



*ASTROSAT LAXPC*

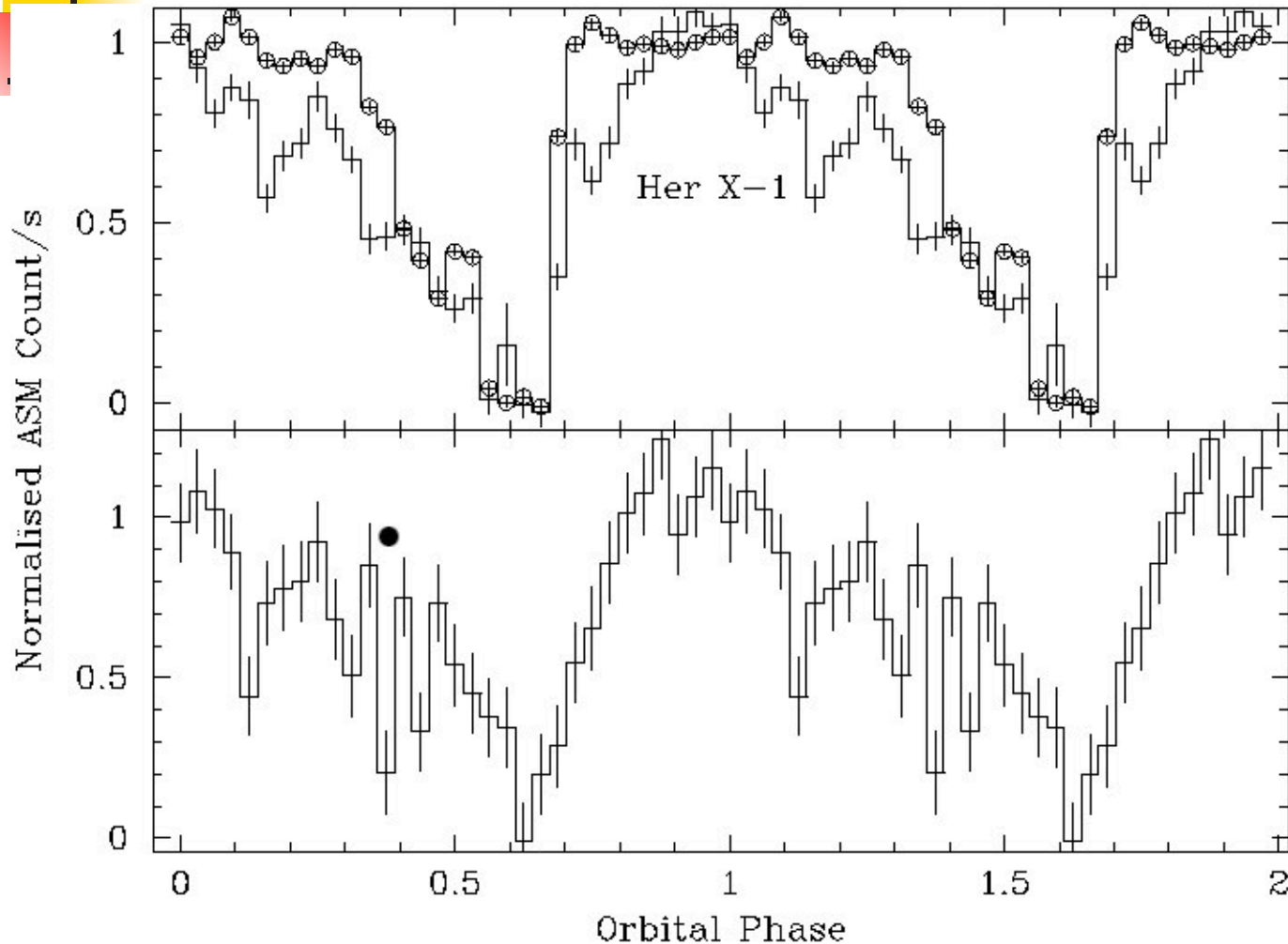
*Long term intensity variations in Cen X-3  
and the orbital modulation*



*Long term intensity variations in Cen X-3  
and the orbital modulation*



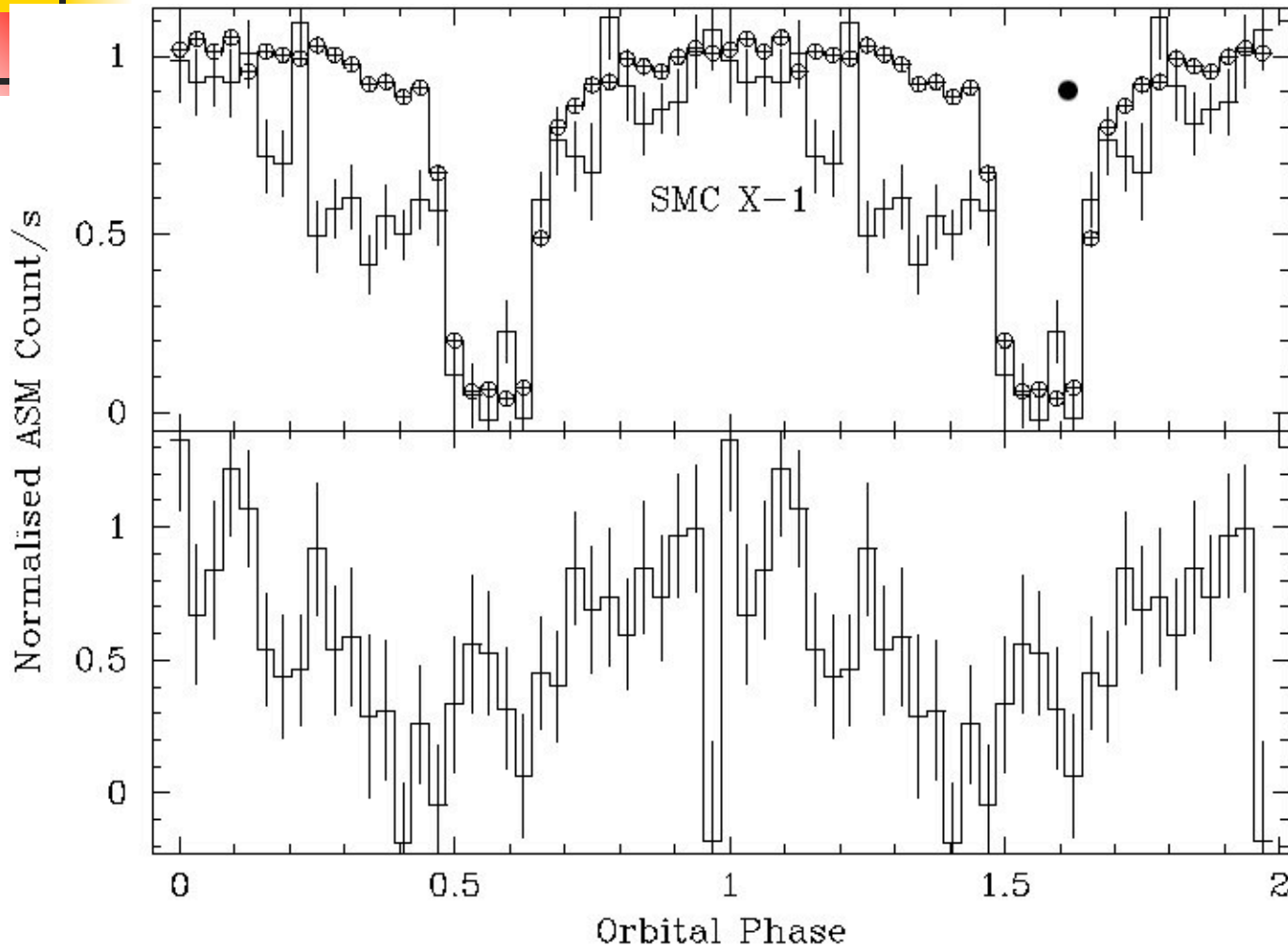
# Long term intensity variations in Cen X-3 and the orbital modulation



*Long term intensity variations in Cen X-3  
and the orbital modulation*



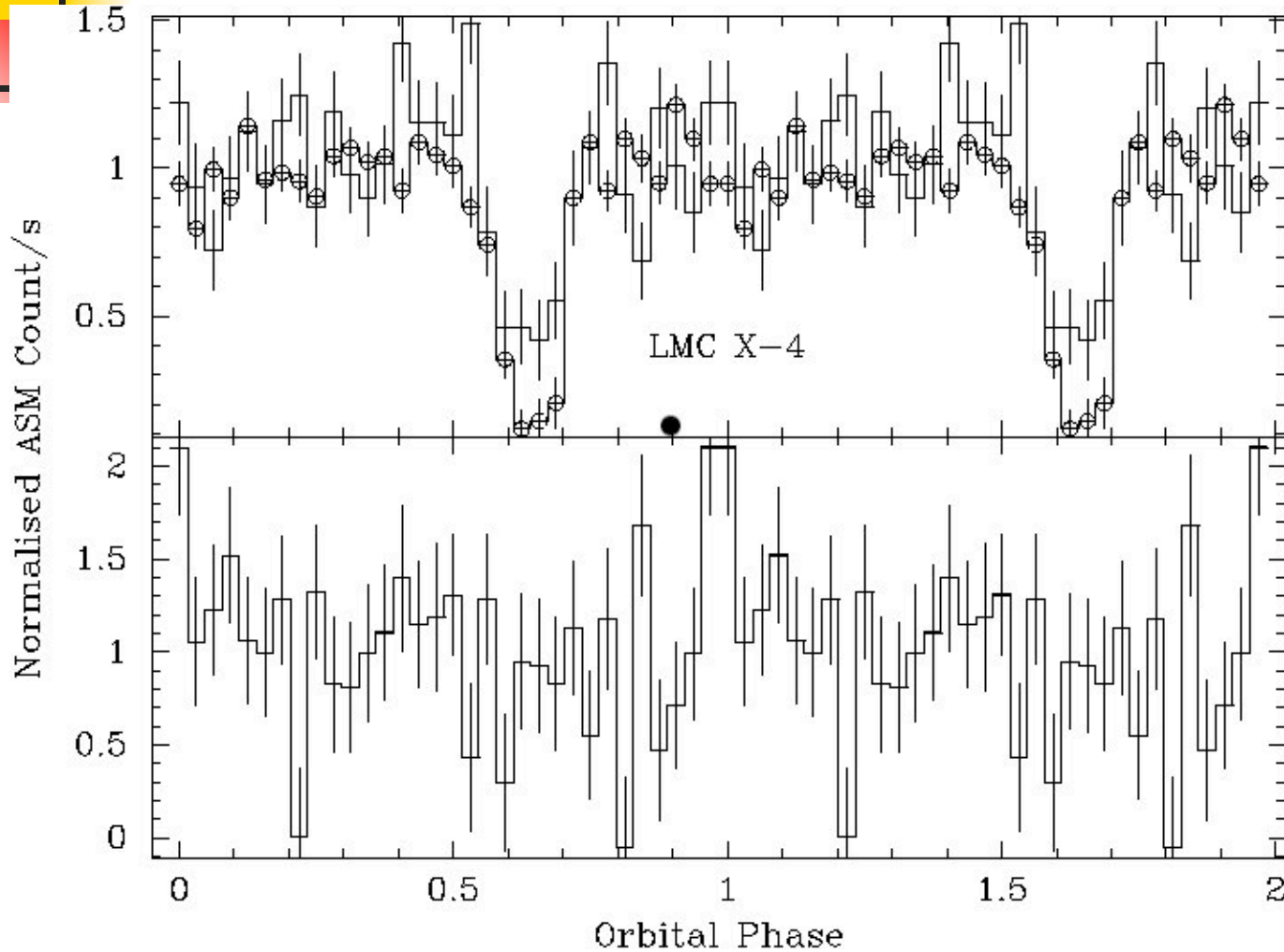
# Long term intensity variations in Cen X-3 and the orbital modulation



*Long term intensity variations in Cen X-3  
and the orbital modulation*



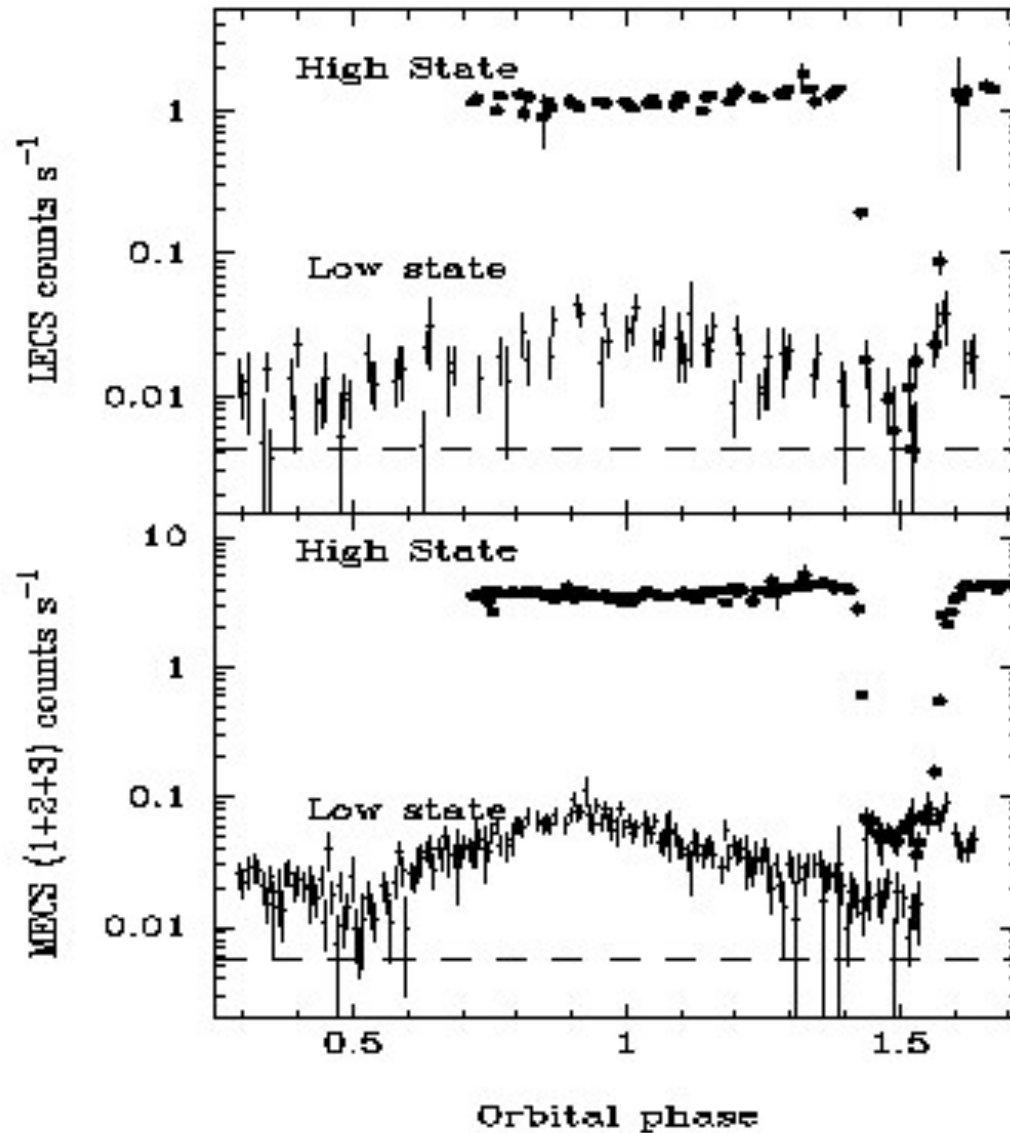
# Long term intensity variations in Cen X-3 and the orbital modulation



*Long term intensity variations in Cen X-3  
and the orbital modulation*



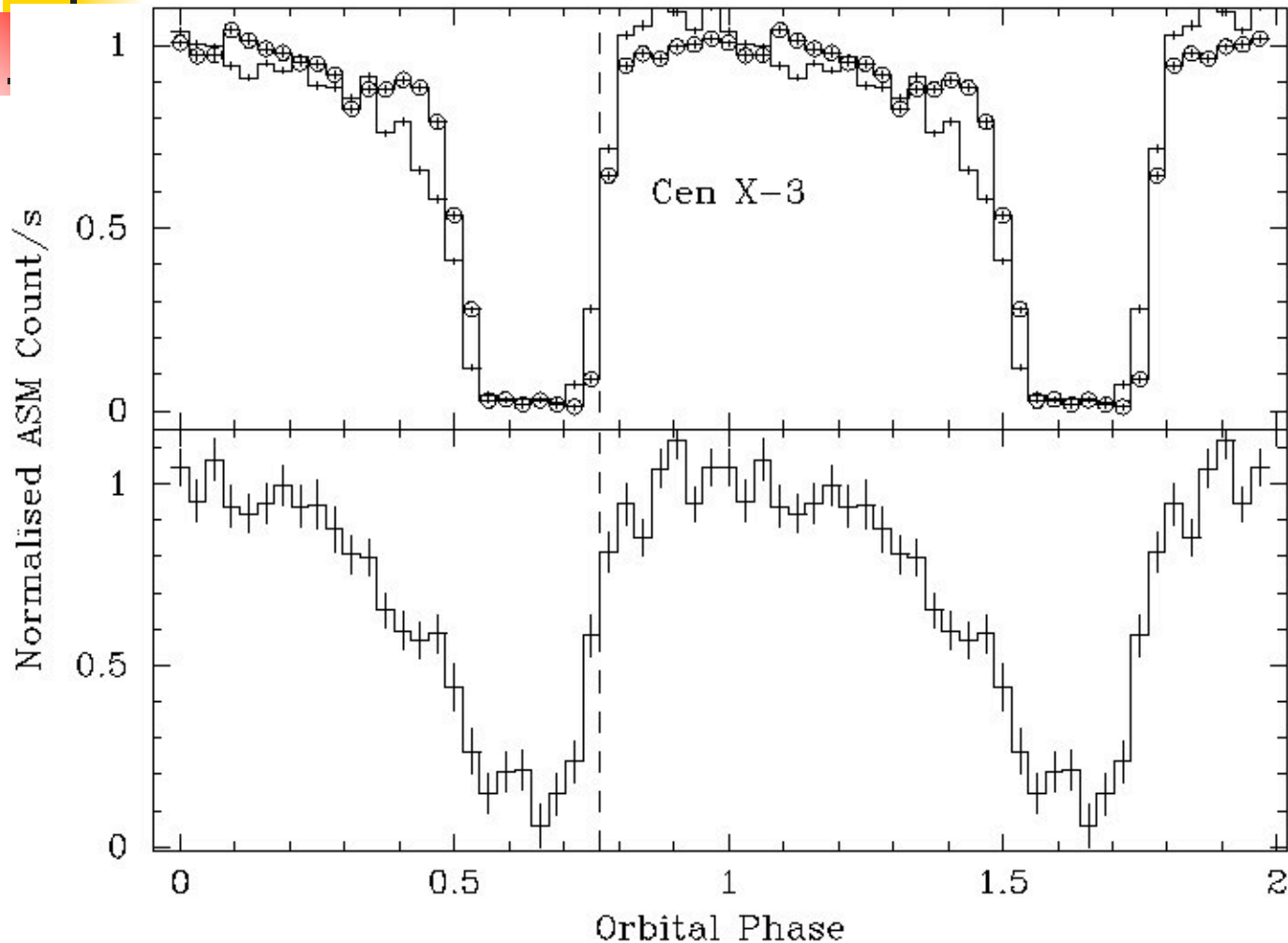
# Long term intensity variations in Cen X-3 and



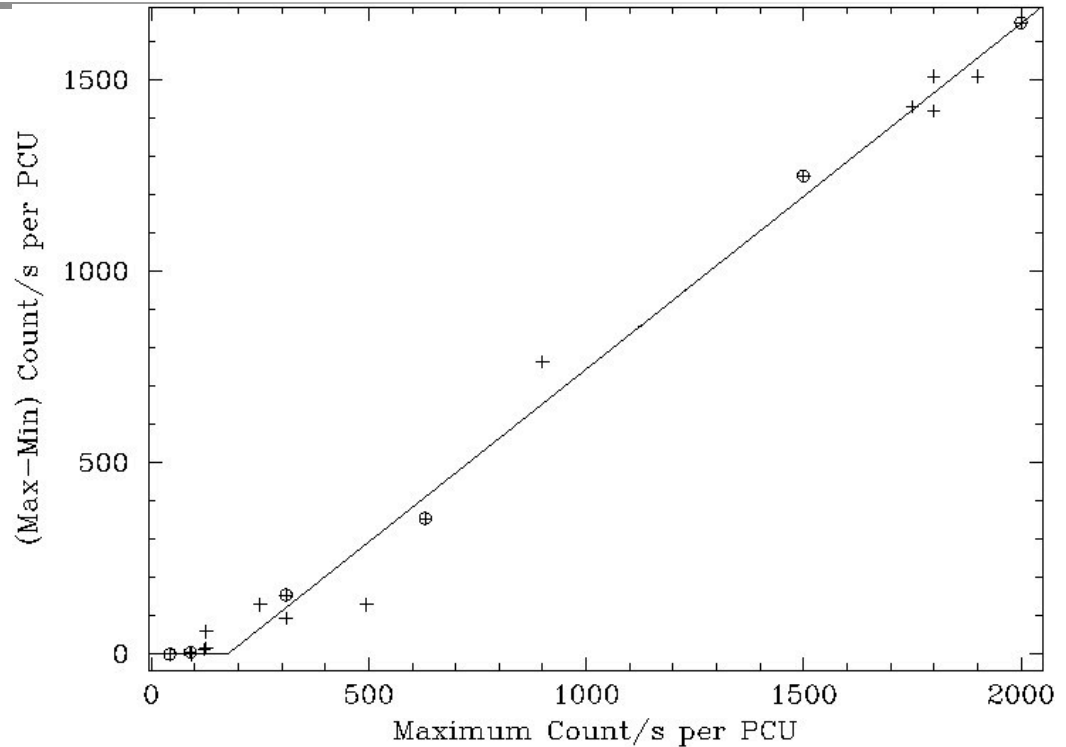
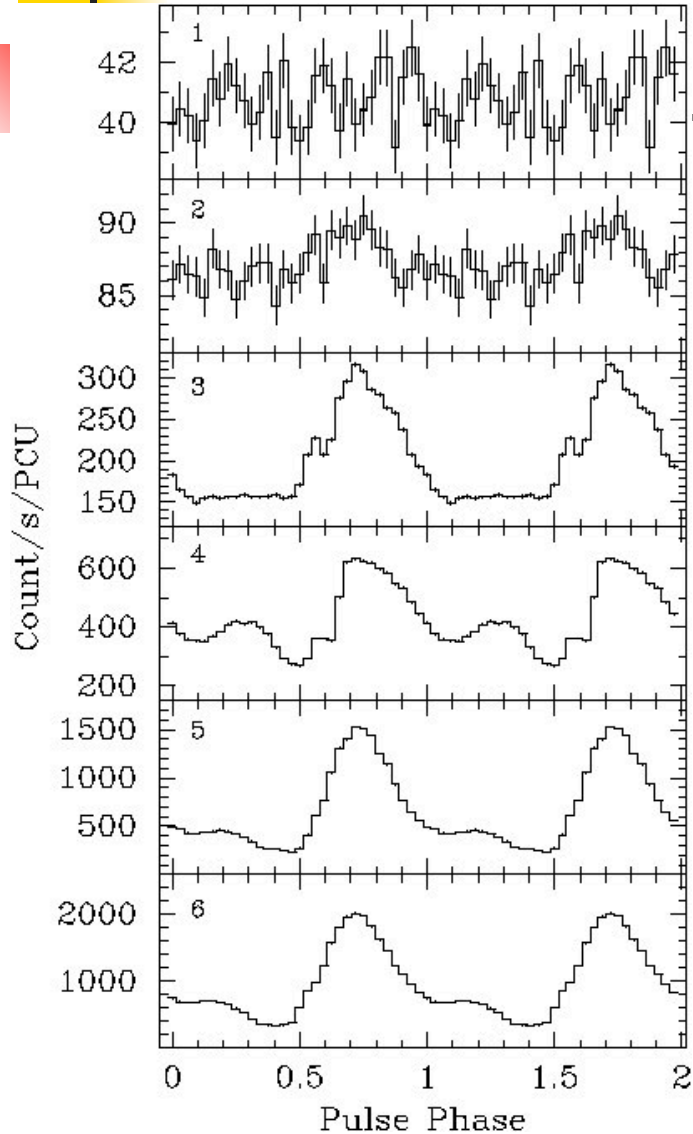
*Long term intensity variations in Cen X-3  
and the orbital modulation*



# Long term intensity variations in Cen X-3 and the orbital modulation



# Gen X-3: Intensity dependence of the pulsed fraction

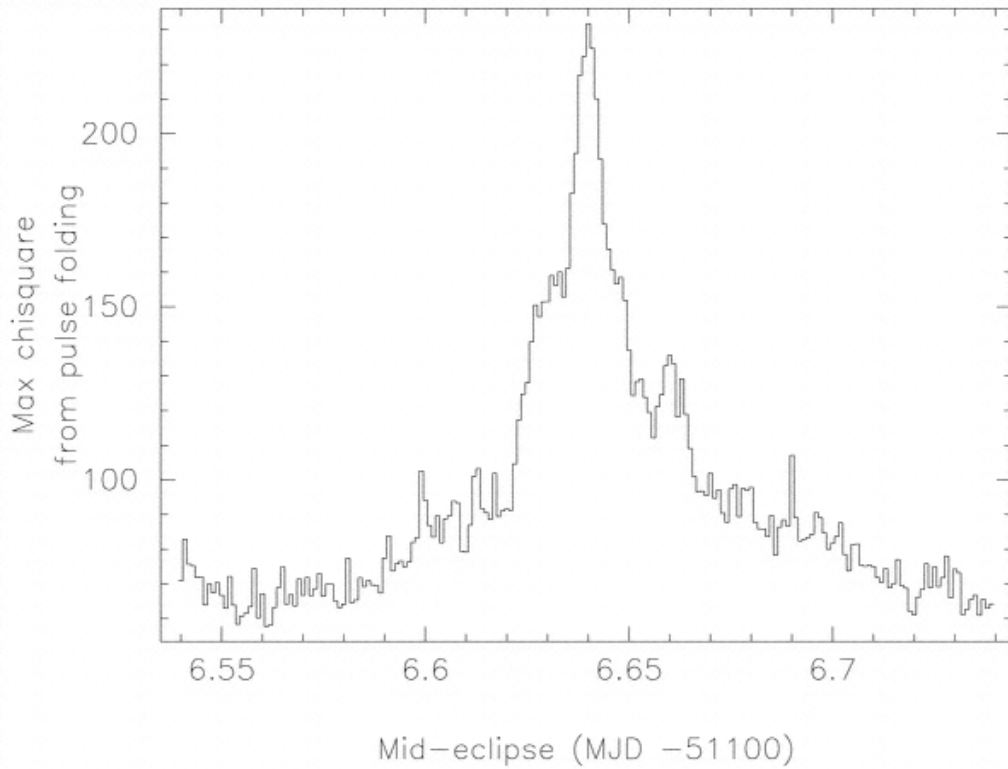




# *Orbital Evolution of HMXB Pulsars*

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# *Orbital Evolution of HMXB Pulsars*

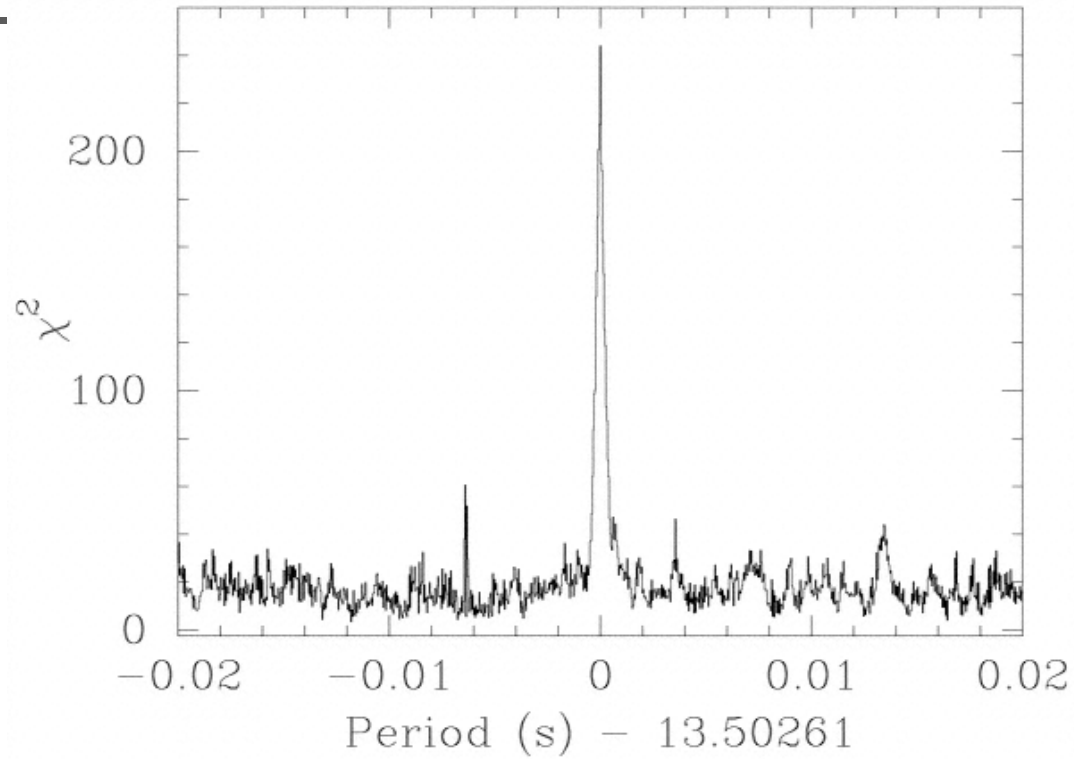




# *Orbital Evolution of HMXB Pulsars*

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# *Orbital Evolution of HMXB Pulsars*

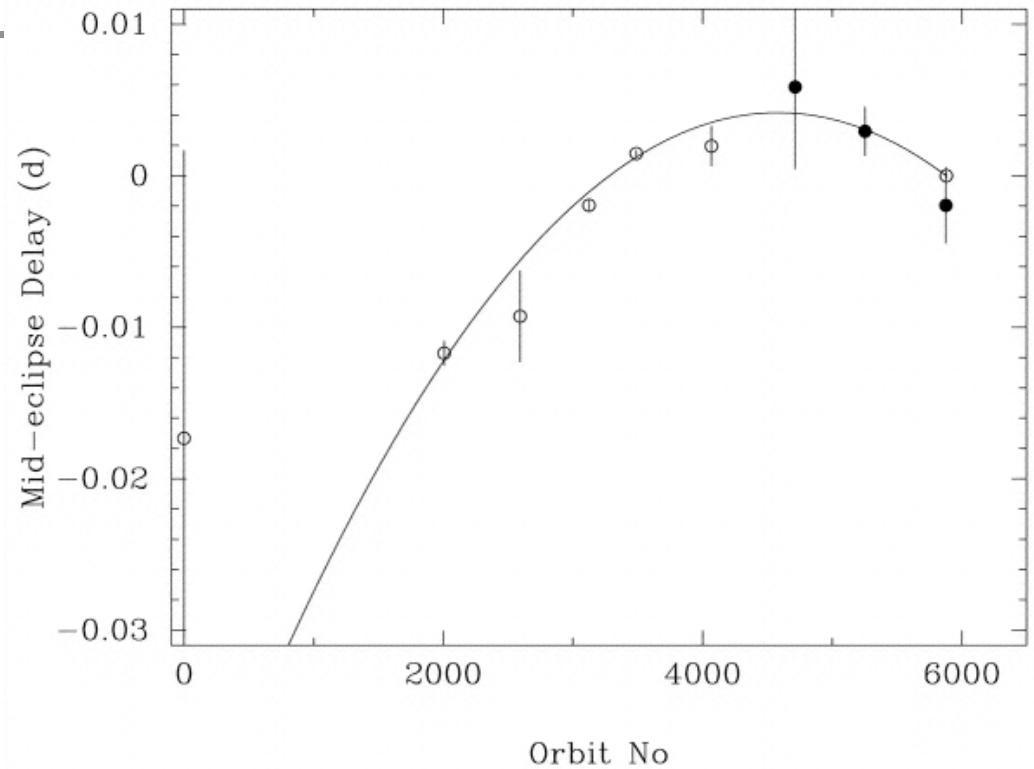




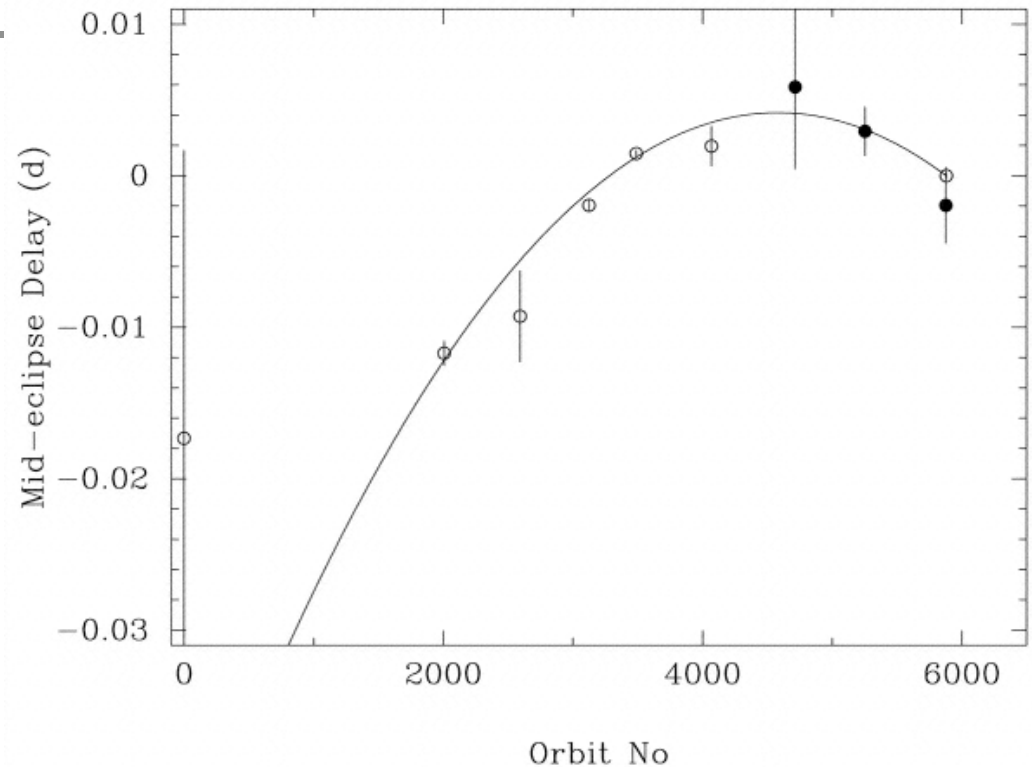
# *Orbital Evolution of HMXB Pulsars*

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# *Orbital Evolution of HMXB Pulsars*



# Orbital Evolution of HMXB Pulsars



*LMC X-4*

*Evolution time scale :  $10^6$  yrs*

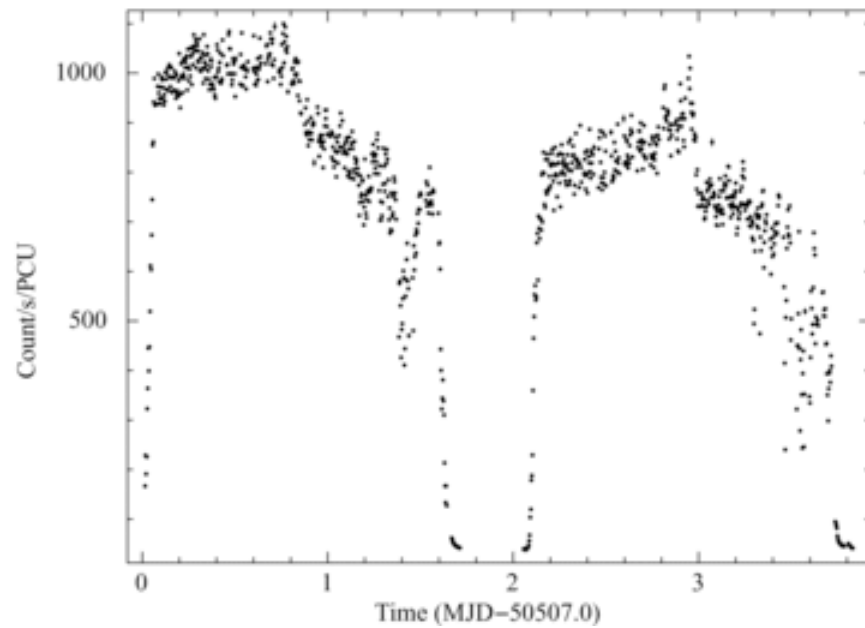
*Paul et al. 2002, Naik and Paul 2004a*



*Orbital Evolution of HMXB Pulsars: Cen X-3*

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# *Orbital Evolution of HMXB Pulsars: Cen X-3*

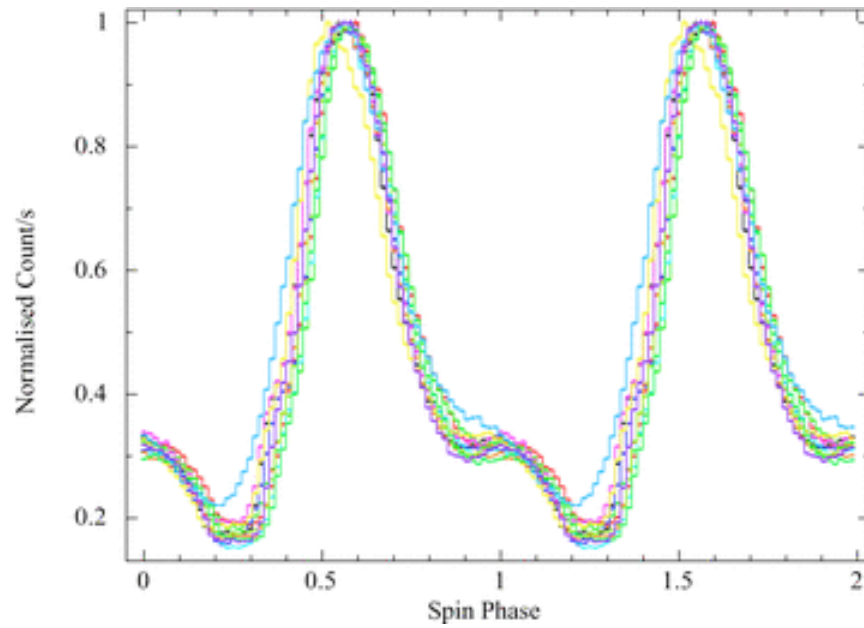




*Orbital Evolution of HMXB Pulsars: Cen X-3*

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# *Orbital Evolution of HMXB Pulsars: Cen X-3*

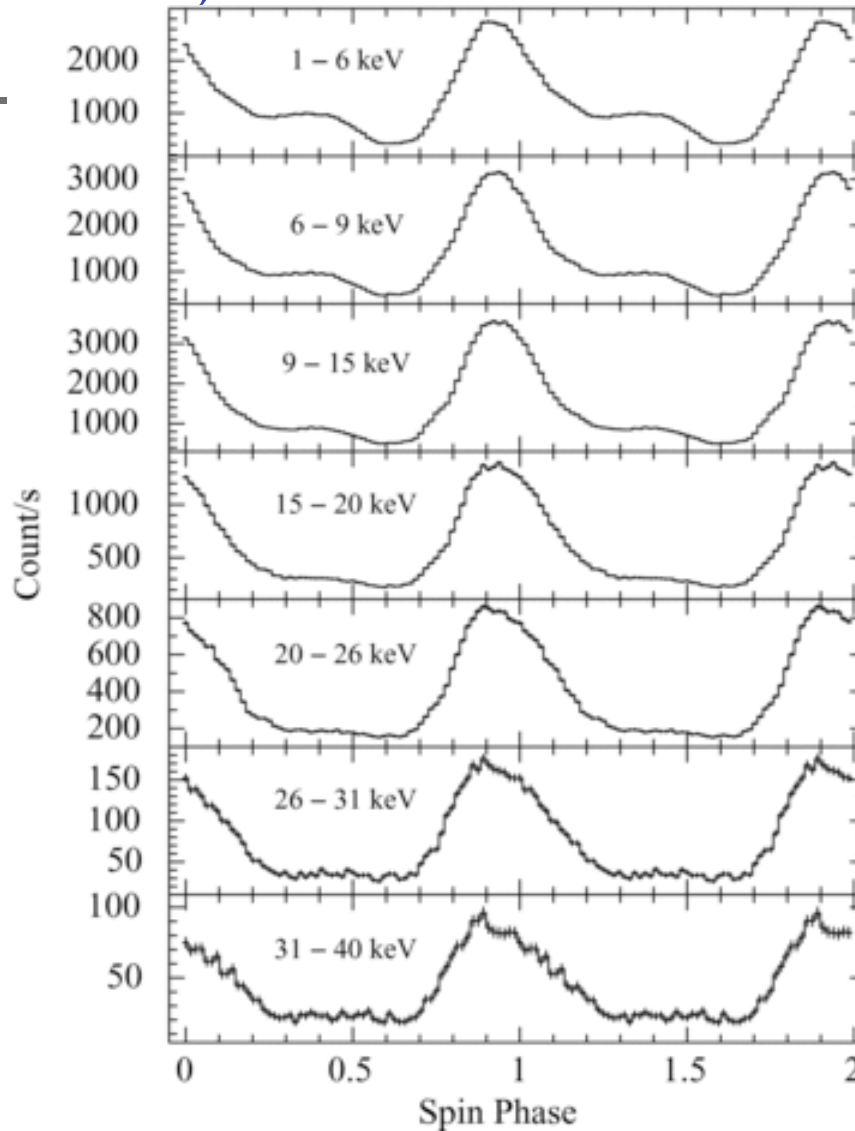




*Orbital Evolution of HMXB Pulsars: Cen X-3*

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# *Orbital Evolution of HMXB Pulsars: Cen X-3*

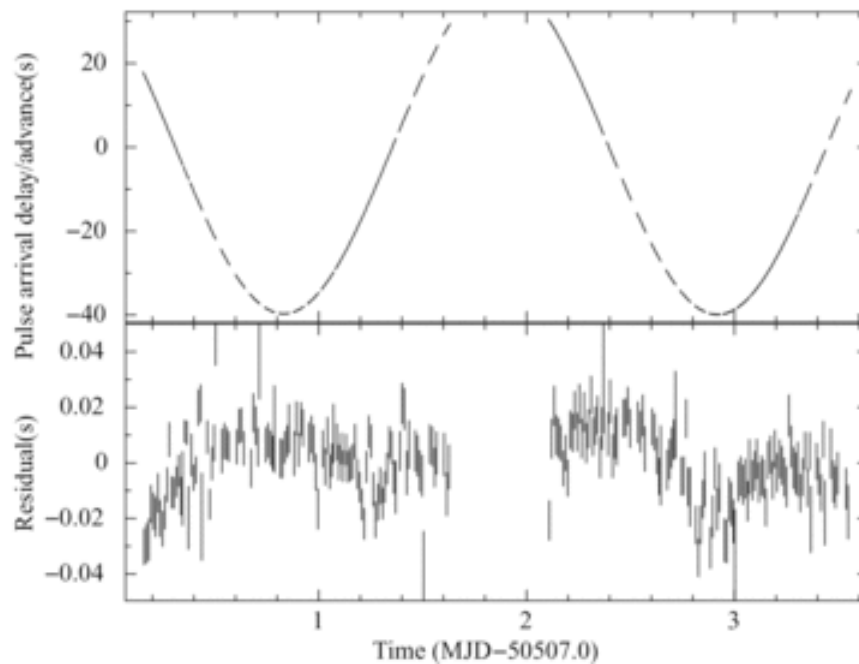




*Orbital Evolution of HMXB Pulsars: Cen X-3*

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# *Orbital Evolution of HMXB Pulsars: Cen X-3*

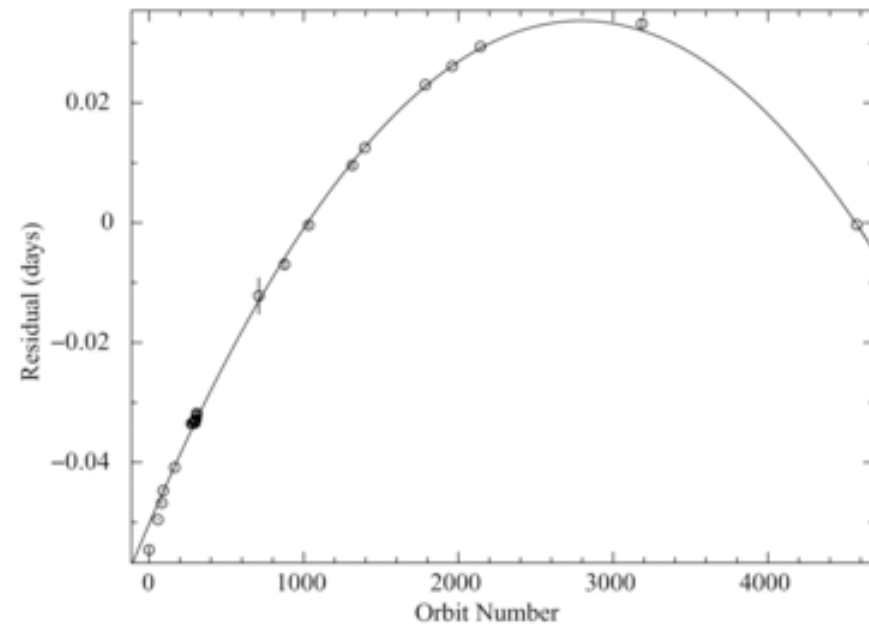




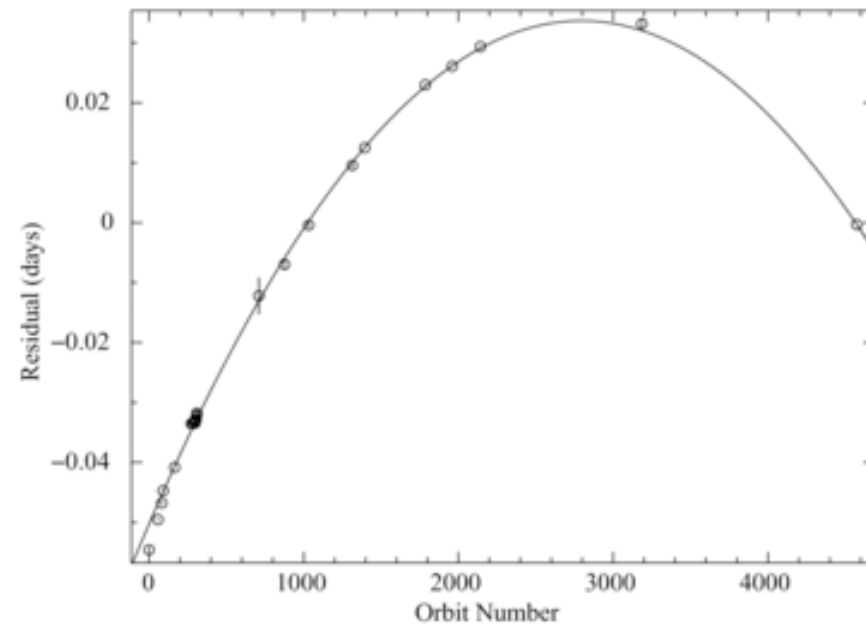
*Orbital Evolution of HMXB Pulsars: Cen X-3*

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## *Orbital Evolution of HMXB Pulsars: Cen X-3*



## *Orbital Evolution of HMXB Pulsars: Cen X-3*



*Cen X-3:*

*Evolution time scale :  $2.210^5$  yrs*

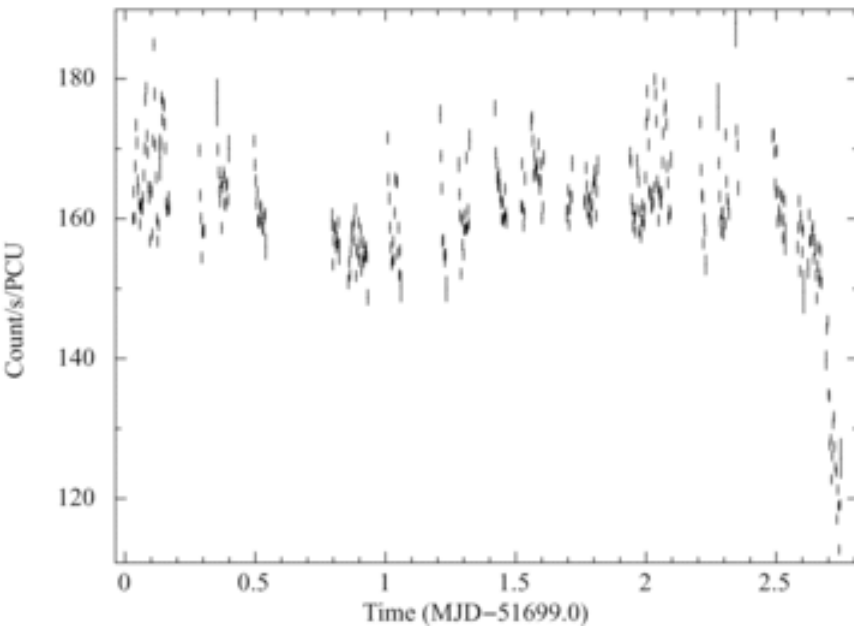
*Raichur and Paul 2010a*



*Orbital Evolution of HMXB Pulsars: SMC X-1*

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# *Orbital Evolution of HMXB Pulsars: SMC X-1*

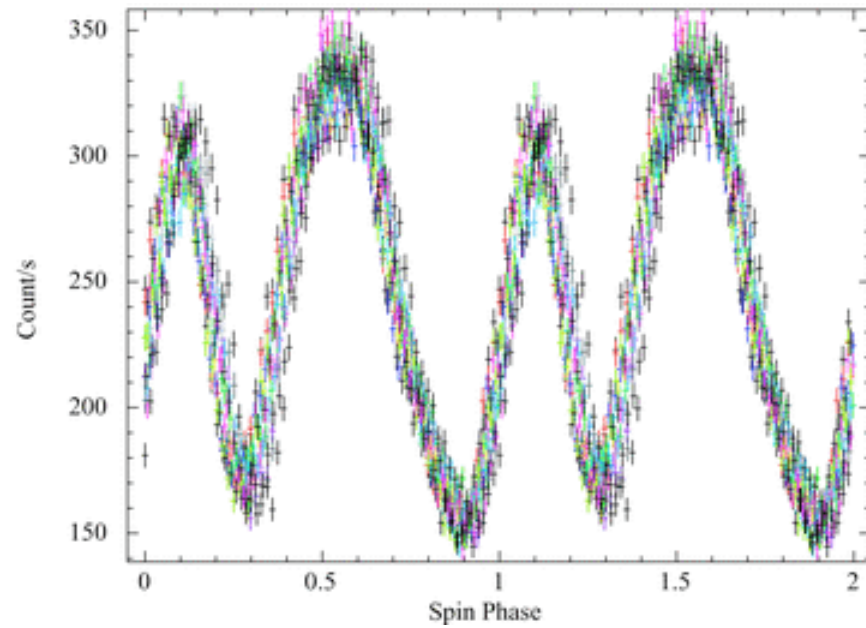




*Orbital Evolution of HMXB Pulsars: SMC X-1*

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# *Orbital Evolution of HMXB Pulsars: SMC X-1*

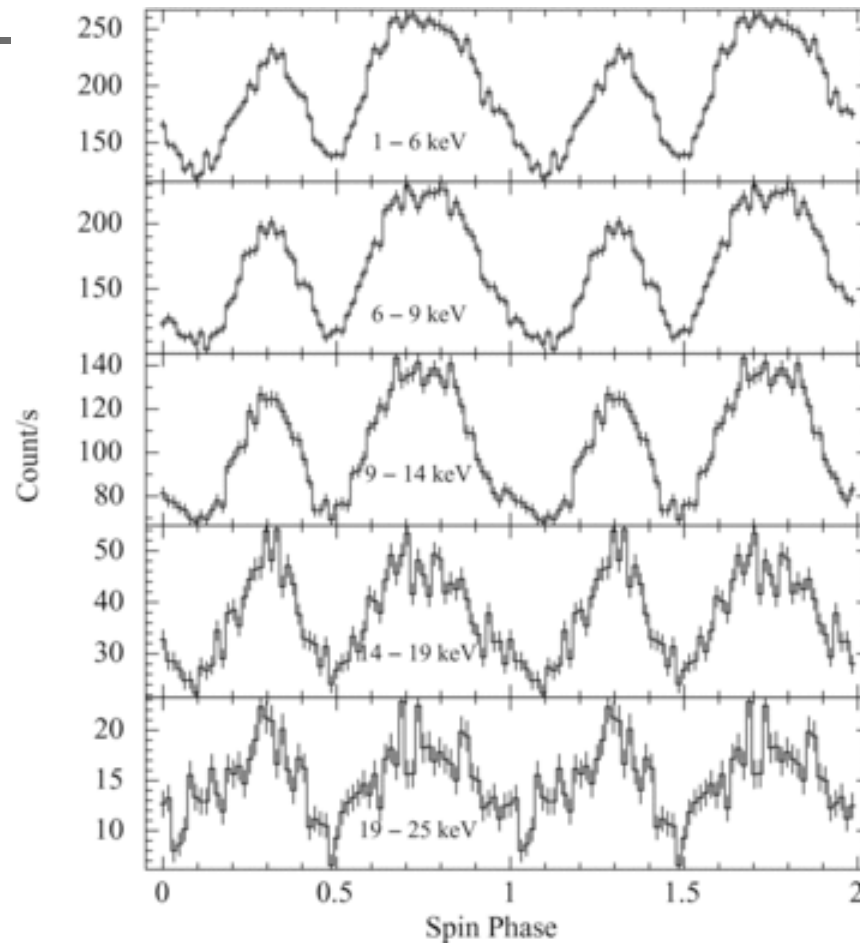




*Orbital Evolution of HMXB Pulsars: SMC X-1*

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# *Orbital Evolution of HMXB Pulsars: SMC X-1*

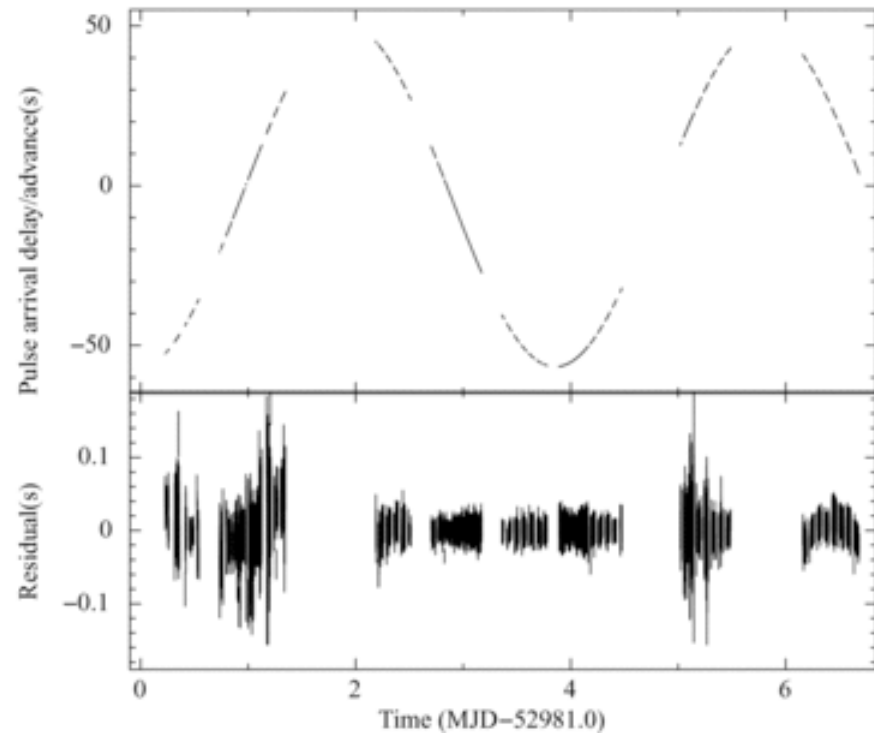




*Orbital Evolution of HMXB Pulsars: SMC X-1*

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# Orbital Evolution of HMXB Pulsars: SMC X-1

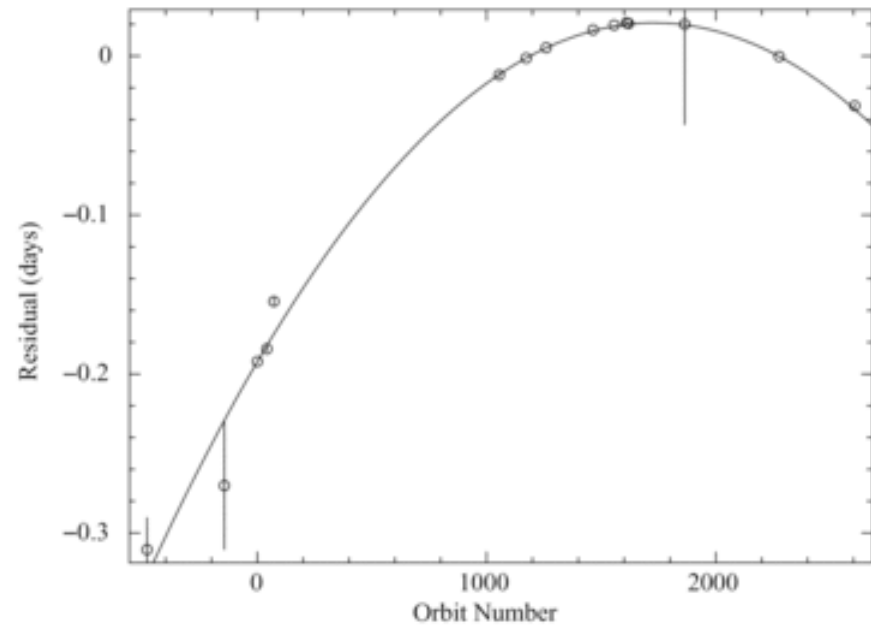




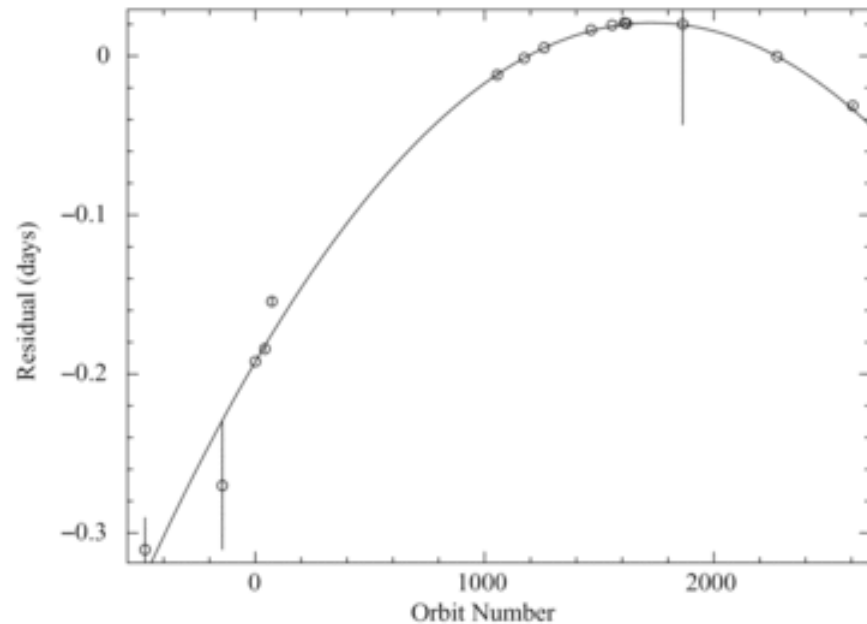
*Orbital Evolution of HMXB Pulsars: SMC X-1*

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# Orbital Evolution of HMXB Pulsars: *SMC X-1*



# Orbital Evolution of HMXB Pulsars: SMC X-1



*SMC X-1*

*Evolution time scale :  $3 \cdot 10^5$  yrs*

*$E = 0.00021 \pm 0.00001$*

*Paul et al. 2002, Raichur and Paul 2010a*

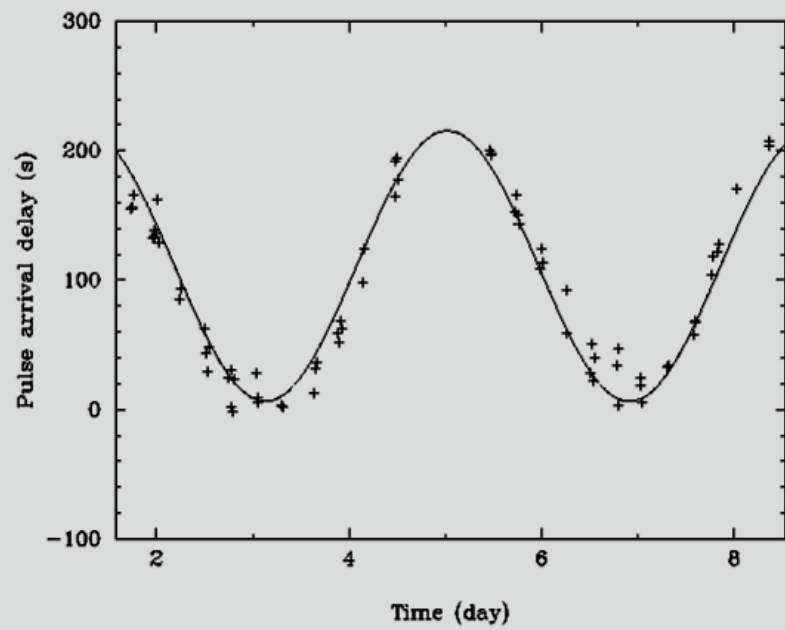


*4U 1538-52*

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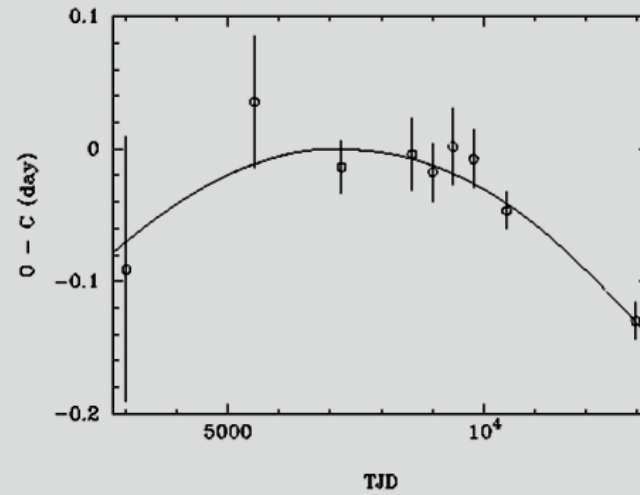
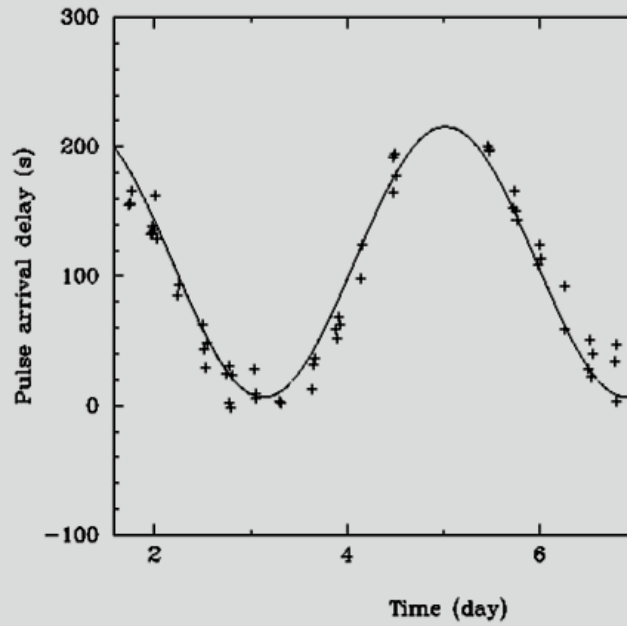
19 1500 50

4U 1538-52 (RXTE-PCA 2003)



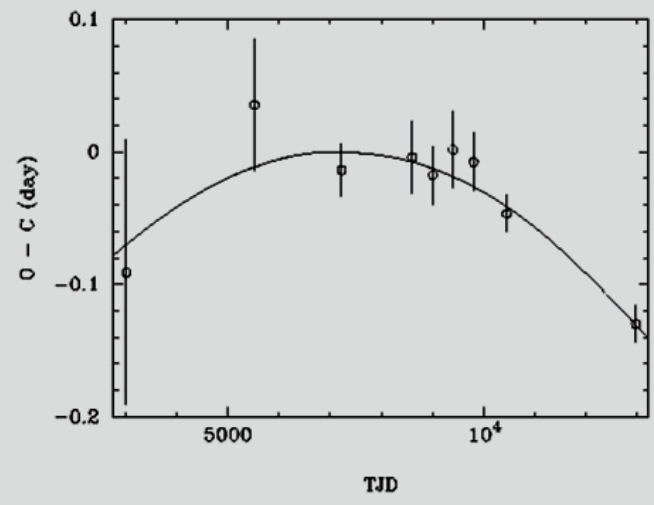
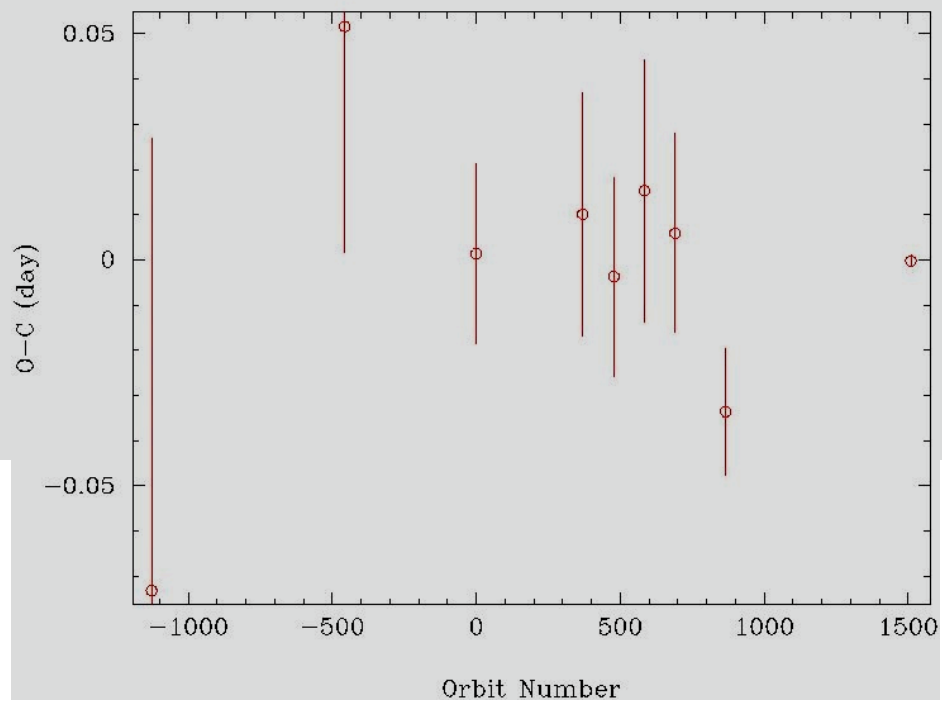
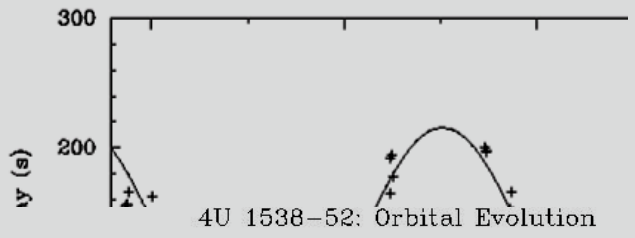
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4U 1538-52 (RXTE-PCA 2003)



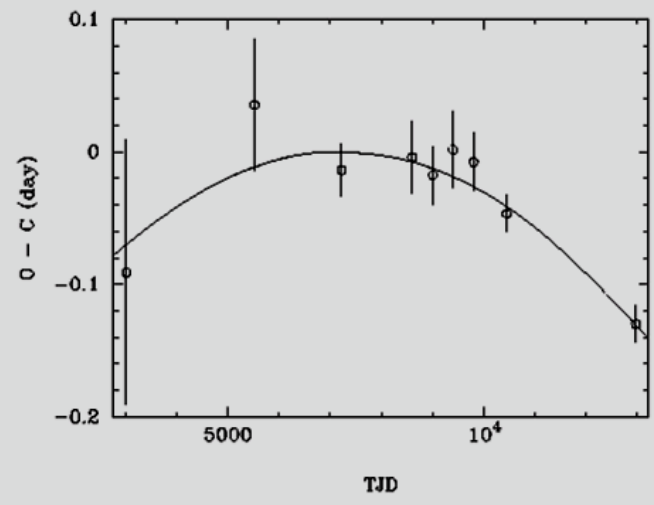
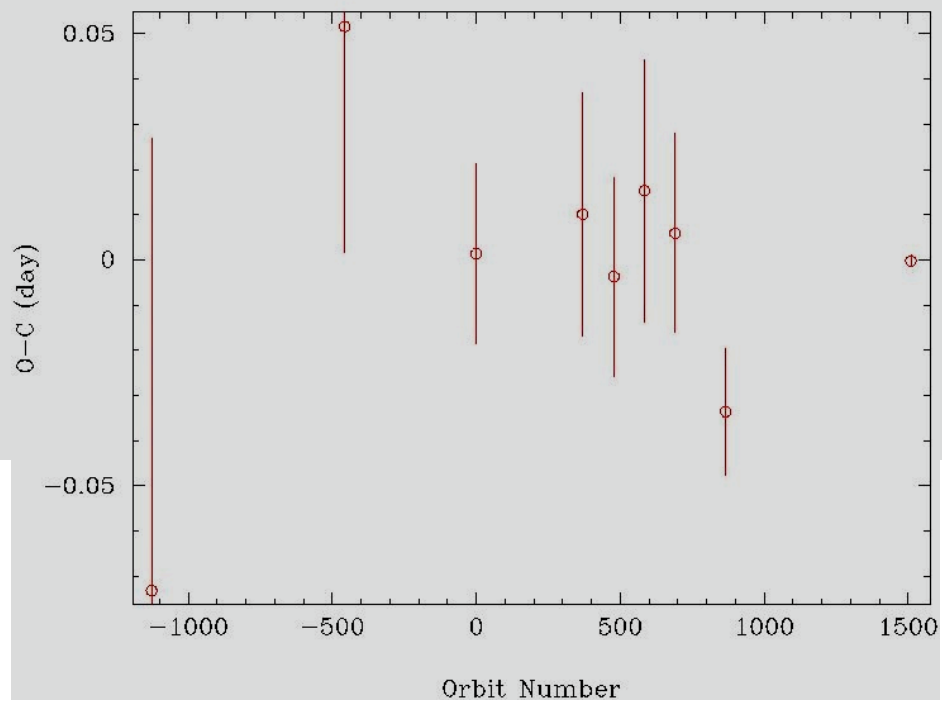
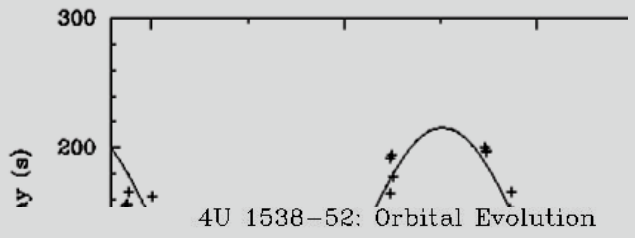
19 1500 50

4U 1538-52 (RXTE-PCA 2003)



12 1500 50

4U 1538-52 (RXTE-PCA 2003)



*Raichur & Paul  
Mukherjee et al. 2007*