On the nature of 35-day cycle in Her X-1

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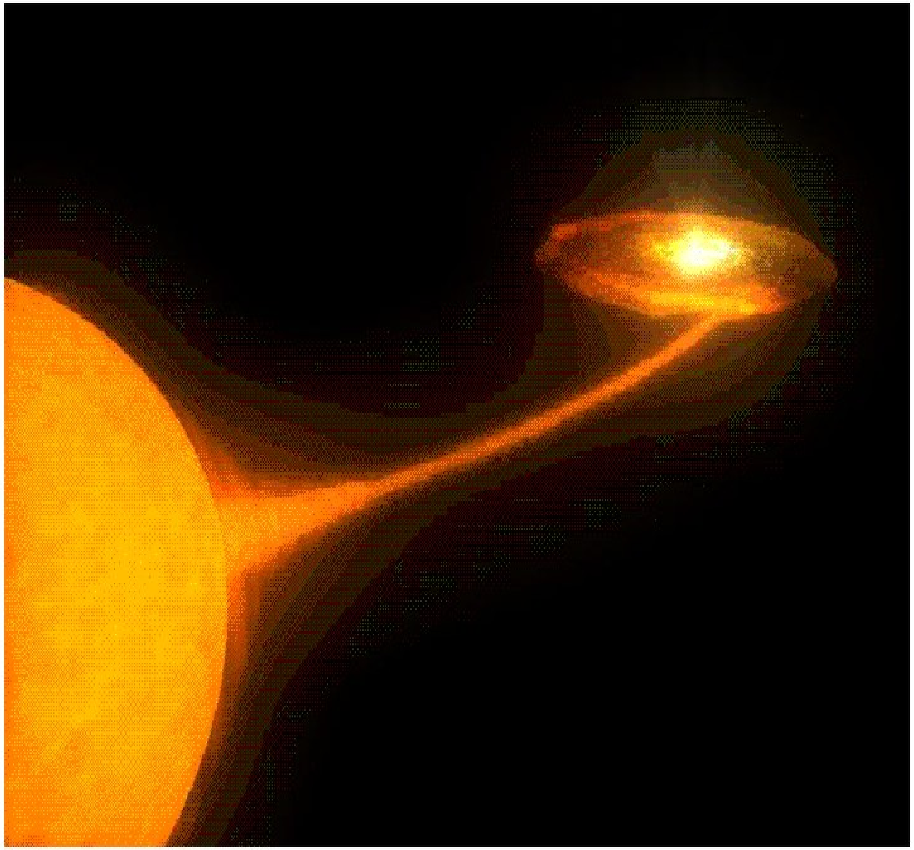
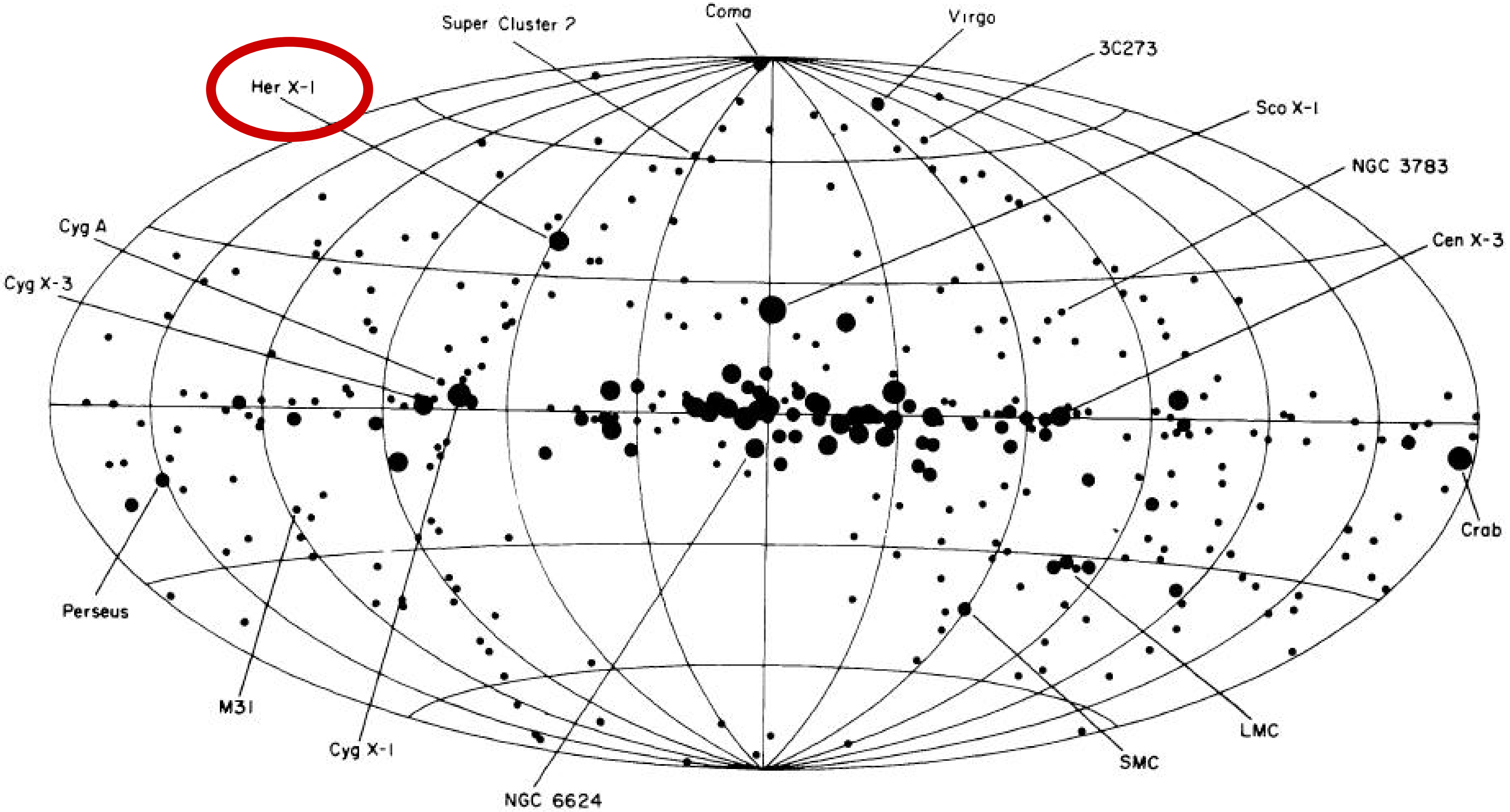
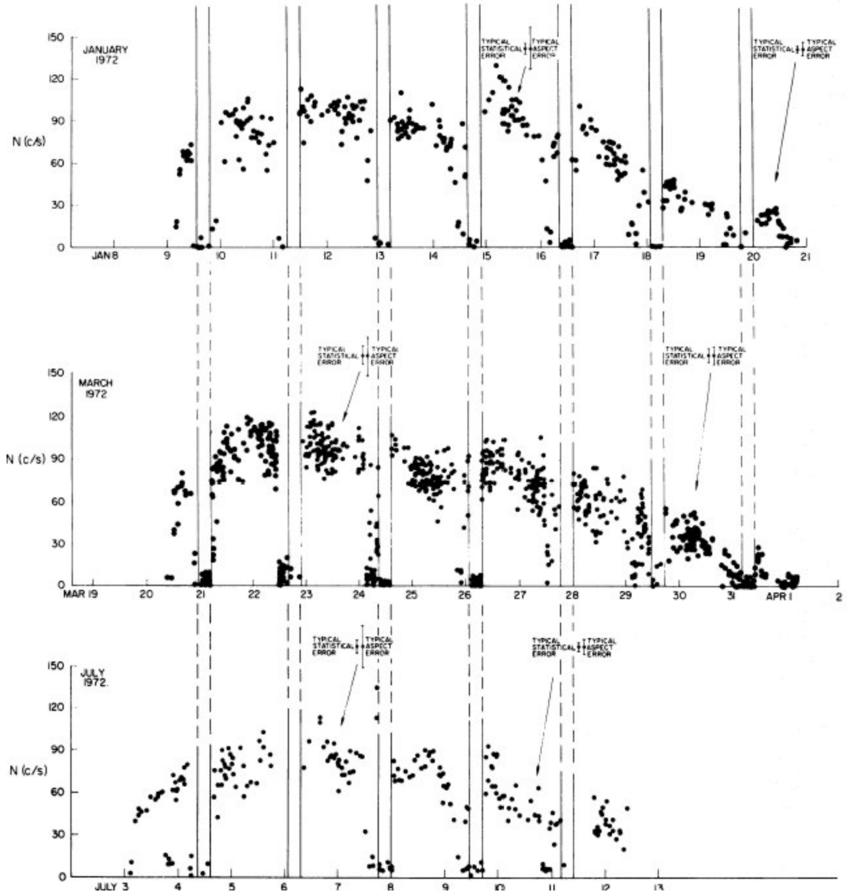
Outlook



- Introduction
- 35-day periodicity in Her X-1
- Neutron star free precession
- Clues from X-ray pulse profiles
- Locking with disk precession


Super Cluster ?
Coma
Virgo
3C273
Her X-1
Sco X-1
NGC 3783
Cyg A
Cen X-3
Cyg X-3
Crab
Perseus
M31
Cyg X-1
NGC 6624
SMC
LMC

UHURU discovery



- One of the first accreting X-ray binaries (P=1.24 s)
- Complex shape of light curve:
- Eclipses (orbital period 1.7 d)
- Dips (post-eclipse recoveries, anomalous dips)
- Long-term variability (35-day cycle)
- Turn-ons at ~0.25 and ~0.75 orbital phases

From Giacconi et al. 1973

Later observations

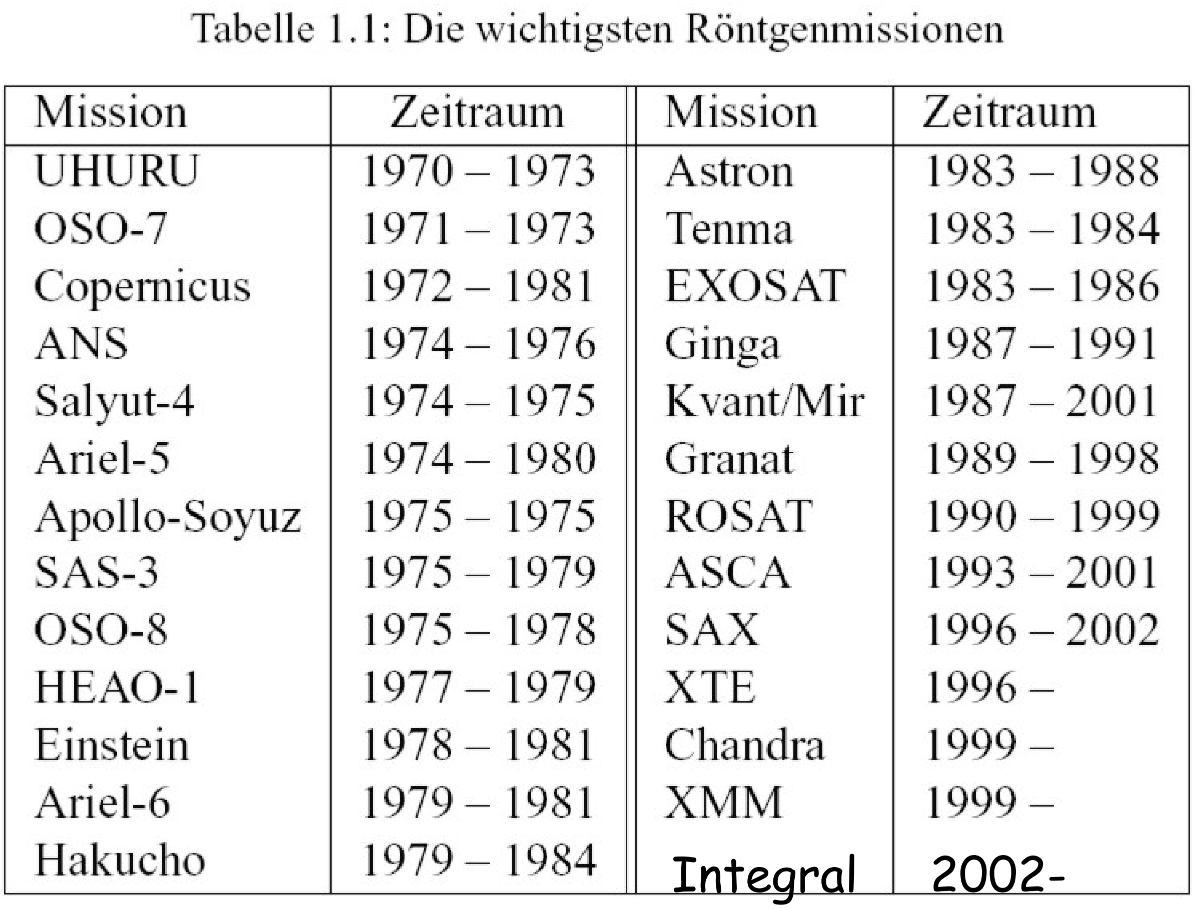
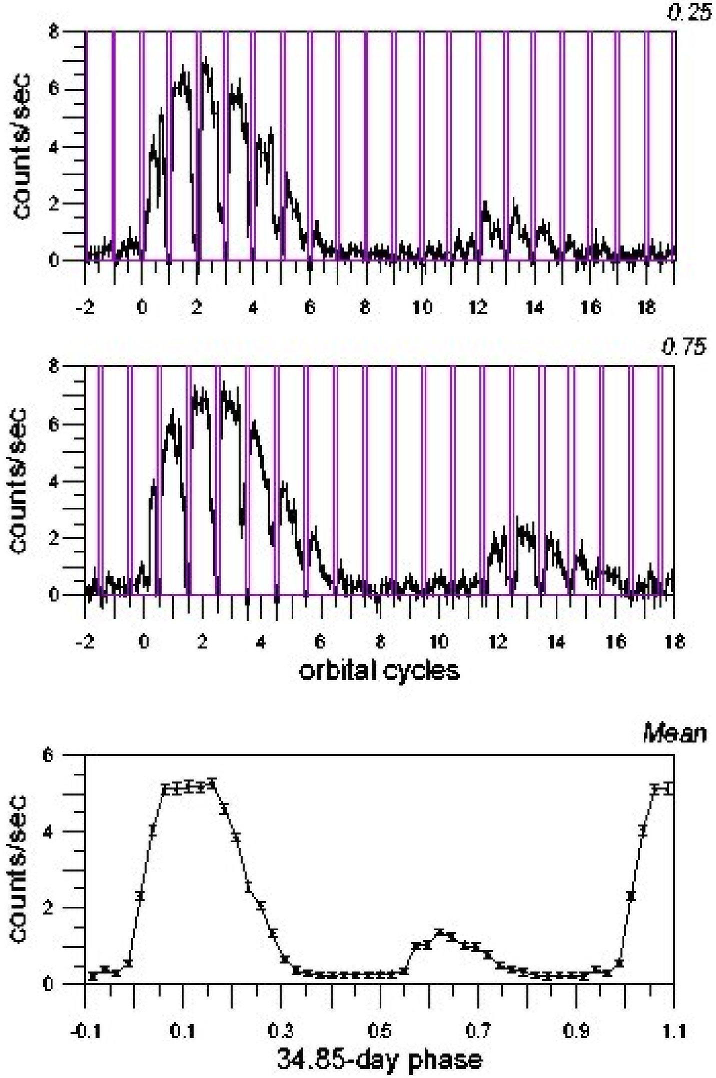


Tabelle 1.1: Die wichtigsten Röntgenmissionen

Mission	Zeitraum	Mission	Zeitraum
UHURU	1970 – 1973	Astron	1983 – 1988
OSO-7	1971 – 1973	Tenma	1983 – 1984
Copernicus	1972 – 1981	EXOSAT	1983 – 1986
ANS	1974 – 1976	Ginga	1987 – 1991
Salyut-4	1974 – 1975	Kvant/Mir	1987 – 2001
Ariel-5	1974 – 1980	Granat	1989 – 1998
Apollo-Soyuz	1975 – 1975	ROSAT	1990 – 1999
SAS-3	1975 – 1979	ASCA	1993 – 2001
OSO-8	1975 – 1978	SAX	1996 – 2002
HEAO-1	1977 – 1979	XTE	1996 –
Einstein	1978 – 1981	Chandra	1999 –
Ariel-6	1979 – 1981	XMM	1999 –
Hakucho	1979 – 1984	Integral	2002-

Her X-1 has been observed by both balloons (Truemper et al., first evidence for cyclotron line) and most X-ray missions

RXTE ASM average light curve



For 0.25 TO

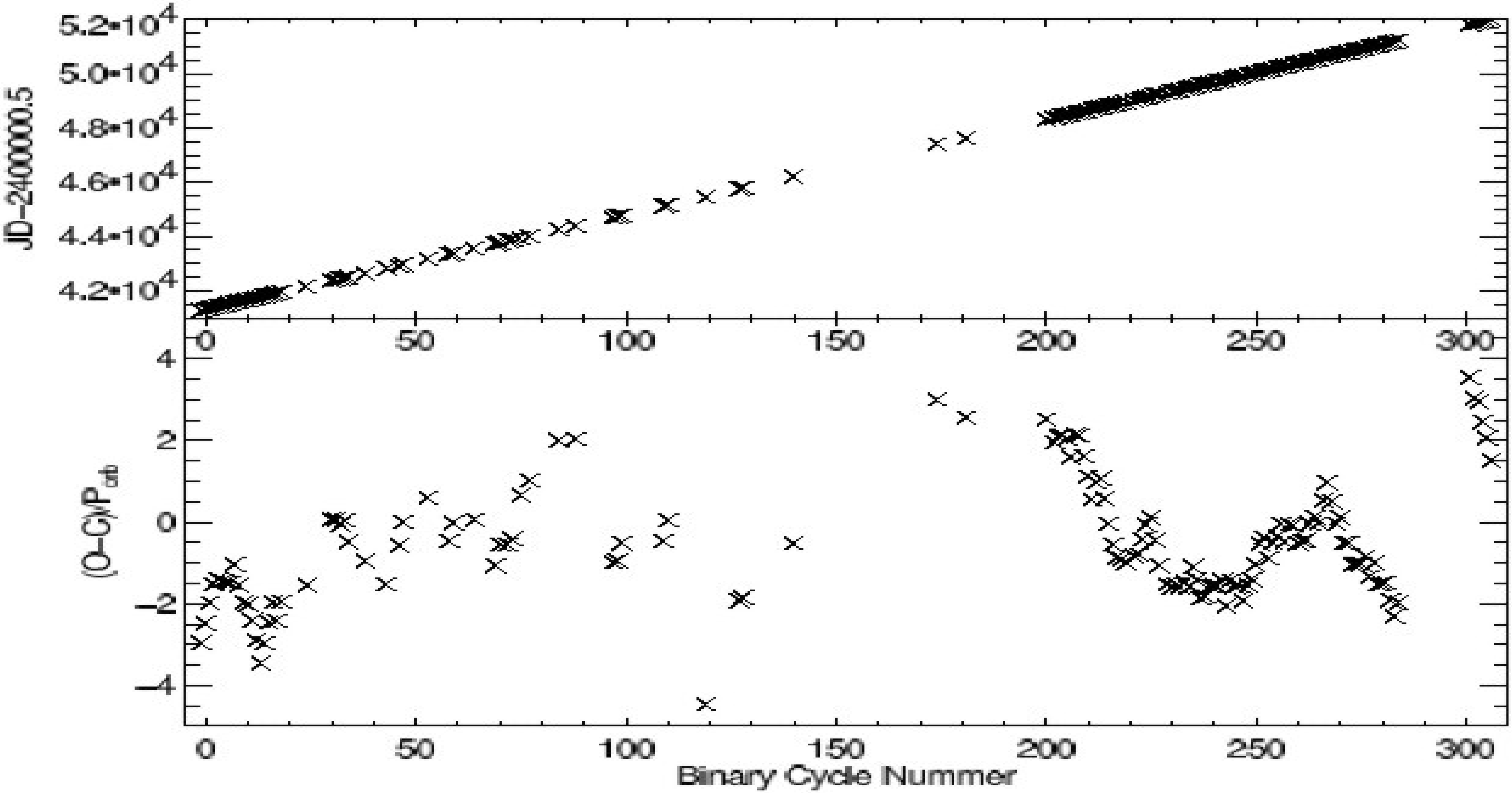
For 0.75 TO

Mean

Main-on Short-on

From Shakura et al. 1999

35-day cycle stability



(From P.Risse PhD Thesis, IAAT)

Turn-On ephemeris:

$T_{main-on}$ (JD)=2441501.649+20.5 P_{orb} (#-5)

Average precession period:

P_{prec} =34.858 d=20.503 P_{orb}

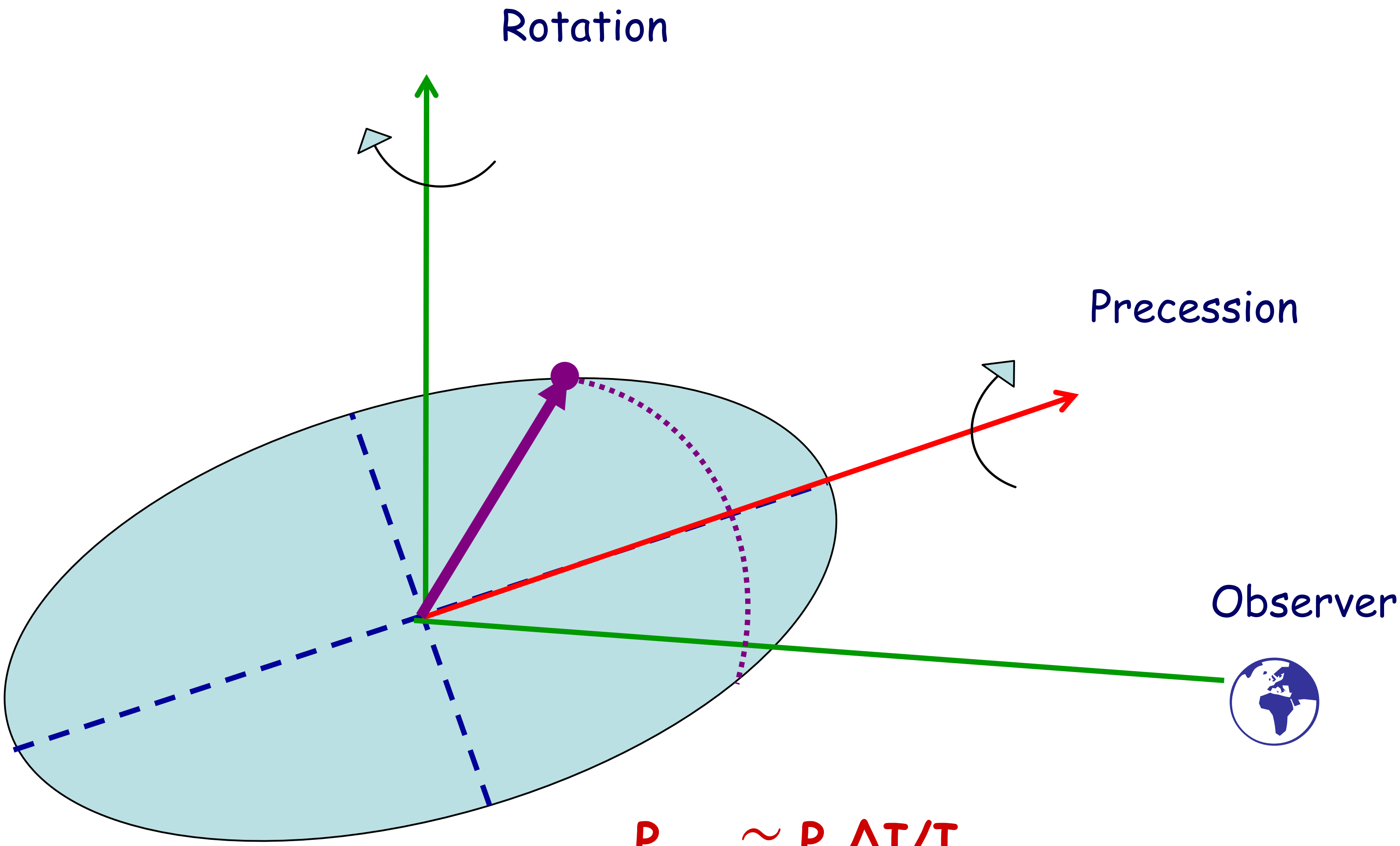
Orbital period:

P_{orb}=1.70017 d

Causes of the 35-day cycle variability

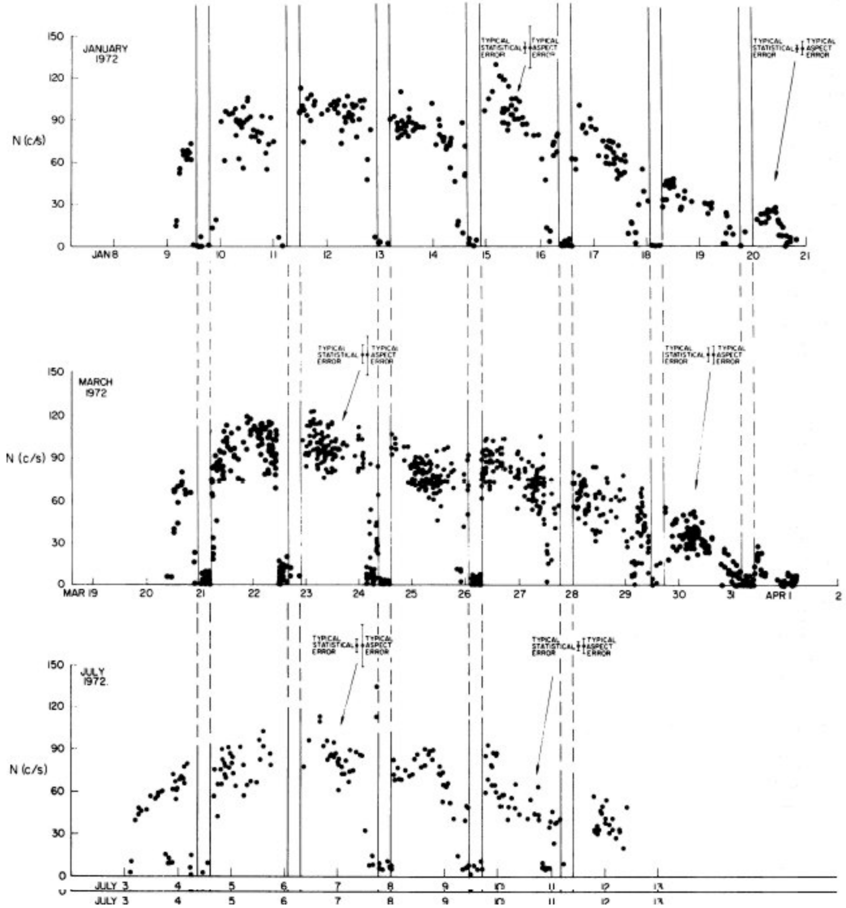
- X-ray turn-ons due to screening by precessing accretion disc (Boynton 1978)
- Long-term stability of 35-day period seems astonishing for precessing accretion disc ➔ some clock mechanism should operate
- Neutron star free precession as the clock mechanism (Brecher 1972). Evidence for NS free precession was suggested by Truemper et el (1986) from analysis of EXOSAT pulse profiles
- This work: describe X-ray pulse profile evolution using GINGA and RXTE detailed profiles in the NS free precession model

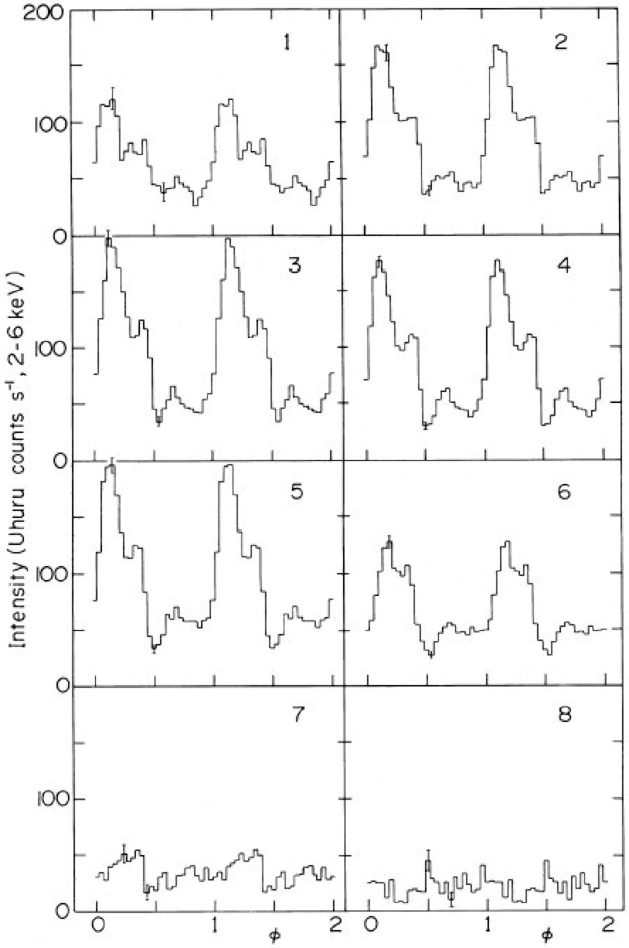
Schematic view of freely precessing NS (two-axial ellipsoid)



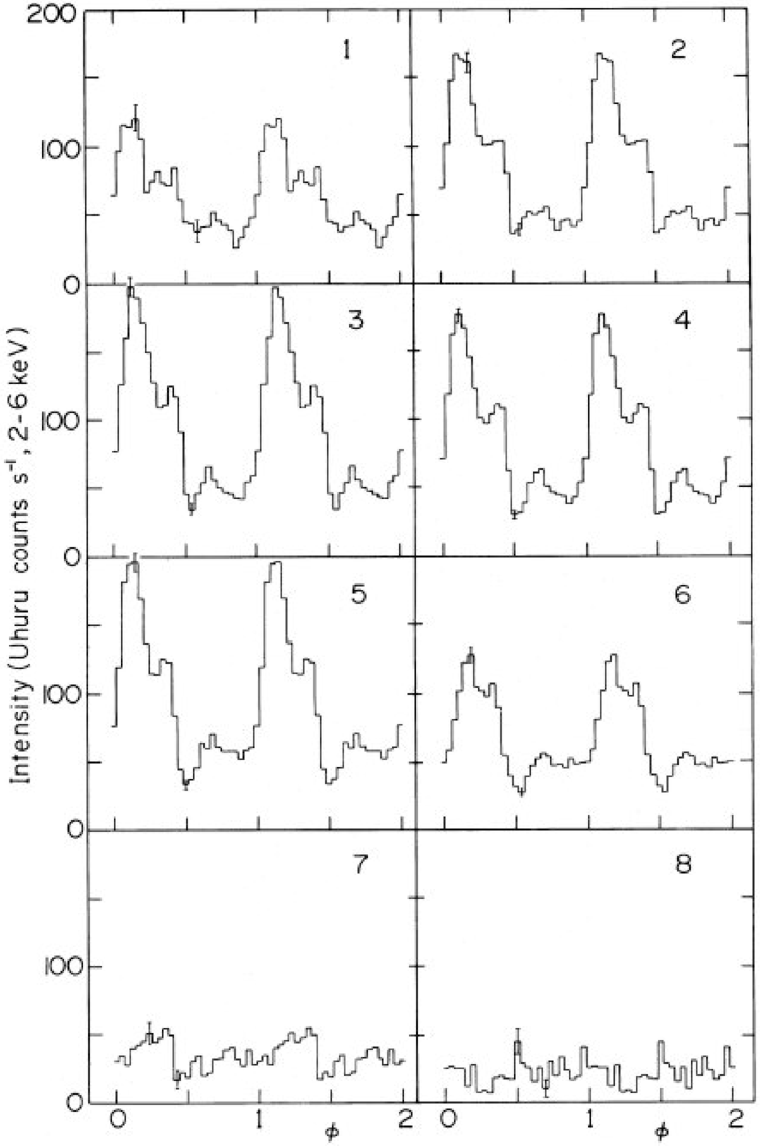
$P_{prec} \simeq P\ \Delta I/I$

X-ray pulse profile evolution

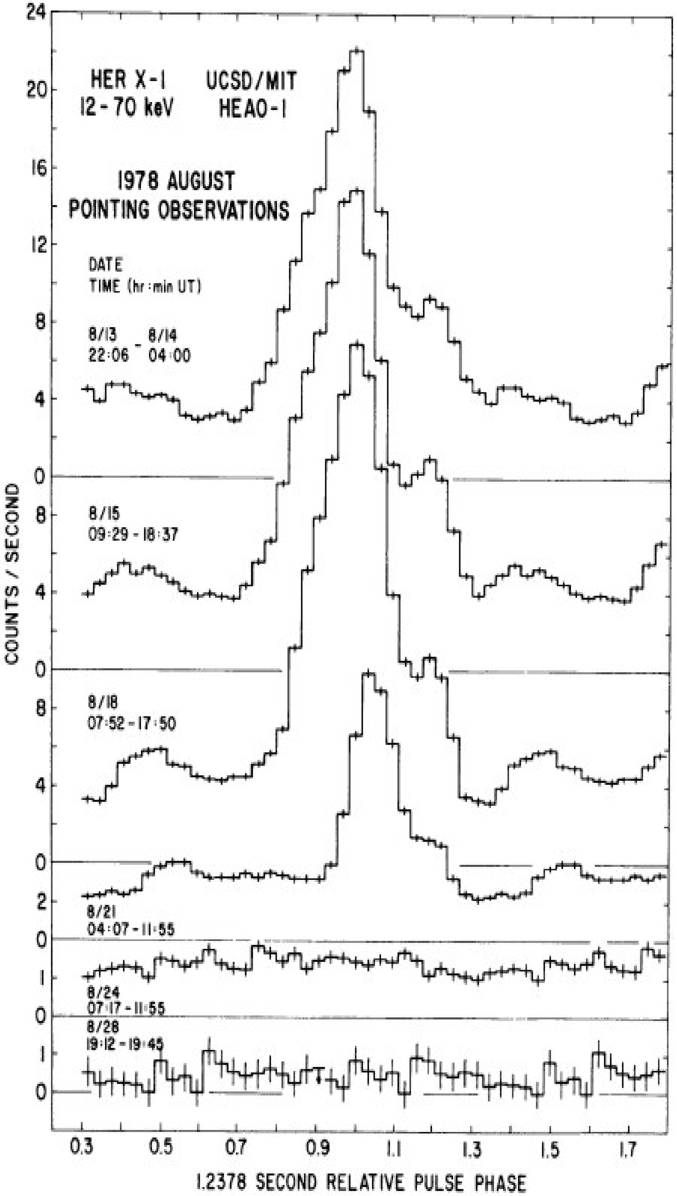




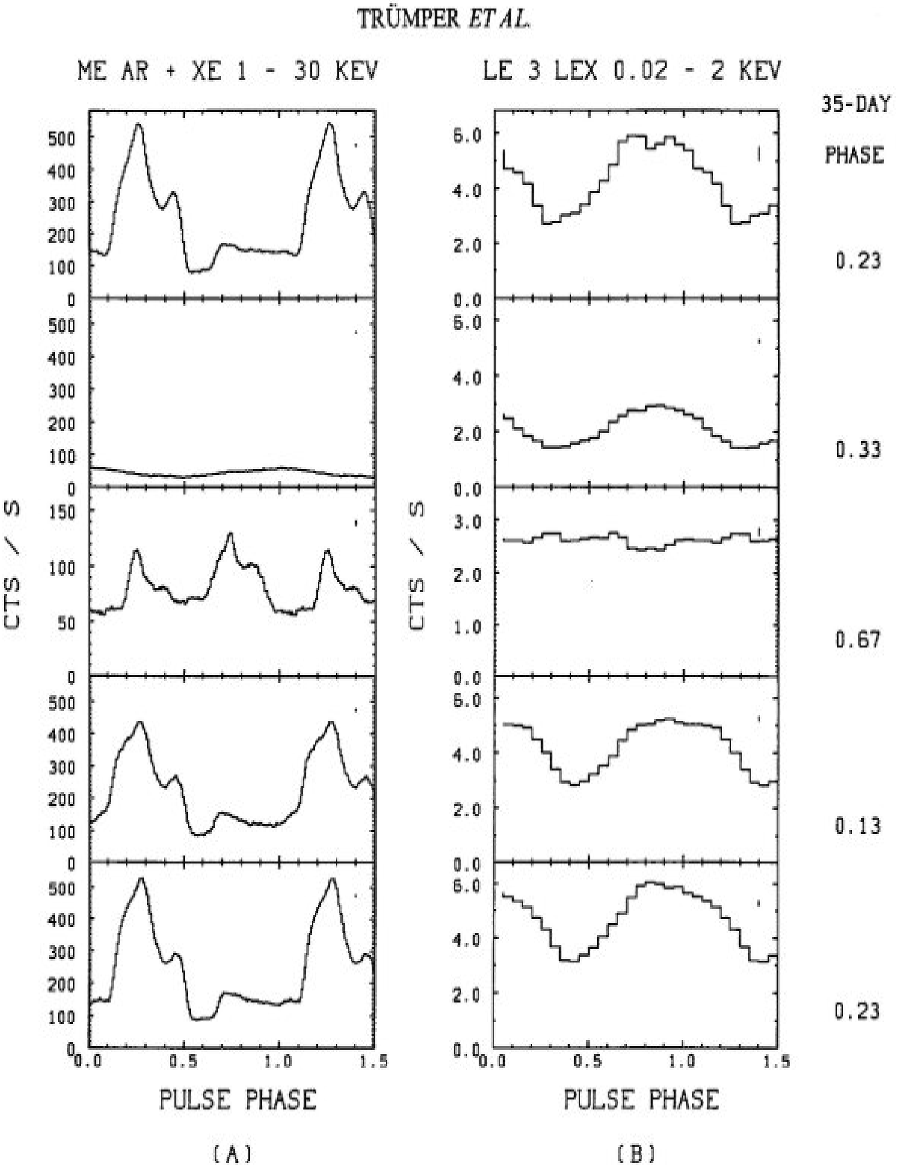
UHURU profiles (Joss et al. 1978)



UHURU Jan 72



HEAO-1 Sep 78 (Soong et al)



EXOSAT 1976 (Truemper et al)

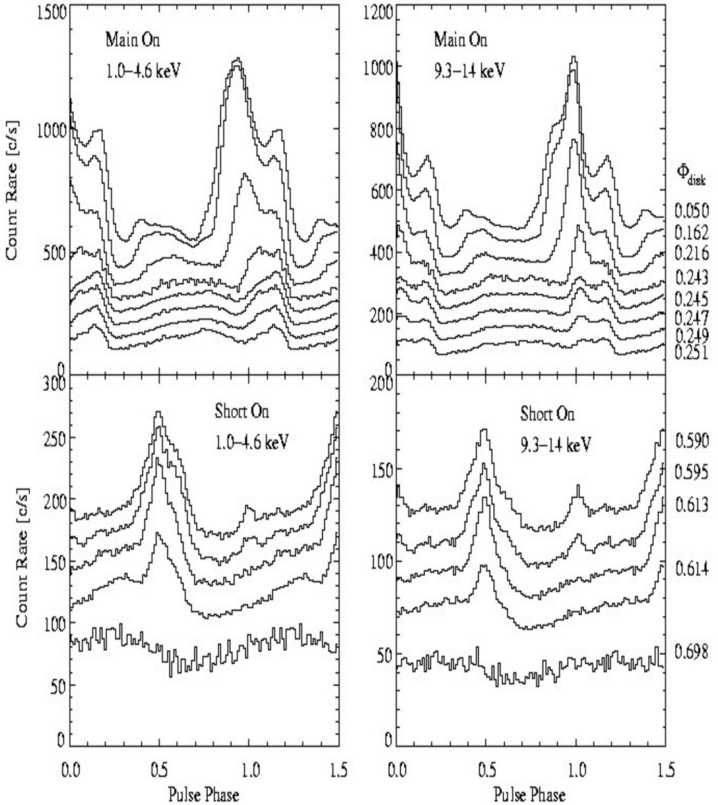
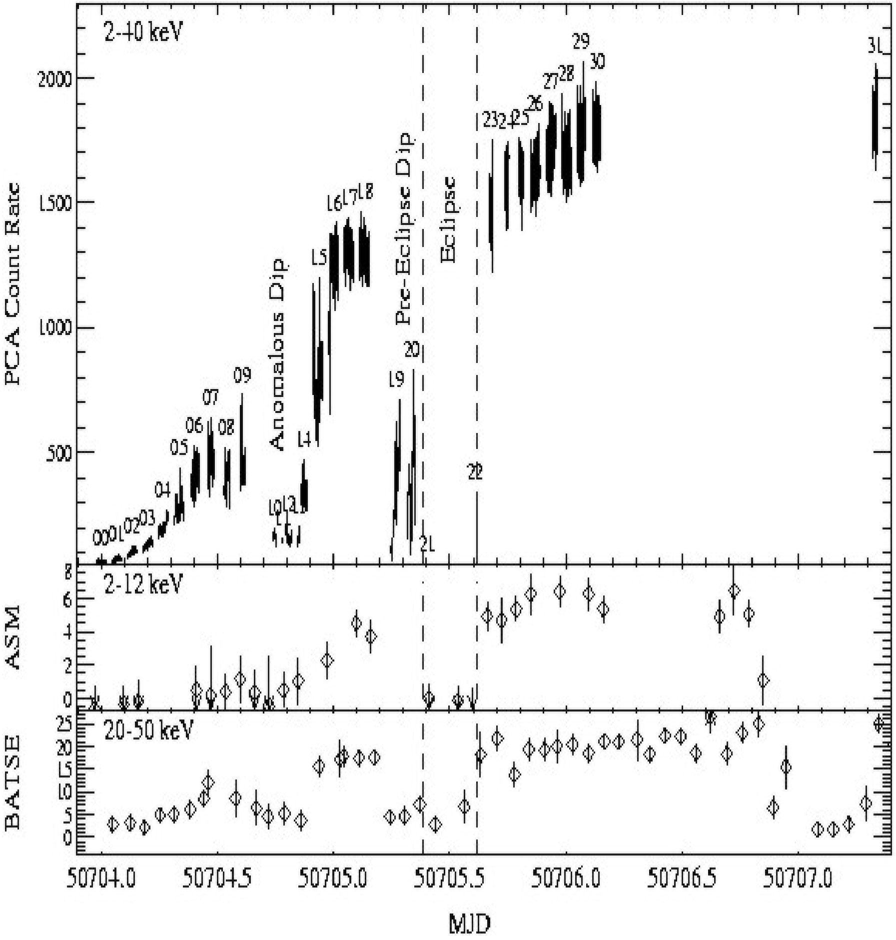


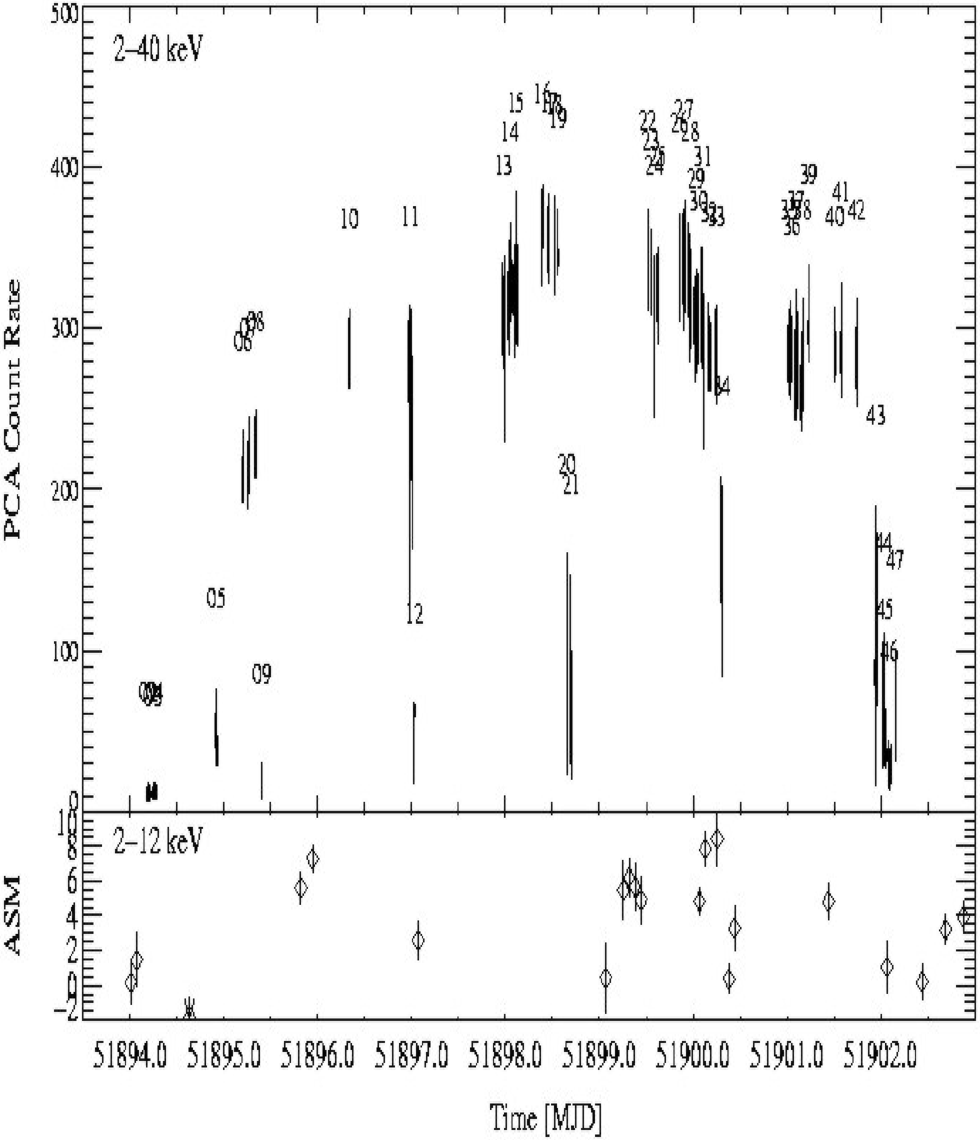
Figure 6.5: Changes in shape and flux of the pulse profile during the main-on and short-on of the 35^d cycle, observed in 1989 April with *Ginga*. Shown are pulse profiles in two energy bands 1.0–4.6 keV (left panel) and 9.3–14.0 keV (right panel). The 35^d phase of the accretion disk (ϕ_{35}) is indicated for each pulse profile on the right side for both, the right and left panel (after Fig. 6 of Scott et al., 2000).

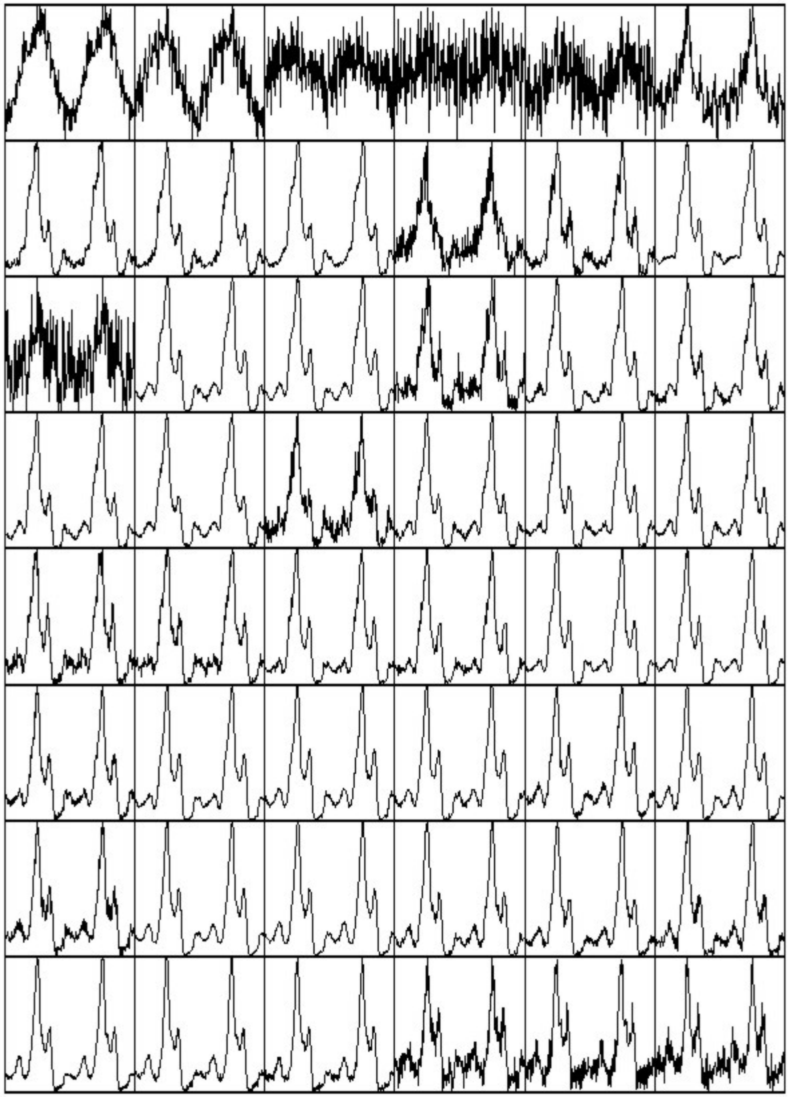
GINGA 1989 (Scott & Leahy)



RXTE 1997 (turn-on of #269) Kuster et al.

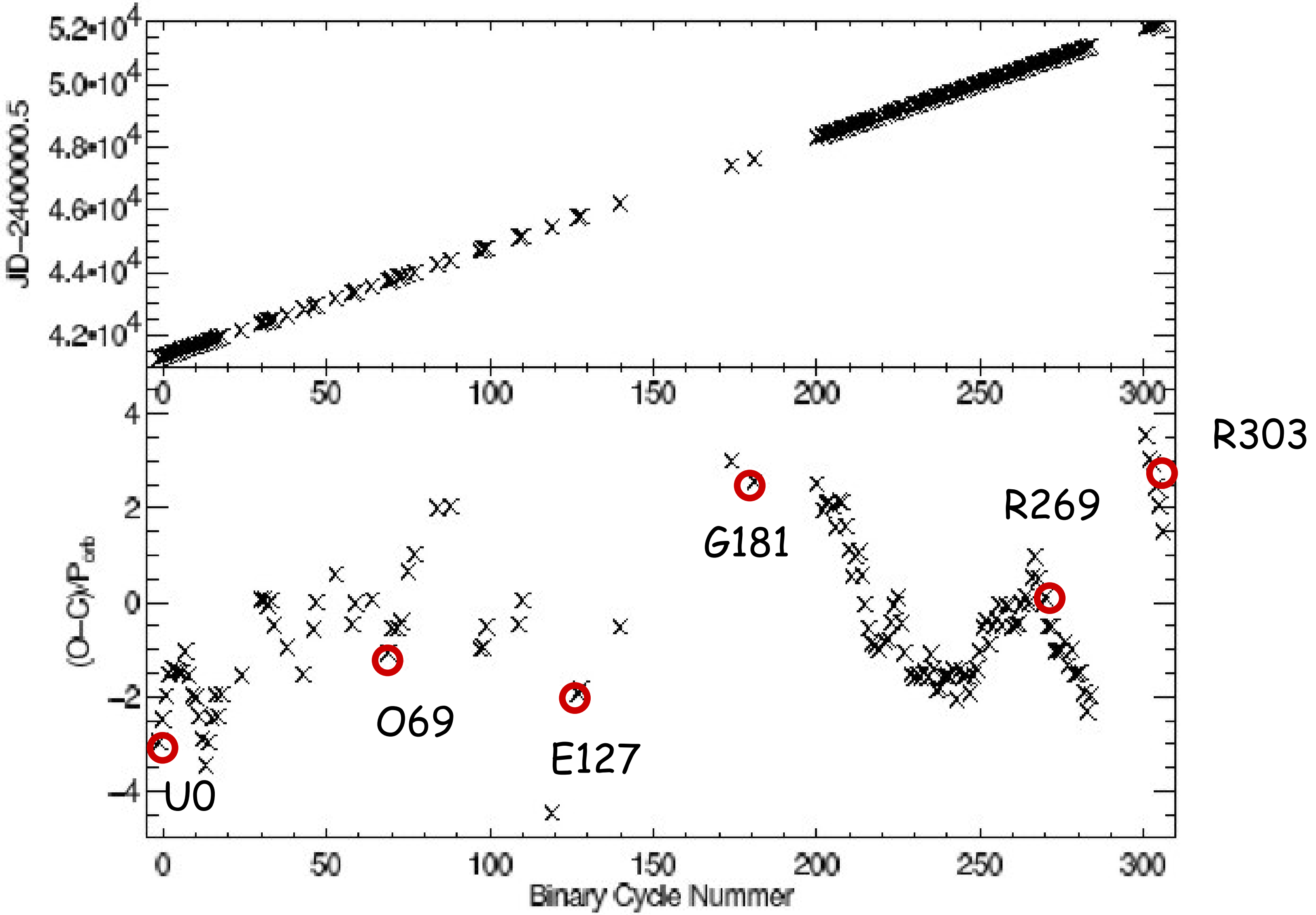
9-14 keV





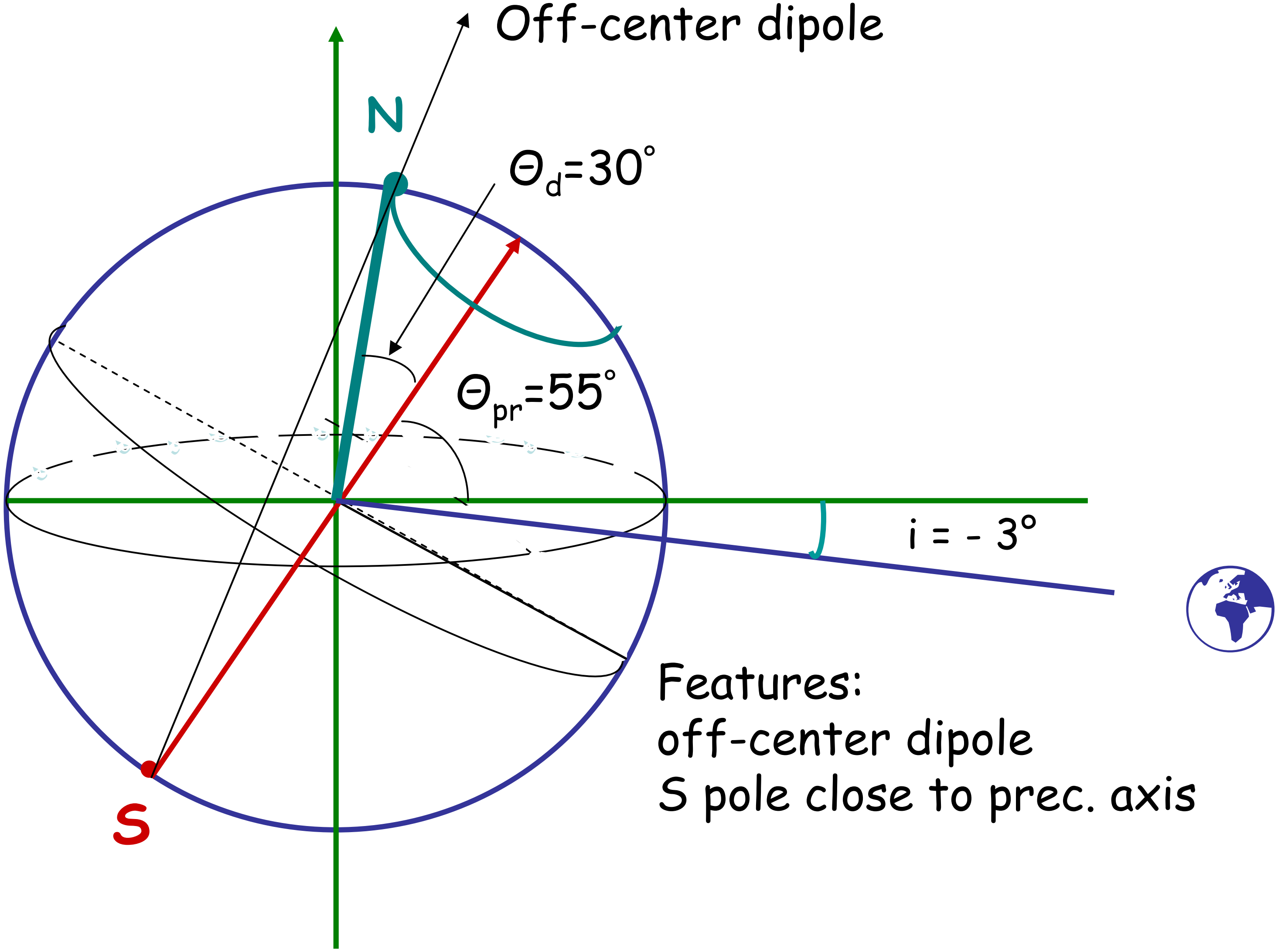
RXTE #303 10.59-15.42 keV (Staubert et al.)

Pulse profile evolution correlates with turn-on location on the O-C diagram



⇨ If NS free precession underlies the 35-day cycle
pulse profile shape is determined by the NS precession phase at the turn-on

Model parameters: geometry



Features:
off-center dipole
S pole close to prec. axis

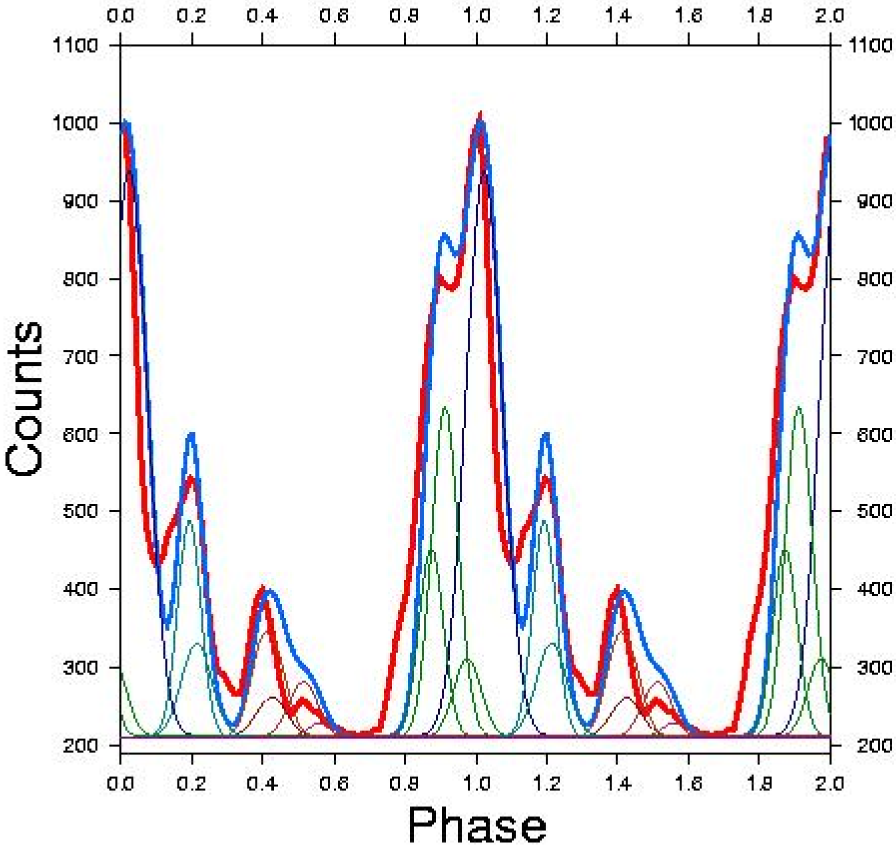
Model parameters: emitting regions

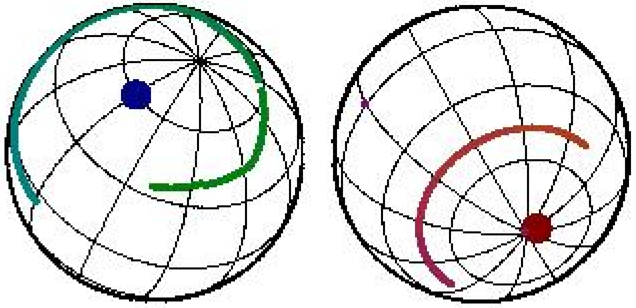
- Two magnetic poles (N and S) of an off-center dipole surrounded by arc-like regions
- Narrow pencil-beam emission diagram (half-width $\Delta\theta \sim 13-15$ deg)
- No fan-like emission, so no need for relativistic treatment of light propagation (like in Scott & Leahy model)

Applying the model to GINGA (#181) and RXTE (#269) pulse profiles:

$\Phi_{35}=0.05$

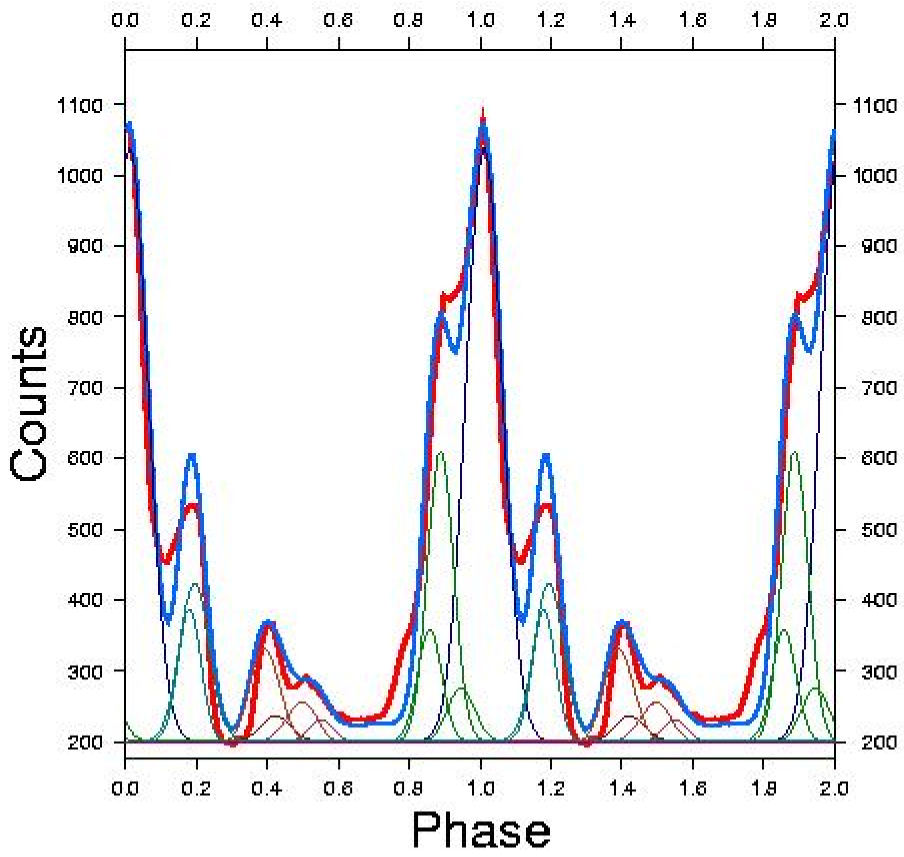
$\varphi_{NS}=-248$

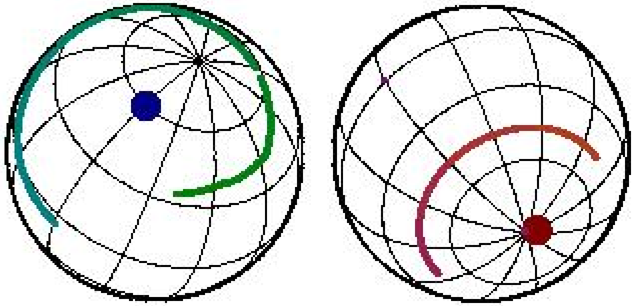




Φ_{35}=0.084

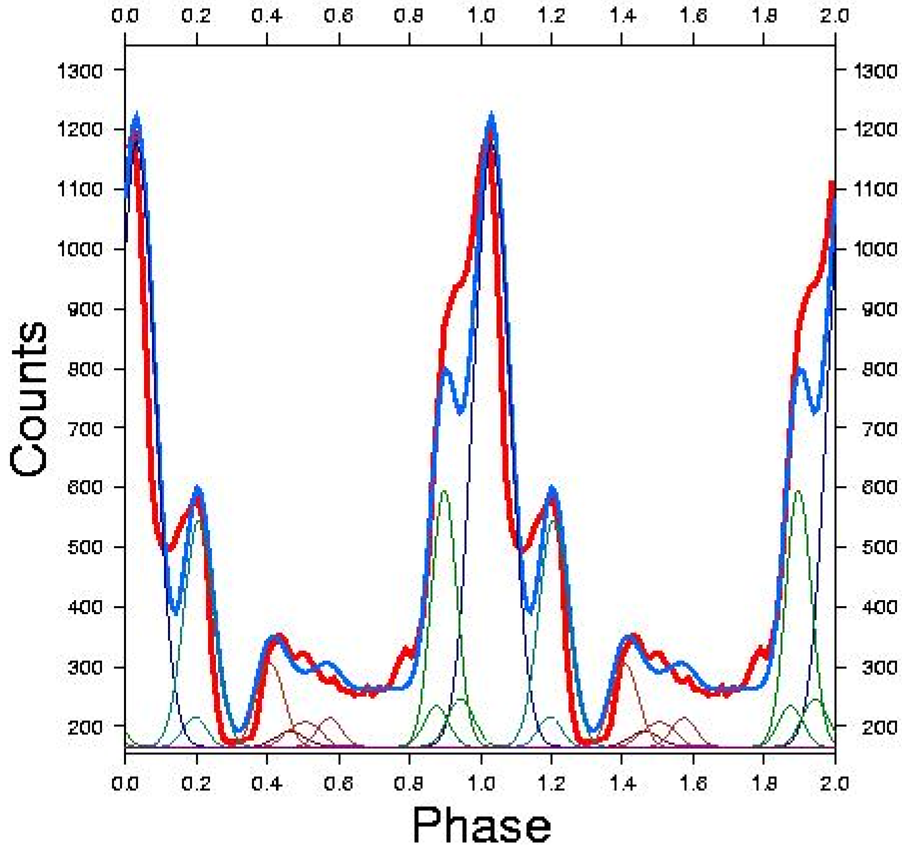
φ_{NS}=-236

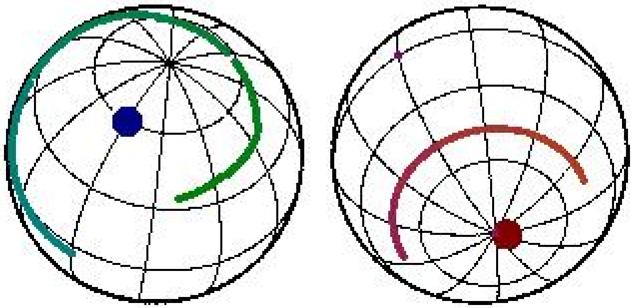




Φ_{35}=0.134

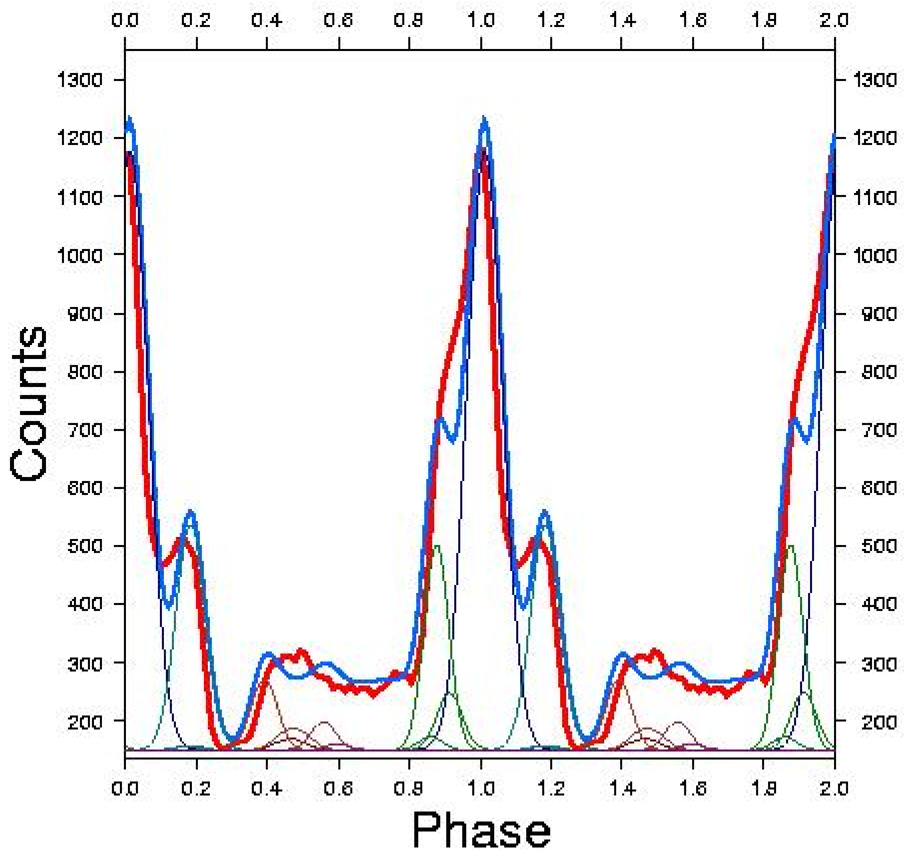
φ_{NS}=-218

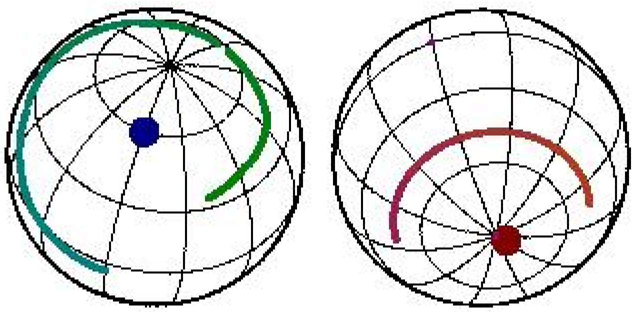




$\Phi_{35}=0.175$

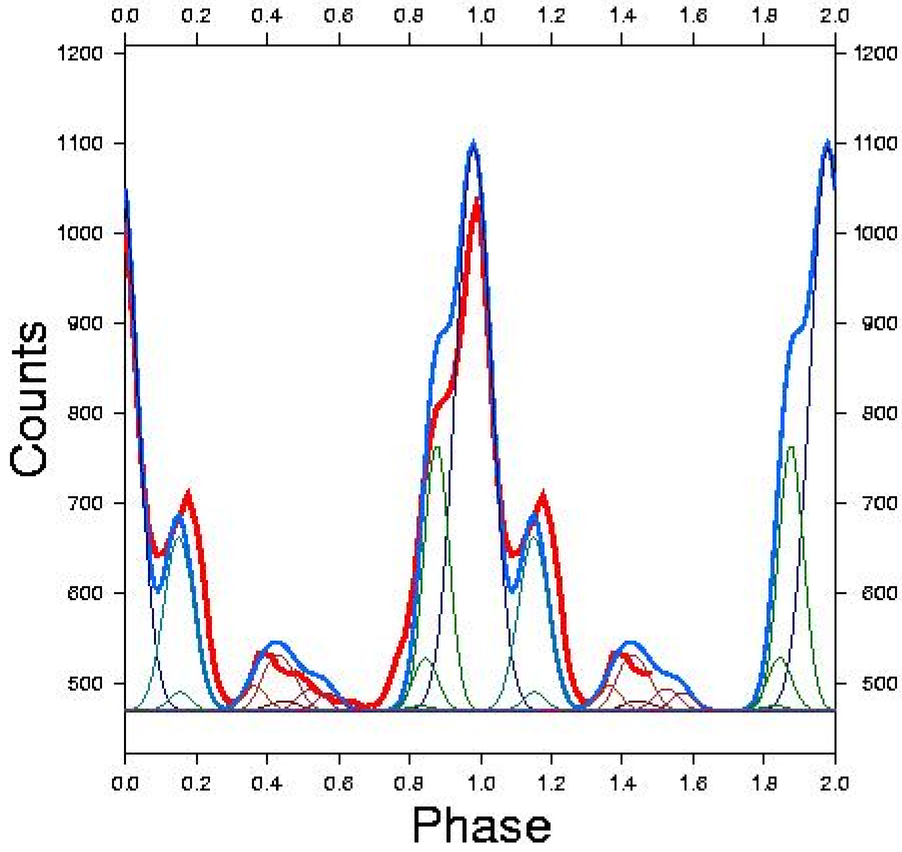
$\varphi_{NS}=-204$

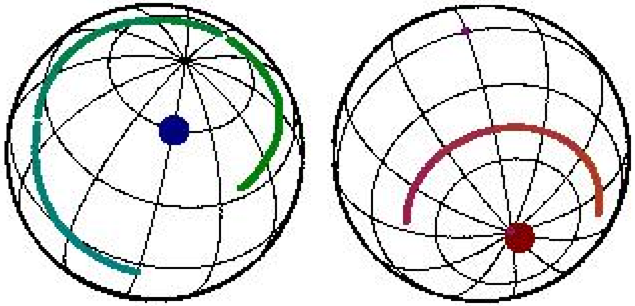




$\Phi_{35}=0.05(G)$

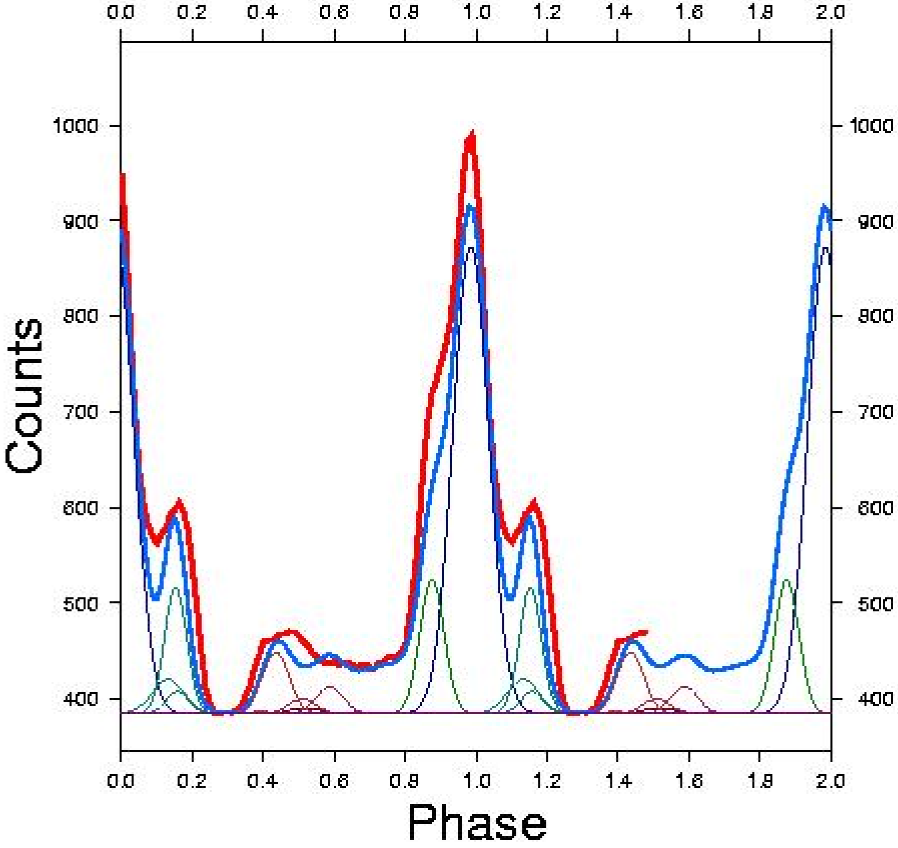
$\varphi_{NS}=-194$

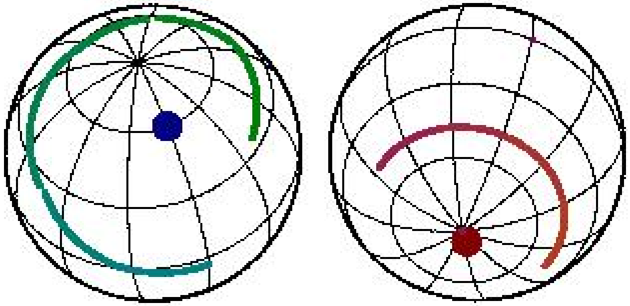




$\Phi_{35}=0.162(G)$

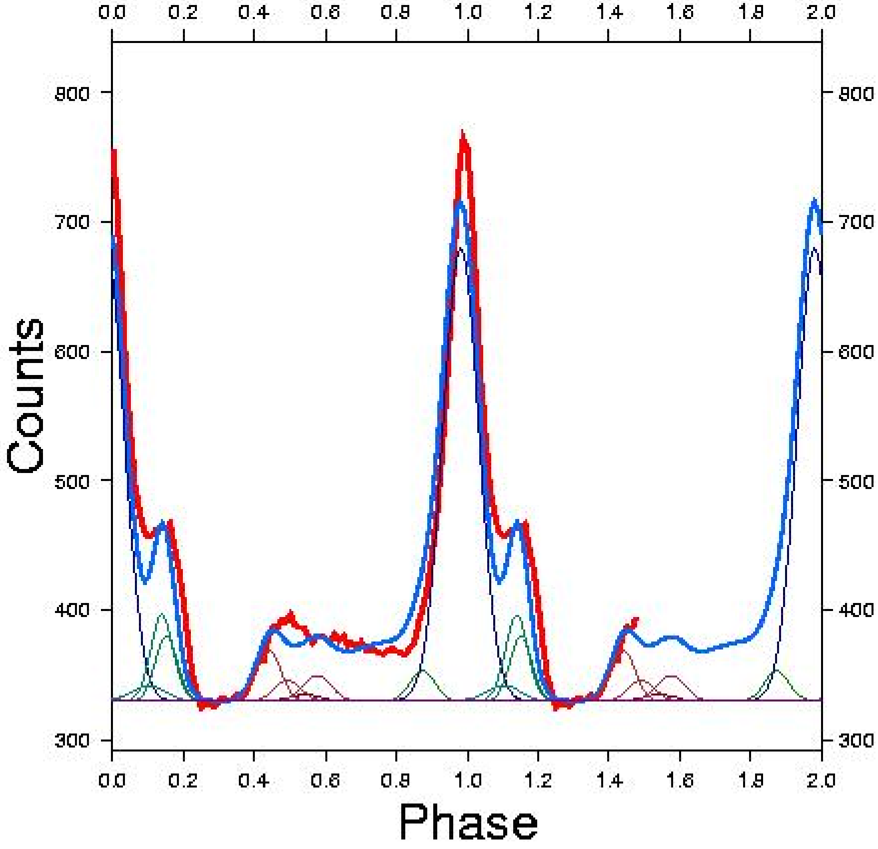
$\varphi_{NS}=-154$

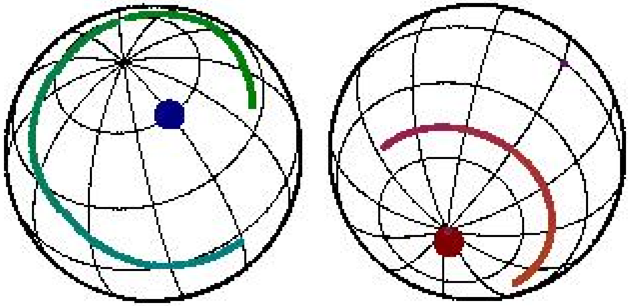


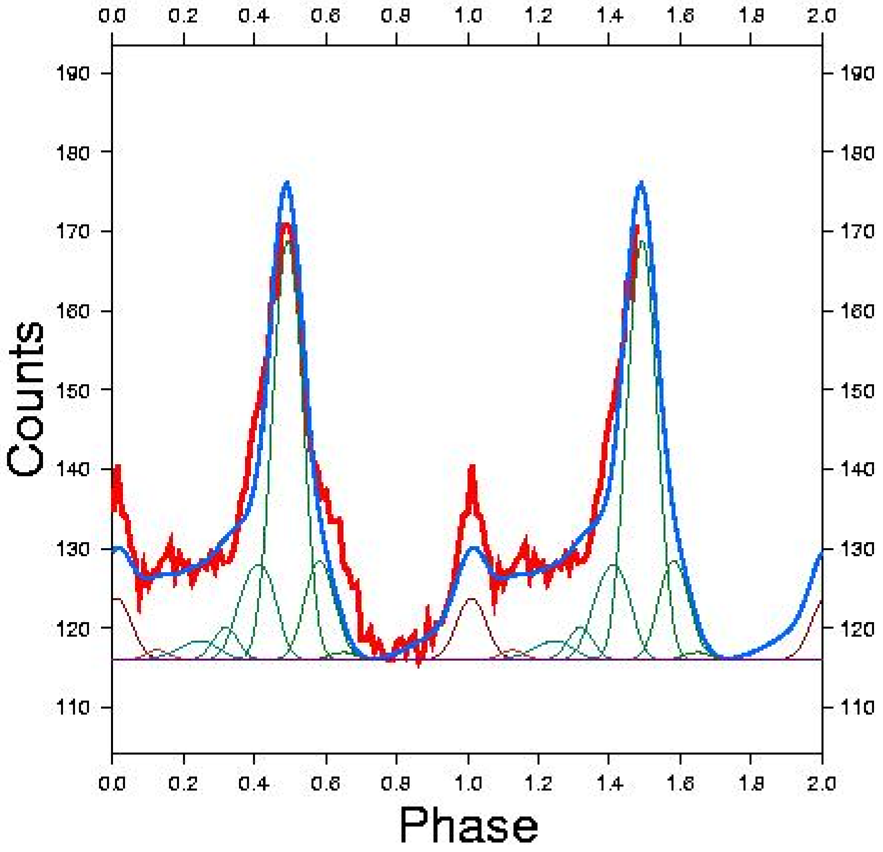


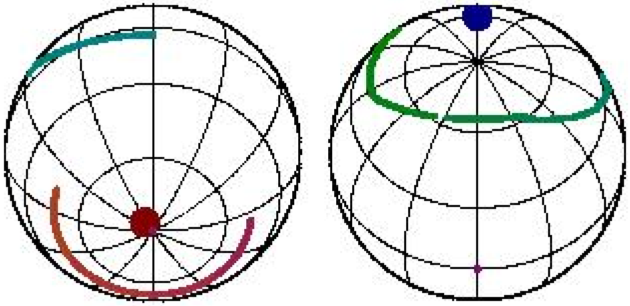
$\Phi_{35}=0.216(G)$

$\varphi_{NS}=-135$







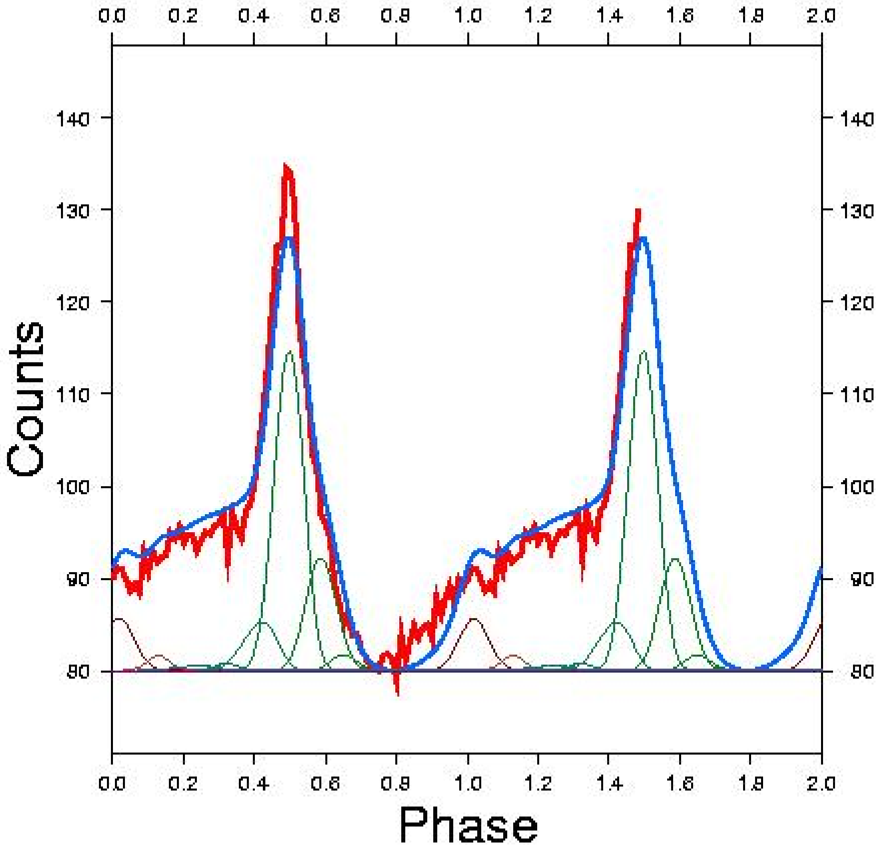


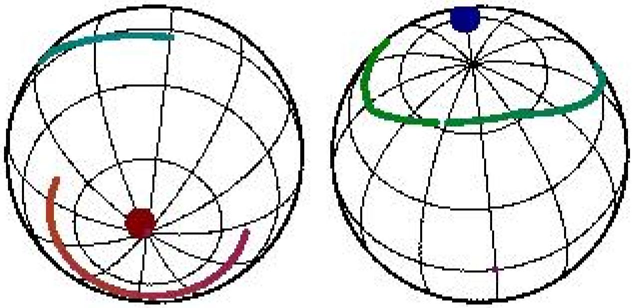
Φ_{35}=0.59(G)

φ_{NS}= 0

Φ_{35}=0.613(*G*)

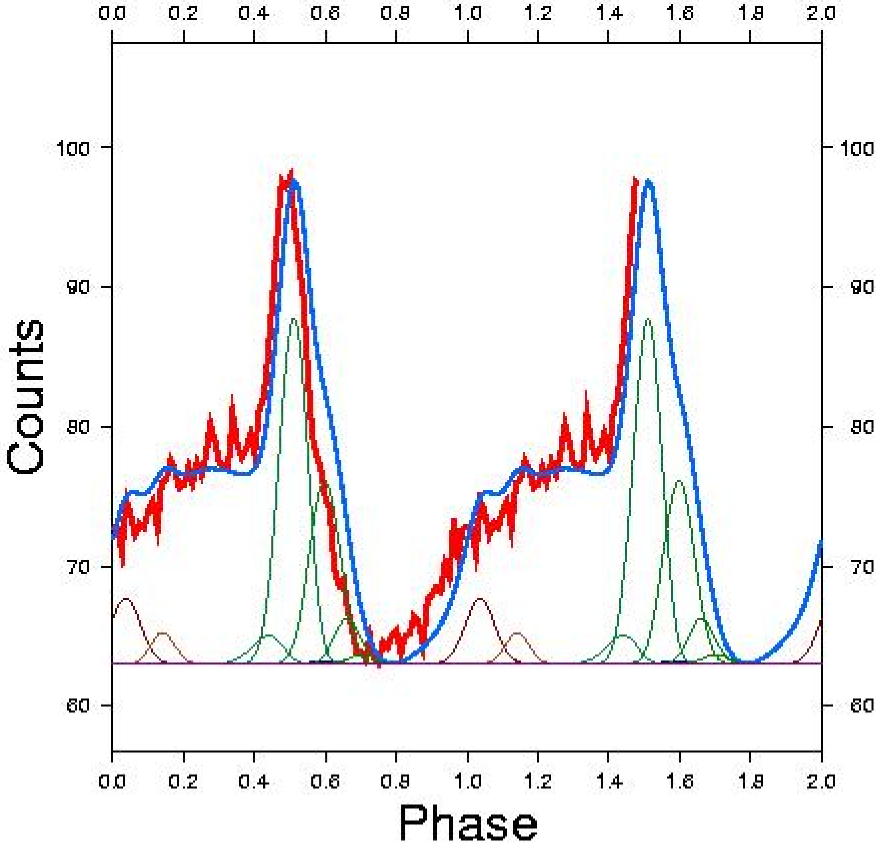
φ_{NS}= 8

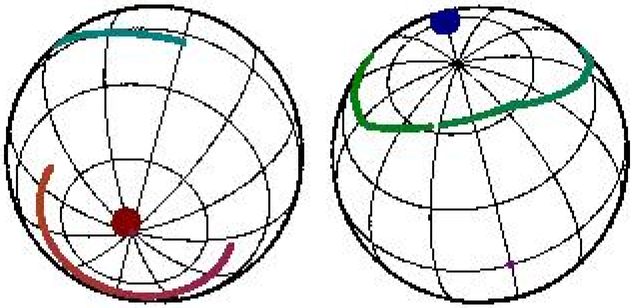




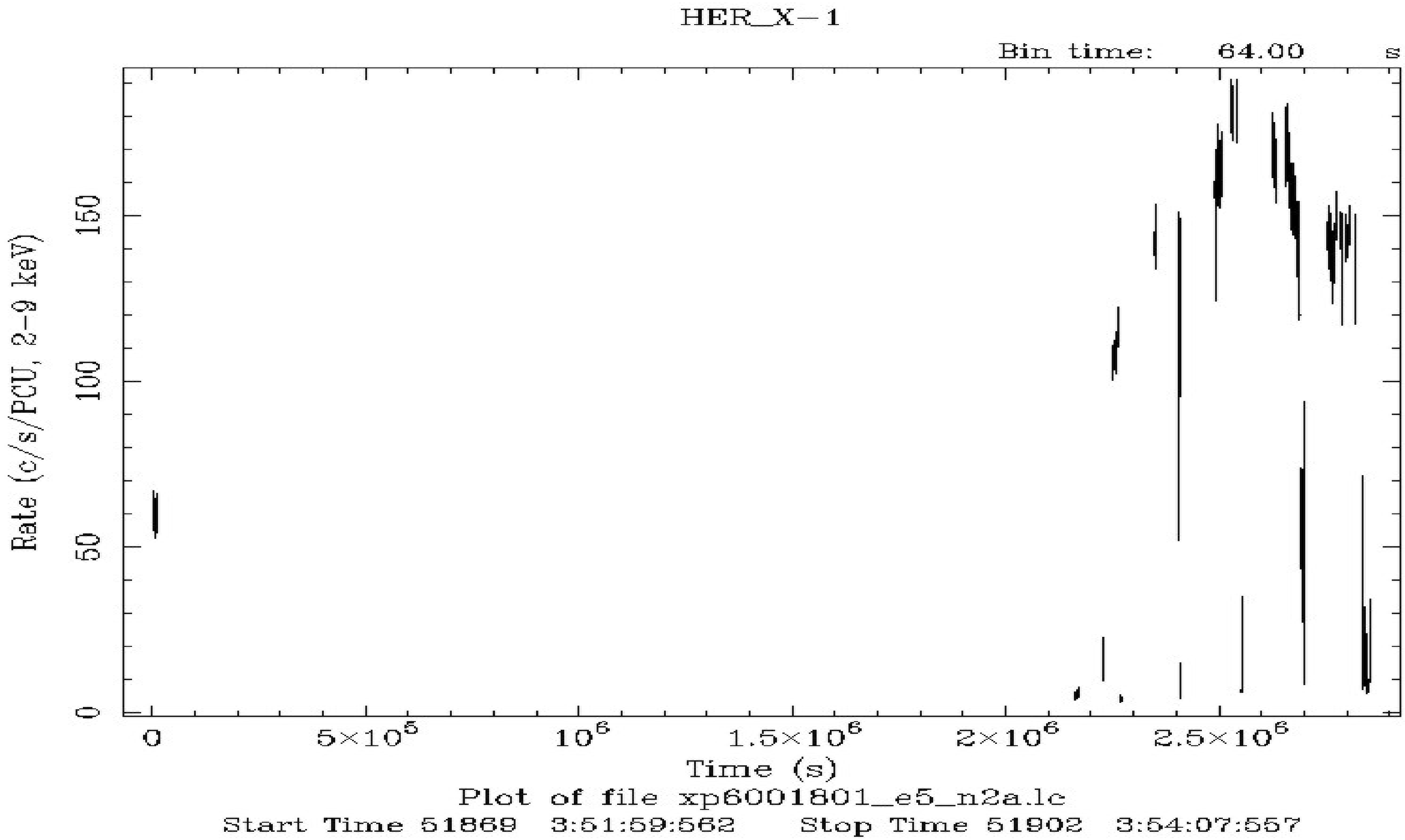
$\Phi_{35}=0.641(G)$

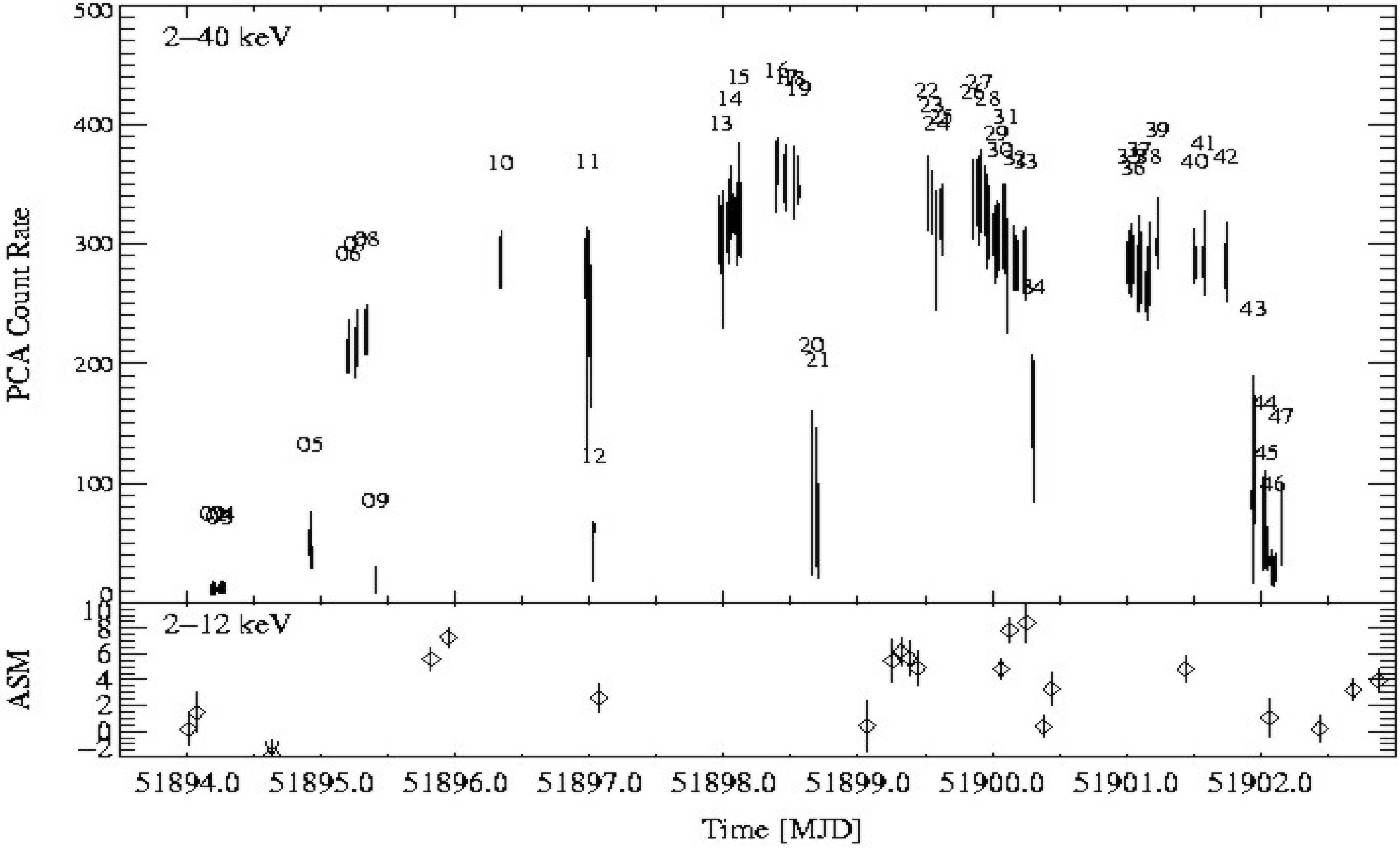
$\varphi_{NS}= 18$





Cycle #303 (RXTE xp60018)




2–40 keV
PCA Count Rate
500
400
300
200
100
0
2–12 keV
ASM
10
8
6
4
2
0
−2
51894.0
51895.0
51896.0
51897.0
51898.0
51899.0
51900.0
51901.0
51902.0
Time [MJD]
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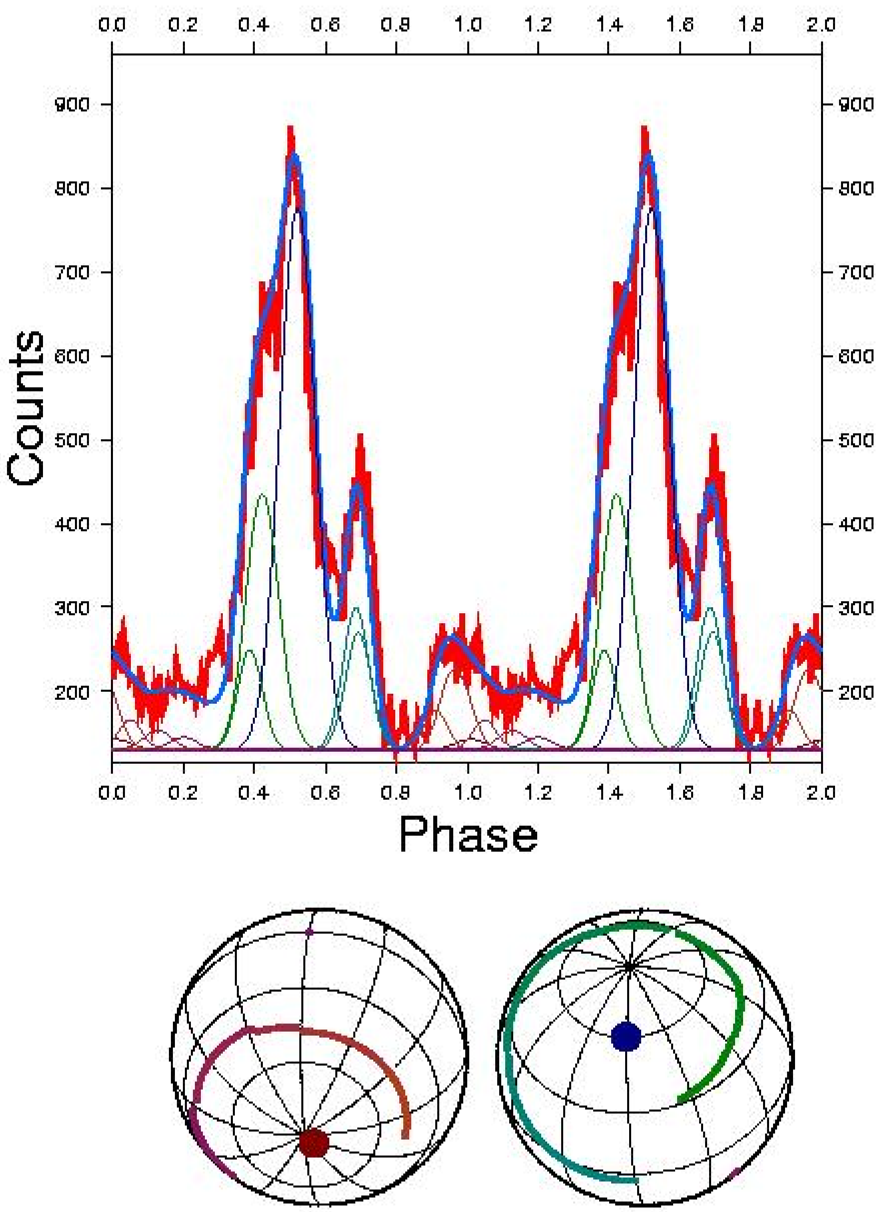
Now apply the model to RXTE #303 using the NS free precession phase (~ -180) according to turn-on #303 on O-C plot (similar to GINGA #181):

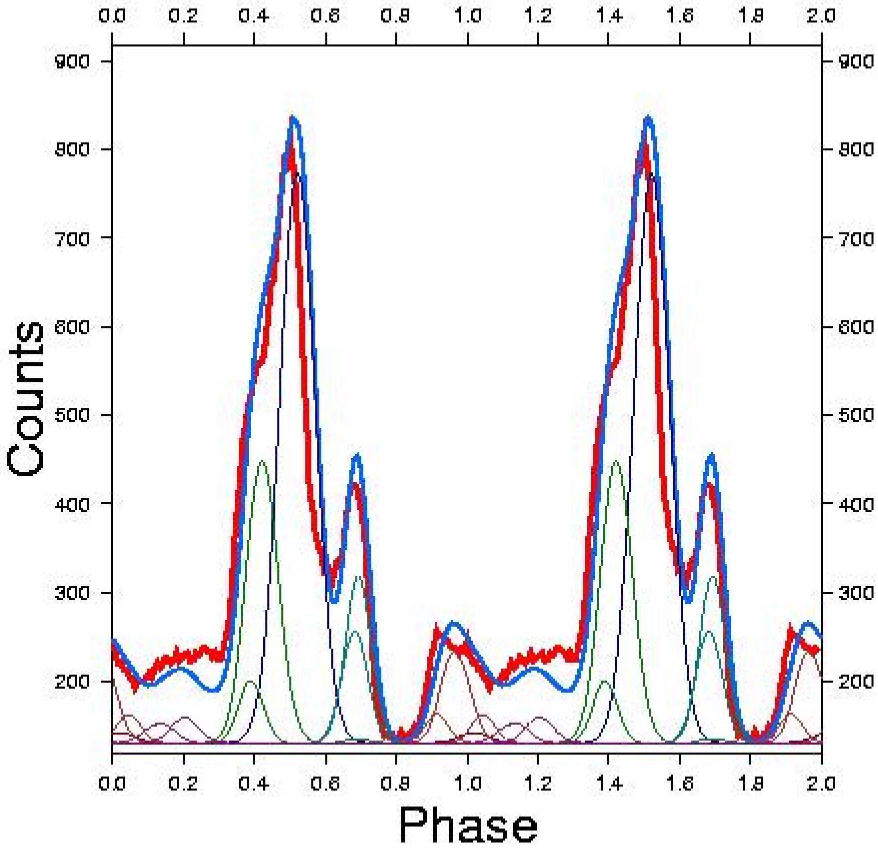
10

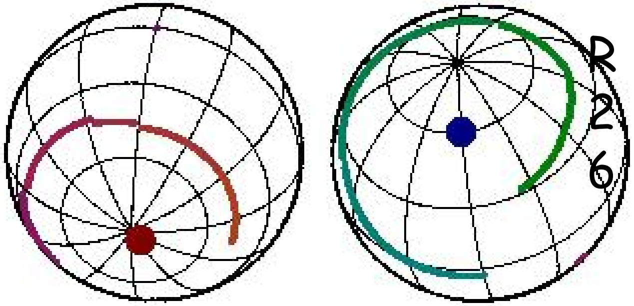
φ_{NS}=-181



11

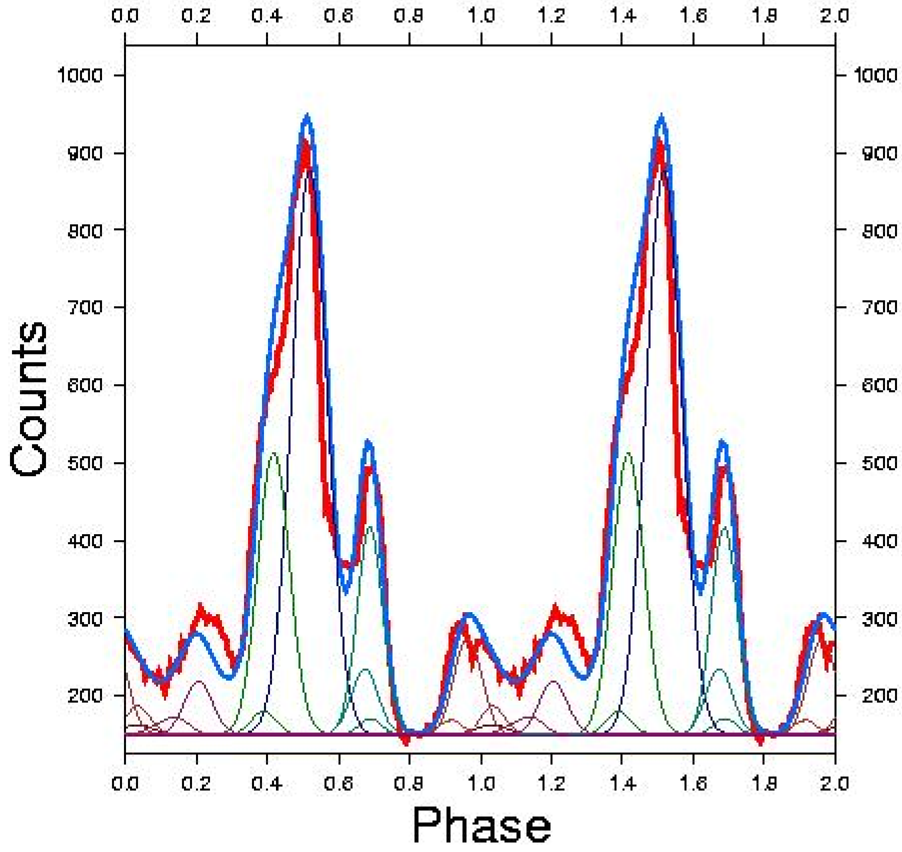
φ_{NS}=-174

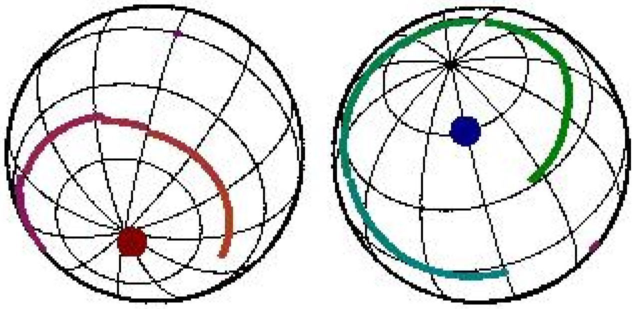




13

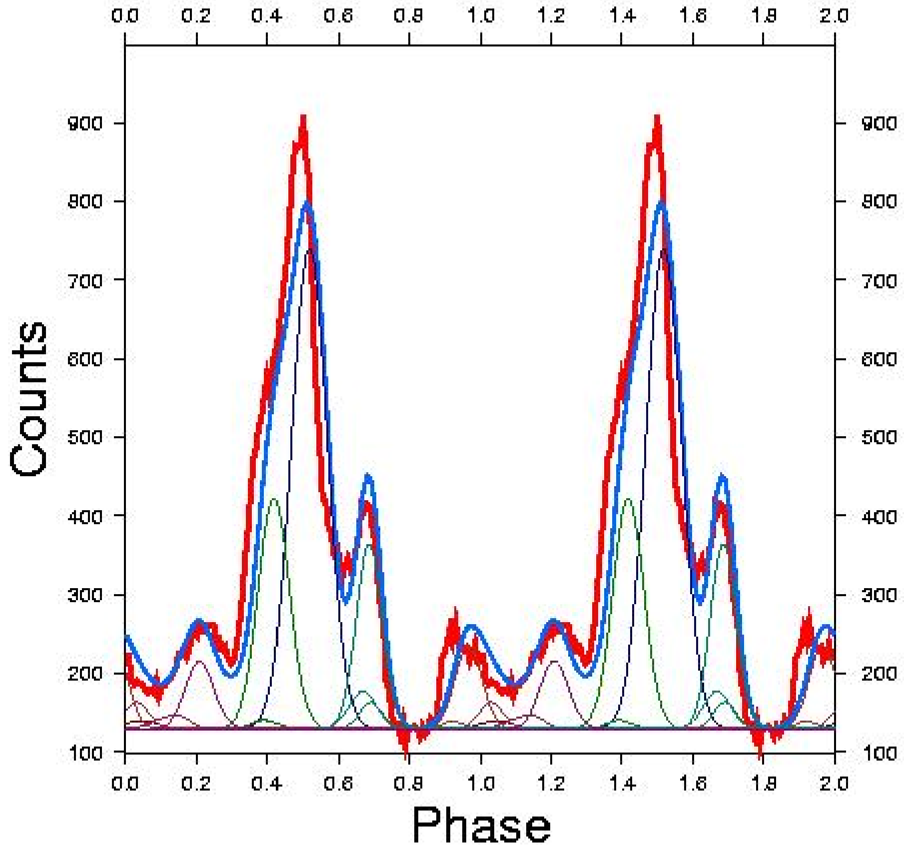
φ_{NS}=-163

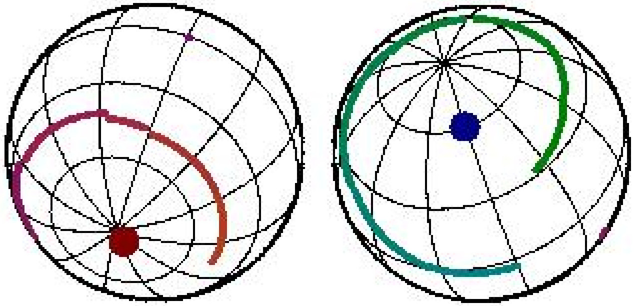




19

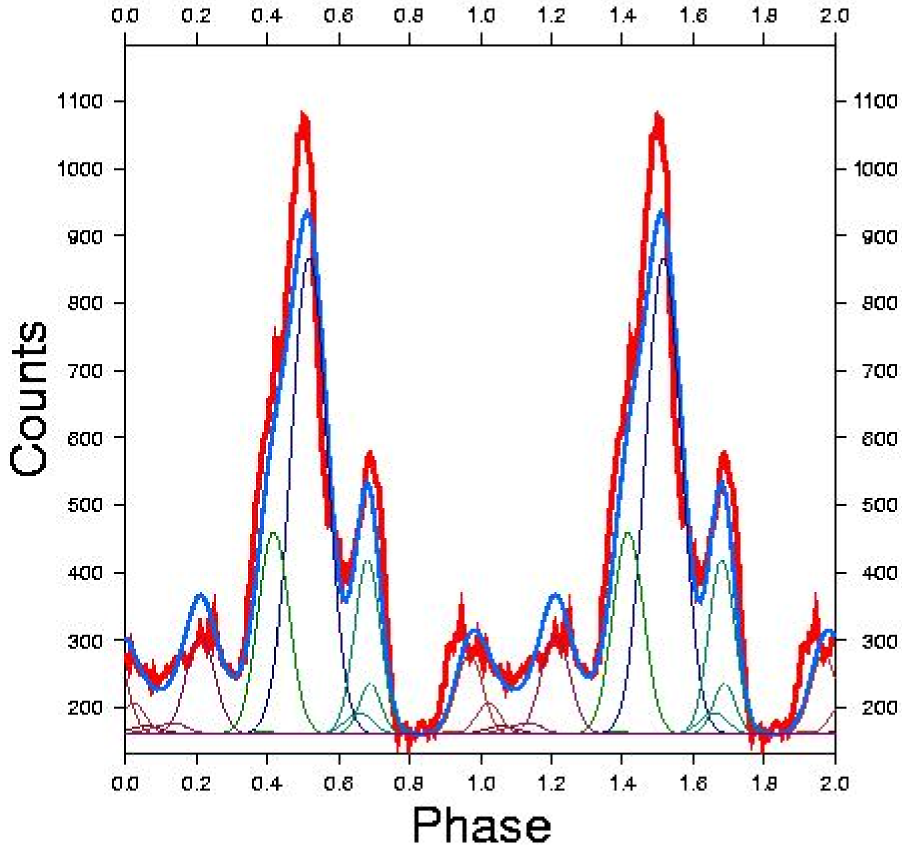
φ_{NS}=-156

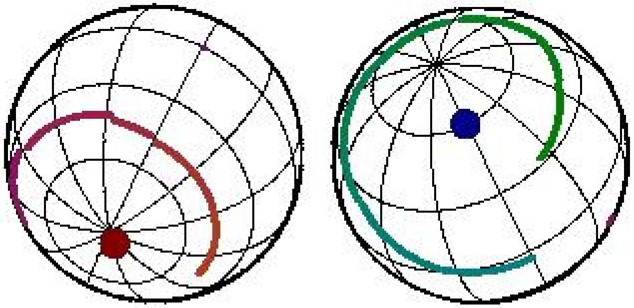




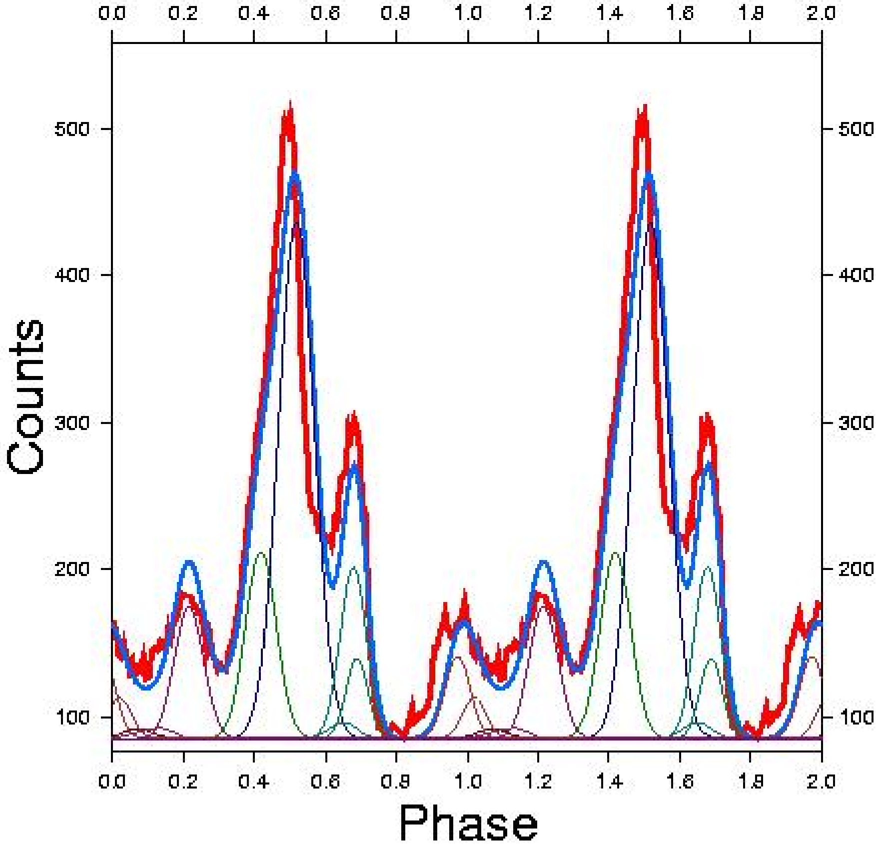
22

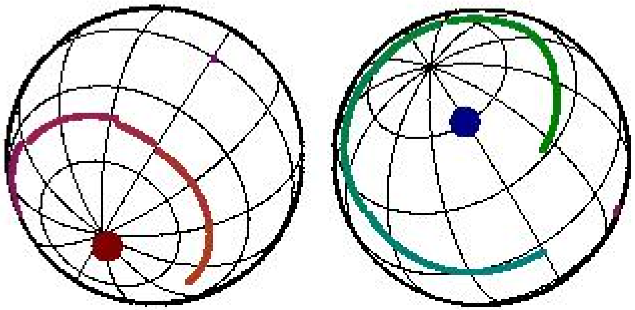
$\varphi_{NS}=-147$



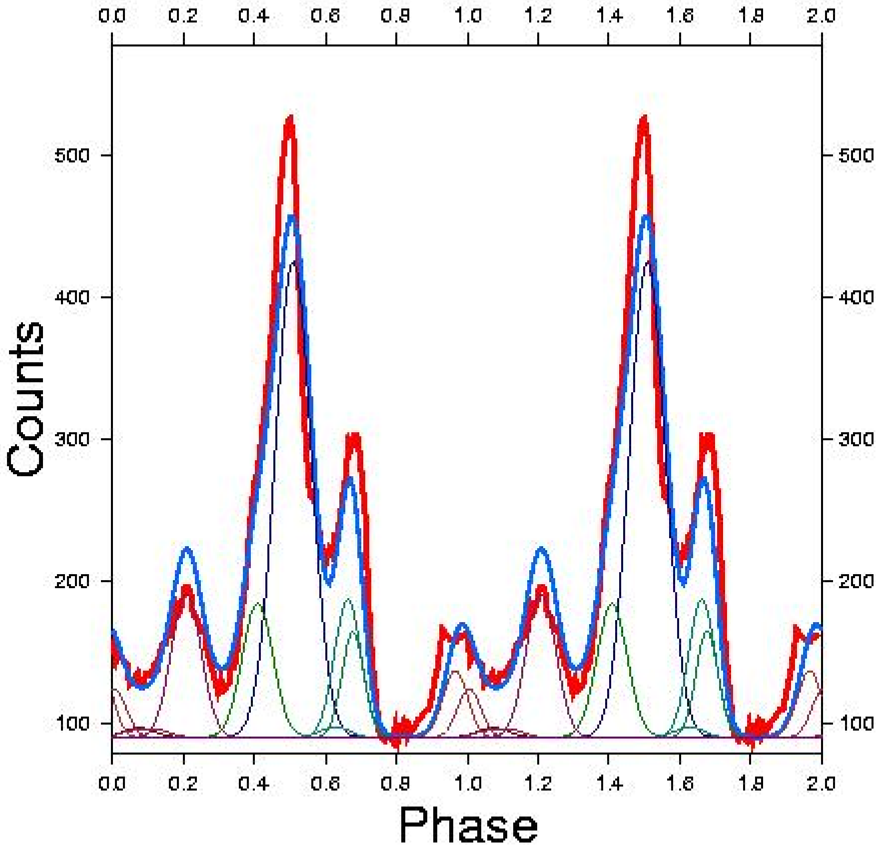


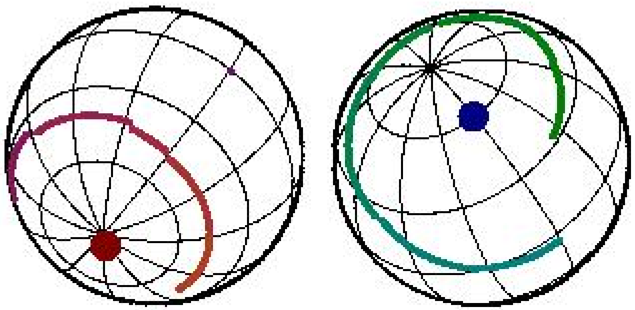
φ_{NS}=-140



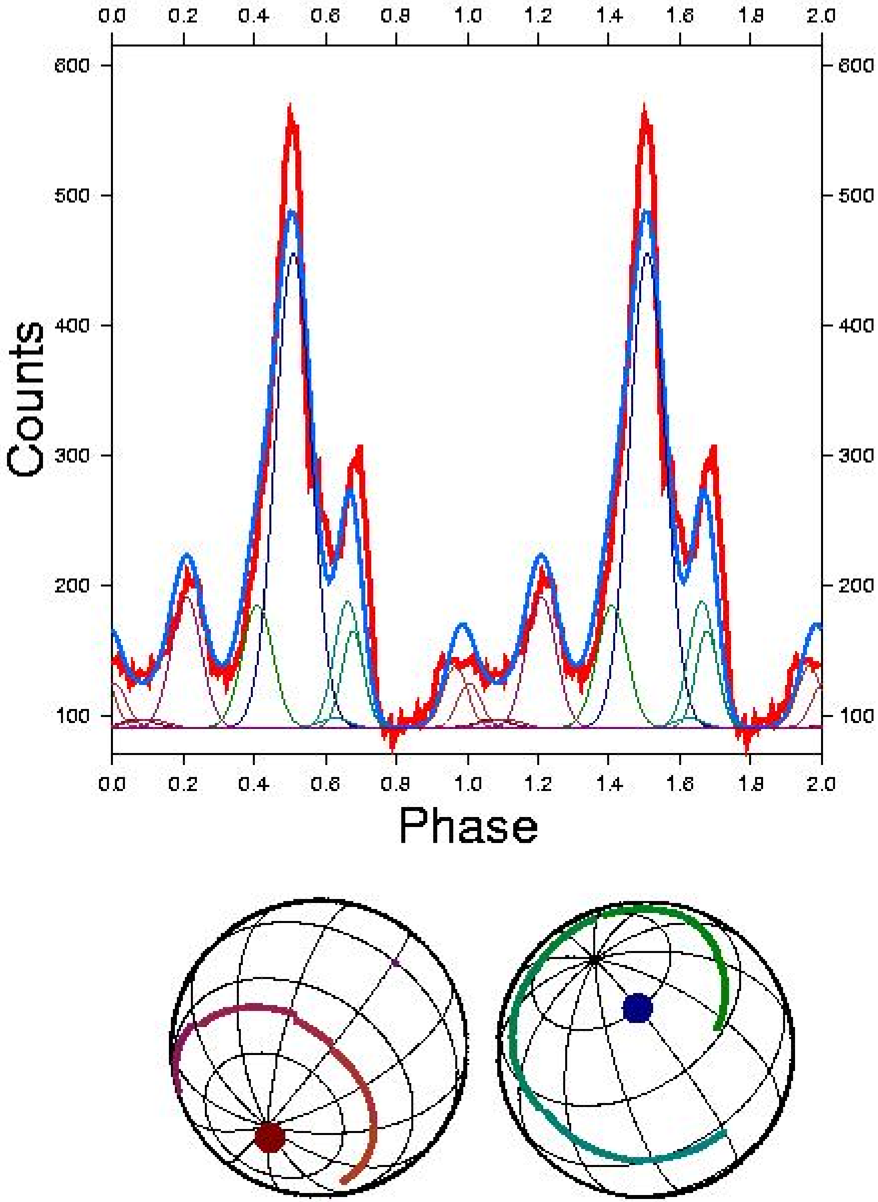


φ_{NS}=-132

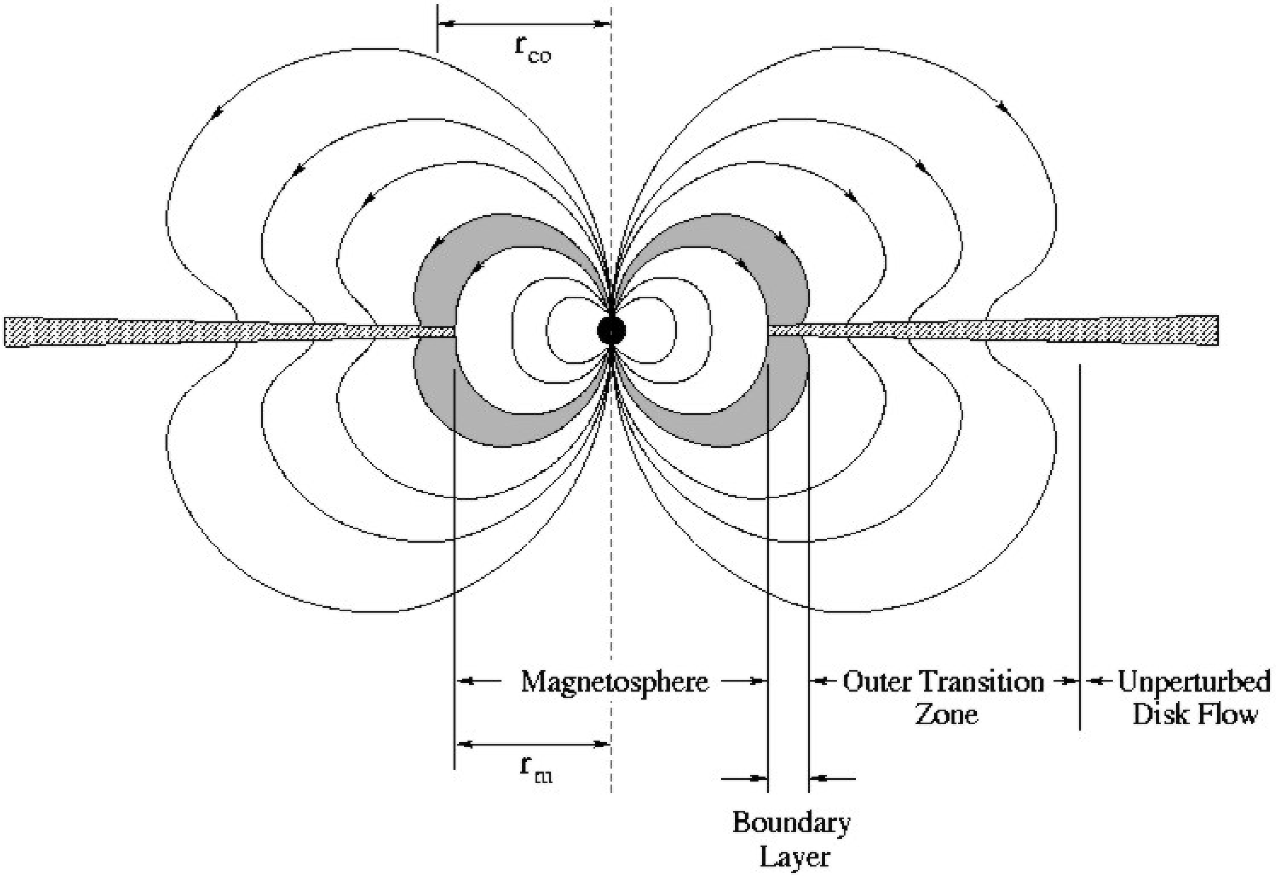




φ_{NS}=-124



Why such emission region geometry?



A canonical (simplest) picture (Ghosh and Lamb)

Zoom into the accreting poles: non-dipole magnetic field structure

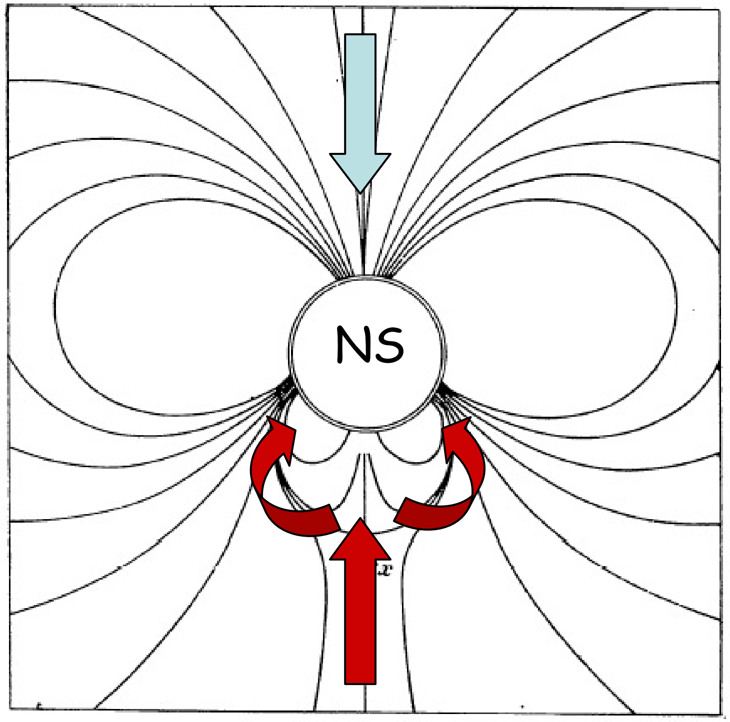


FIG. 3. Configuration of magnetic field lines near a neutron star with parameters obtained from an analysis of the x-ray pulses of Her X-1. The axes of the magnetic dipole and quadrupole are directed vertically. The surface of the neutron star is marked by the double line, and R_x is the branch point of the magnetic field lines.

Simplest case: add dipole and coaxial quadrupole (Shakura, Postnov, Prokhorov 1989)
➔Circular emitting area around magnetic pole appears

Further complication: off-center Dipole axis (Panchenko & Postnov 1993, Blum & Kraus 2000…)
➔Horse shoe-like region around magnetic pole forms

Why narrow pencil-beam diagram?

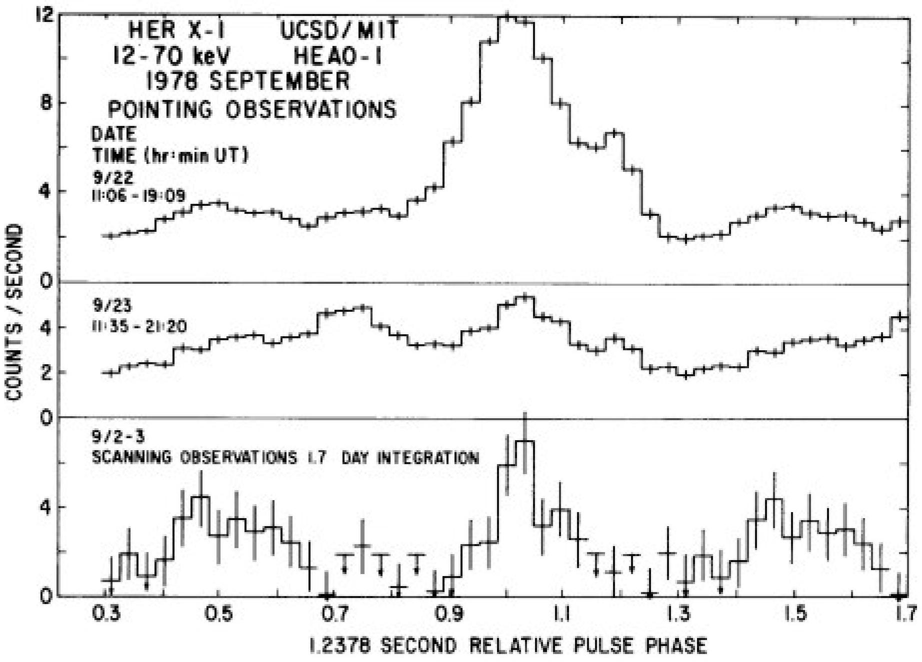
Most photons are ordinary and scatter in strong magnetic field almost along magnetic filed lines $(\sigma \sim \sigma_T \sin^2\beta)$.

Extraordinary photons could form a fan-like emission diagram due to resonant scattering but they are less abundant.

X-ray polarisation measurement can help distinguishing o- and e-photons

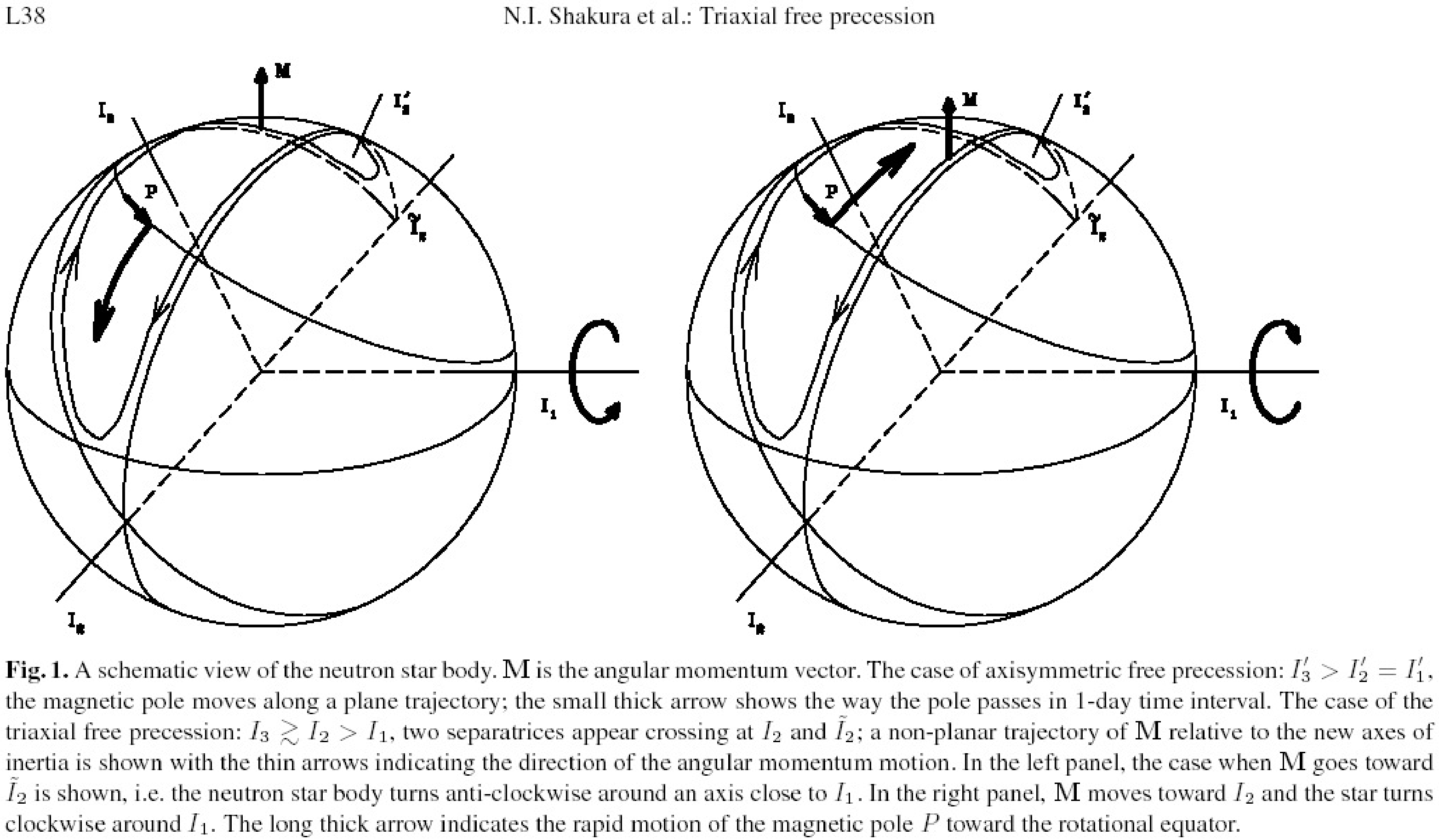
Further study of photon transfer under conditions appropriate to Her X-1 is in progress (V.Zhuravlev, PhD)

Special cases: HEAO-1 Sep 78



Dramatic (over 15 hours) pulse profile change (Soong et al.)

Explanation: just introduce small triaxiality…



L38 N.I. Shakura et al.: Triaxial free precession

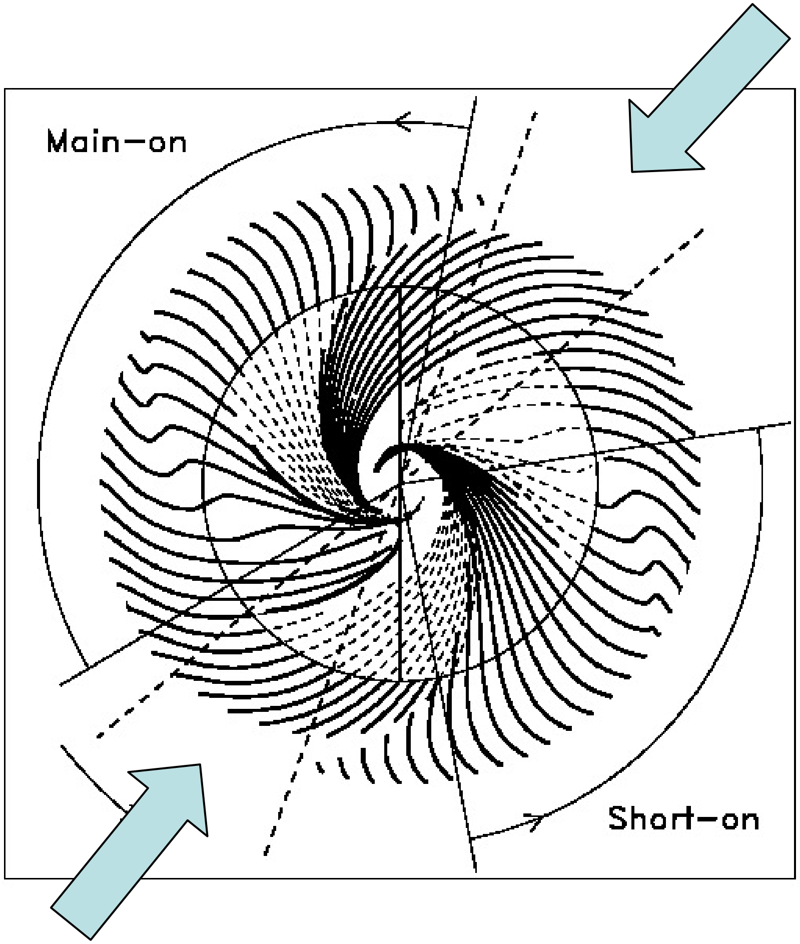
Fig. 1. A schematic view of the neutron star body. $\mathbf{M}$ is the angular momentum vector. The case of axisymmetric free precession: $I'_3 > I'_2 = I'_1$, the magnetic pole moves along a plane trajectory; the small thick arrow shows the way the pole passes in 1-day time interval. The case of the triaxial free precession: $I_3 \gtrsim I_2 > I_1$, two separatrices appear crossing at I_2 and $\tilde{I}_2$; a non-planar trajectory of $\mathbf{M}$ relative to the new axes of inertia is shown with the thin arrows indicating the direction of the angular momentum motion. In the left panel, the case when $\mathbf{M}$ goes toward $\tilde{I}_2$ is shown, i.e. the neutron star body turns anti-clockwise around an axis close to I_1. In the right panel, $\mathbf{M}$ moves toward I_2 and the star turns clockwise around I_1. The long thick arrow indicates the rapid motion of the magnetic pole P toward the rotational equator.

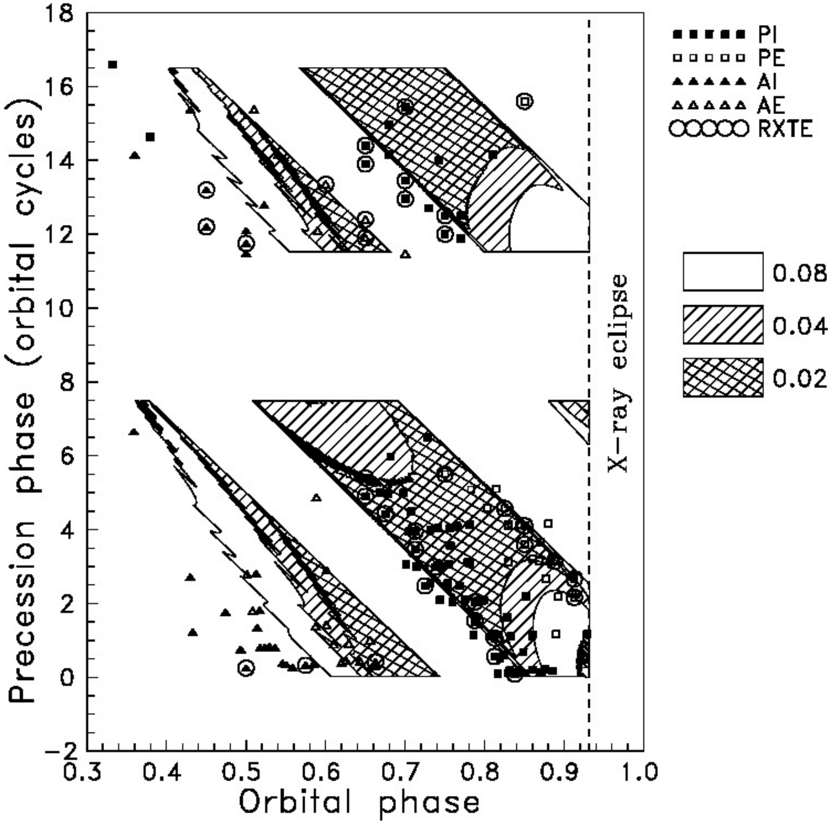
(from Shakura, Postnov, Prokhorov 1999)

Locking NS precession with disk precession

- Disk-magnetosphere interaction forces inner disk to keep in the NS rotational equator (Lipunov 1981, Semenov et al. 1982, Lai 1999) ➔ twisted disk
- Twisted disk forms complicated shadow for X-ray emission from central source
- Optical star-donor (HZ Her) periodically enters the shadow ➔ gas stream direction through L1 point is modulated with NS period (Ketsaris et al. 2001)
- Outer parts of the disk form inclined. Outer disk precession period is determined both by tidal torque and the dynamical action of the stream

Model for X-ray dips: screening by the gas streams (Ketsaris et al. 2001)





No (weak) stream when L1 point is screened

Conclusions

- Neutron star free precession as the clock mechanism for 35-day variability in Her X-1 is manifested in X-ray pulse profile evolution
- Emitting regions on the NS surface indicate complex multipole structure of the NS magnetic field
- Precessing outer regions of accretion disk are (weakly) coupled to NS free precession via gaseous stream non-coplanar to the orbital plane
- Issues to investigate: Why is the first turn-on after anomalous low states (outer disk in the orbital plane) always retarded in O-C? How do disk occultation effects show up in X-ray pulse profile? What physics is underlying correlations between dP/dt and O-C? ....etc.
- X-ray pulse resolved spectroscopy of the cyclotrone line and polarisation measurements are of major importance to test the model

Thank you very much!