Discovery of the Orbit of the Transient X ray Pulsar SAX J2103.5+4545

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Received __________________; accepted __________________

ABSTRACT

Using X-ray data from the Rossi X-Ray Timing Explorer (RXTE), we carried out pulse timing analysis of the transient X-ray pulsar SAX J2103.5+4545. An outburst was detected by All Sky Monitor (ASM) October 25 1999 and reached a peak X-ray brightness of 27 mCrab October 28. Between November 19 and December 27, the RXTE/PCA carried out pointed observations which provided us with pulse arrival times. These yield an eccentric orbit ($e=0.4 \pm 0.2$) with an orbital period of 12.68 ± 0.25 days and light travel time across the projected semimajor axis of 72 ± 6 sec. The pulse period was measured to be 358.62171 ± 0.00088 s and the spin-up rate $(2.50 \pm 0.15) \times 10^{-13}$ Hz s^{-1}. The ASM data for the February to September 1997 outburst in which BeppoSAX discovered SAX J2103.5+4545 (Hulleman, in't Zand and Heise 1998) are modulated at time scales close to the orbital period. Folded light curves of the 1997 ASM data and the 1999 PCA data are similar and show that the intensity increases at periastron passages.

Subject headings: binaries: close – pulsars: individual: SAX J2103.5+4545 – stars: neutron – X-rays: stars

1. Introduction

About 50 accretion powered X-ray pulsars are known. Although most of them are in binary systems, binary orbital parameters are known for only half of them (Bildsten et al. 1997). The optically identified companions are generally high mass stars (van Paradijs 1995). Among the high mass companions half of them are giant or supergiant stars and the other half are Oe and Be stars with episodic mass loss events.

The X-ray source SAX J2103.5+4545 was discovered using the BeppoSAX X-ray satellite (Hulleman, in't Zand, and Heise 1998). Pulsations at 358.61 s were found. The X-ray spectrum was a power law with photon number index of 1.27, typical of accreting high–field pulsars. In analogy to other X-ray pulsars this object was proposed to be a neutron star in a binary. It was noted that the B8 star HD 200709 was at the edge of the BeppoSAX error box.

In this work, we report on X-ray observations made with the Rossi X-ray Timing Explorer (RXTE) during an outburst two years later. We determine the orbital parameters using pulse arrival time analysis (see also Baykal, Stark, and Swank 2000).

2. Observations

SAX J2103.5+4545 was observed during 1999 November 19 and December 27 for an RXTE guest observer proposal to study the decays of transient pulsars. The results presented here are based on data collected with the Proportional Counter Array (PCA) (Jahoda et al. 1996) and All Sky Monitor (ASM) (Levine et al. 1996). The PCA instrument consists of five identical multi-anode proportional counter units (PCUs). The PCA operates in the 2-60 keV energy range, with a total effective area of approximately 7000 cm^2 and a field of view $\sim 1^\circ$ FWHM. The ASM consists of three identical Scanning Shadow Cameras (SSCs) each of which has a net active area for detecting X-rays of $\sim$30 cm^2. The ASM sensitive range is 2 to 12 keV. It perform sets of 90 sec pointed observations, covering $\sim$80% of the sky every $\sim$ 90 minutes.

3. Results

Background light curves were generated by using the background estimator models based upon the rate of very large events, spacecraft activation, and cosmic X-ray emission with the standard PCA analysis tools. The background light curves were subtracted from the source light curves which were obtained from the Good Xenon event data. The background subtracted light curve is presented in figure 1. The observation times were corrected with respect to the barycenter of the Solar system. Then summed power spectra were used to estimate the average pulse frequency. Pulse profiles were obtained by folding the lightcurves at the pulse period deduced from the power spectra. A template pulse profile is presented in figure 2. Pulse arrival times were found by cross-correlating the pulse profiles. In the pulse timing analysis, we have used the harmonic representation of pulse profiles (Deeter & Boynton 1985). The pulse profiles were expressed in terms of harmonic series and cross-correlated with the template pulse profile. Figure 3, presents the pulse arrival times. The pulse arrival times showed a quadratic trend superposed on orbital Doppler delays. The pulse arrival times can be written as (Deeter, Boynton, & Pravdo 1981)

$$\delta t = \frac{\delta P}{P}(t-t_0)+\frac{1}{2}\frac{\dot{P}}{P}(t-t_0)^2+x\sin(l)-\frac{3}{2}xe\sin(w)+\frac{1}{2}xe\cos(w)\sin(2l)-\frac{1}{2}xe\sin(w)\cos(2l). \quad (1)$$

Here t_0 is the mid-time of the observation; δP is the deviation from mean pulse period P; $\dot{P}$ is the time derivative of the pulse period; $x = a_x\sin(i)/c$ is the light traveltime for projected semimajor axis (where i is the inclination angle between the line of sight and the orbital angular momentum vector); $l = 2\pi(t-T_{\pi/2})/P_{orbit}+\pi/2$ is the mean orbital longitude at time t; $T_{\pi/2}$ is the epoch when the mean orbital longitude is equal to 90 °; P_{orbit} is the orbital period; e is the eccentricity; and w is the longitude of periastron. The above expression is fitted to the pulse arrival times data. Table 1 presents the timing solution of SAX J2103.5+4545. Figure 4 presents the pulse arrival times after the removal of the quadratic trend (or intrinsic -$\dot{P}$). The source was spinning up during the observation at the rate of $\dot{\nu} = (2.5 \pm 0.15) \times 10^{-13}$ Hz s^{-1}. The periodic trend of the pulse arrival times yields an eccentric orbit (e=0.4 ± 0.2) with a orbital period of 12.68 ± 0.25 days.

The PCA lightcurve is folded at the orbital period of 12.68 days with respect to the reference time of mean longitude 90°. The folded PCA lightcurve is presented in figure 5. In this figure, orbital phase $\sim$0.4 corresponds to the periastron passage of the neutron star. It is clearly seen that the X-ray flux (or count rate) is increased at the periastron passage of the X-ray pulsar. This is strongly suggesting that the mass accretion rate onto the neutron star is increased during the periastron passage.

Since SAX J2103.5+4545 was observed with the BeppoSAX satellite from February to September 1997 (Hulleman, in't Zand and Heise 1998) we extracted the public ASM data and presented 3 days average of ASM light curve in figure 6. The X-ray pulsar was actively seen in ASM in 1997 for $\sim$ 200 days. In order to see the X-ray flux modulations due to the eccentric orbit, we employed a χ^2 search. The result is shown in figure 7; there is obvious peak centered at 12.6 days. The ASM data folded on the orbital period is shown in figure 8. The folded ASM light curve also shows an increase in X-ray flux at the periastron passage. The ASM and PCA lightcurves are quite similar.

The derived orbital parameters yield a mass function for the companion

$$f(M) = \frac{4\pi^2 (a_x \sin i)^3}{G P_{orb}^2} = \frac{(M_c sini)^3}{(M_x + M_c)^2} \sim 2.5 M_\odot. \quad (2)$$

For an X-ray pulsar mass of ($\sim$1.4M$_\odot$) and an inclination of 45°, the companion mass would be $\sim 7 M_\odot$.

4. Discussion

High mass X-ray binaries fall into three separate groups when the pulse periods are compared with the orbital periods (Corbet 1986). The systems with Be companions show correlations between orbital period and spin periods (Corbet 1986, van Kerkwijk 1989), while systems with giant and supergiant companions fall into two separate regions. X-ray pulsars with Be type companions show transient behavior and these pulsars generally accrete from the variable envelope of a Be star. The mass accretion increases at the periastron passages since the density of plasma is greater when the pulsar is close to the companion star. If SAX J2103.5+4545 has a Be type companion, according to the Corbet diagram, a pulse period of $\sim$ 358 s implies an orbital period of $\sim$190 d (Hulleman, in't Zand and Heise 1998). The measured orbital period and pulse period of SAX J2103.5+4545 suggests that the companion star has to be a giant or a supergiant star (Corbet 1986). It is interesting to note that even if this pulsar has a supergiant companion it is still a transient X-ray pulsar.

Hullemann, in't Zand, & Heise (1998) attempted to use the theoretical relation between $\dot{P}$ and X-ray luminosity to test the consistency of possible locations of the source, but their upper limits on $\dot{P}$ were not restrictive. According to Ghosh & Lamb (1979) the maximum spin-up rate ($-\dot{P}$) is given by

$$-\dot{P} = 2.2 \times 10^{-12} \mu_{30}^{2/7} m_x^{-3/7} R_6^{6/7} I_{45}^{-1} P^2 L_{37}^{6/7} \quad s \quad s^{-1} \tag{3}$$

where μ_{30}, m_x, R_6, and I_{45} are the magnetic dipole moment in units of 10^{30} G cm^3, the mass in units of solar mass ($m_x = M_x/M_{\odot}$), the radius in units of 10^6 cm and the moment of inertia in units of 10^{45} g cm^2, respectively, and L_{37} represents the X-ray luminosity in units of 10^{37} erg s^{-1}. The spin-up rate we observed (-3.2×10^{-8} s s^{-1})implies an accretion luminosity of $L_x = GM\dot{M}/R \sim 8 \times 10^{35}$ erg s^{-1} for a typical surface magnetic field strenght of $\sim 10^{12}$ Gauss.

The average flux seen by the ASM during the period of our PCA measurements was only 5 mCrab and the PCA average spectrum implied a total unabsorbed flux of 2.4×10^{-10} ergs cm^{-2} s^{-1}. A distance can be estimated from this flux and the X-ray luminosity estimate given above; the result is D $= \sqrt{\frac{L_x}{4\pi F_x}} \sim 5$ kpc. is about 5 kpc. The B star HD 200709 was suggested as a marginal candidate of optical counterpart at a distance of ~ 0.7 kpc (Hulleman, in't Zand and Heise 1998). Our finding suggests that SAX J2103.5+4545 is far beyond the star HD 200709 and that deeper searches are required for detection of an optical counterpart.

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Figure Caption

Fig. 1 The total (5 PCU) RXTE/PCA background subtracted X-ray light curve.

Fig. 2 The pulse profile of SAX J2103.5+4545. The normalized count rate is 83 count/sec.

Fig. 3 Pulse arrival times of SAX J2103.5+4545 with respect to the constant pulse period of 358.62171 sec. The quadratic trend shows the intrinsic -$\dot{P}$.

Fig. 4 Pulse arrival times of SAX J2103.5+4545 with respect to the constant pulse period of 358.62171 sec after the quadratic trend is removed (above). Solid line denotes the orbit model. The residuals of pulse arrival times in terms of sigma values (below).

Fig. 5 Folded lightcurve of PCA data at the orbital period. The normalized count rate is 83 count/sec. Orbital phase 0 corresponds to mean longitude of 90 ° and orbital phase $\sim$ 0.4 corresponds to periastron passage.

Fig. 6 The light curve of ASM data.

Fig. 7 χ^2 search of ASM data covering 1997 outburst.

Fig. 8 Folded lightcurve of ASM light curve. Orbital phase 0 corresponds to mean longitude of 90 ° and orbital phase $\sim$ 0.4 corresponds to periastron passage.

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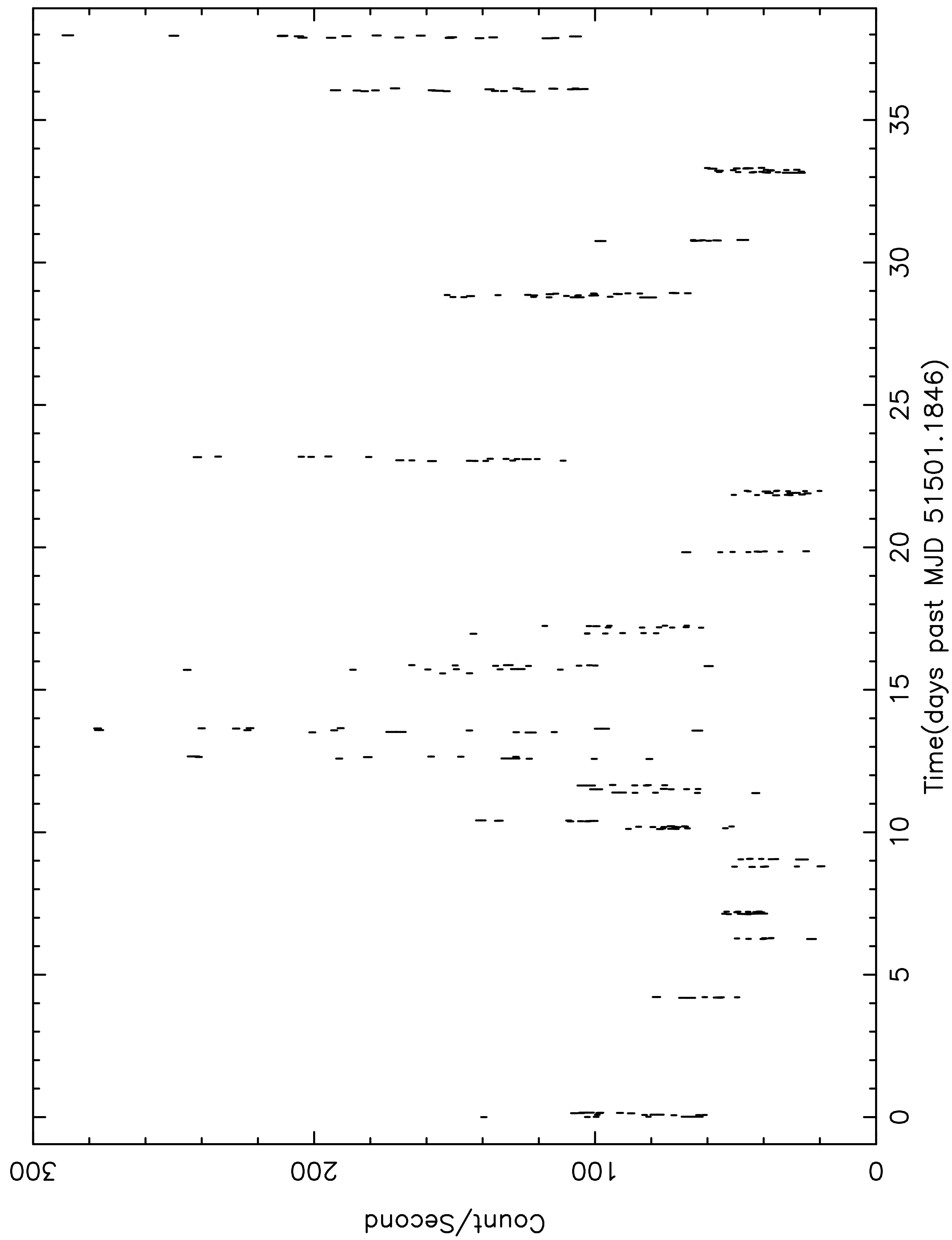
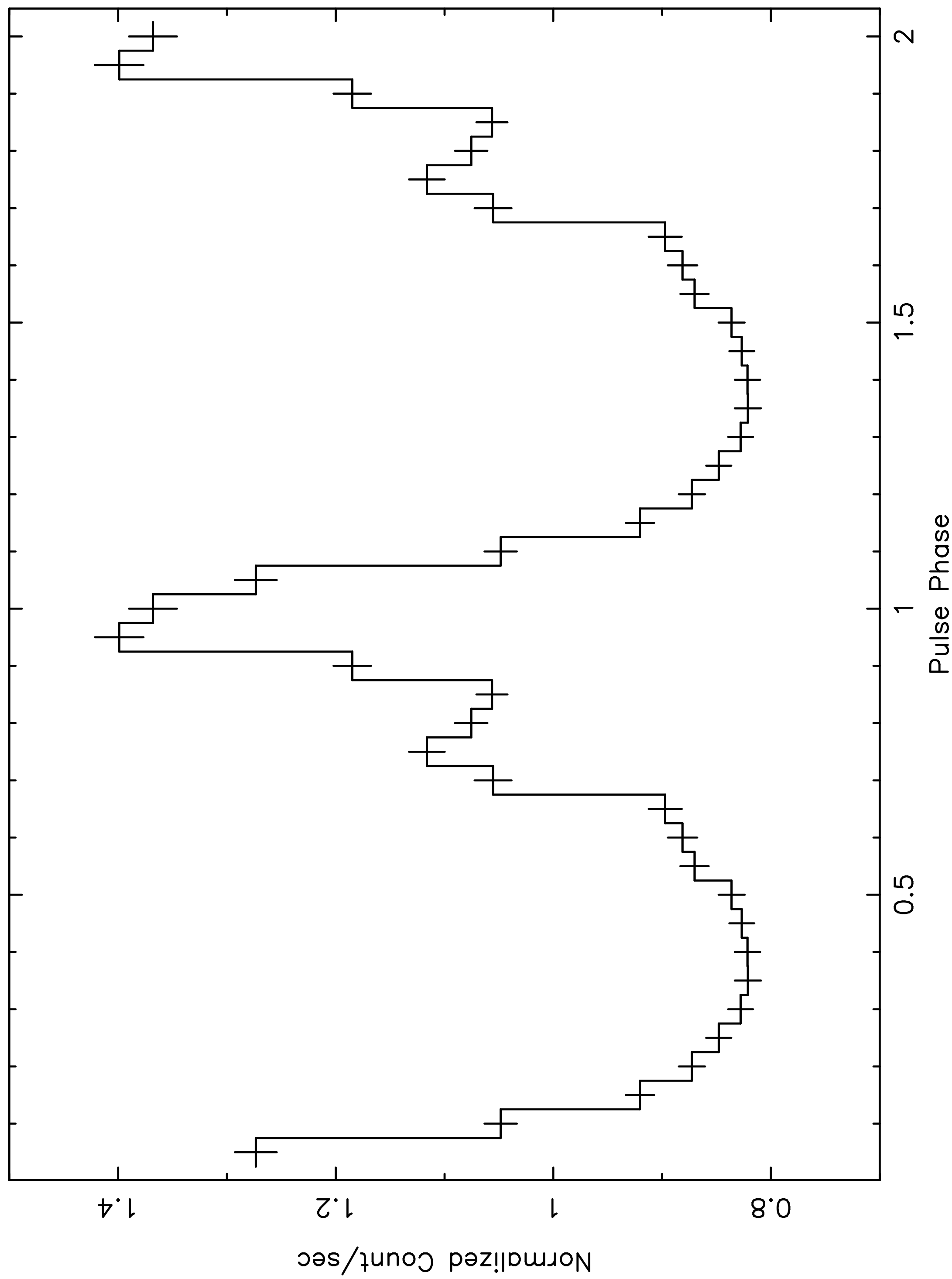
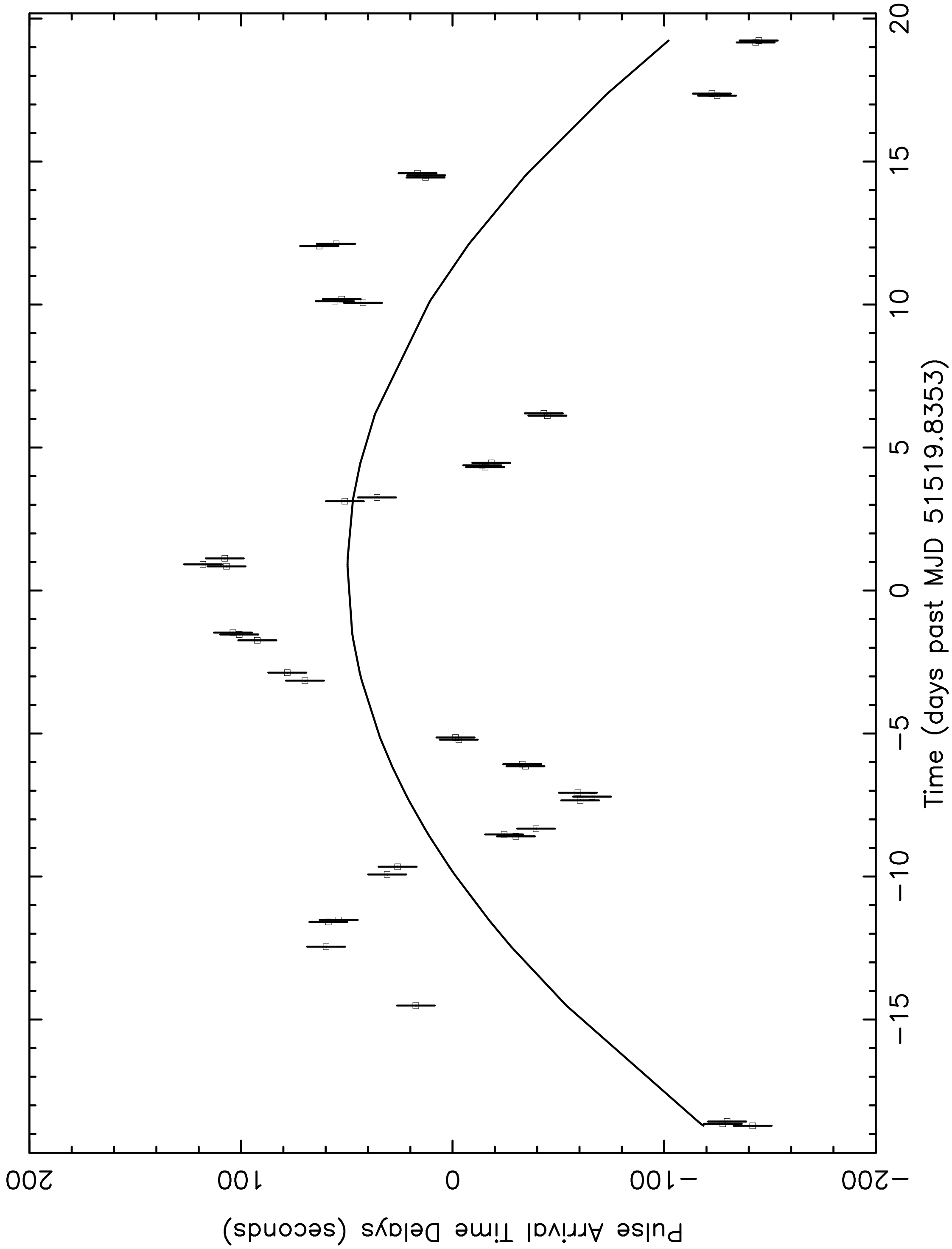
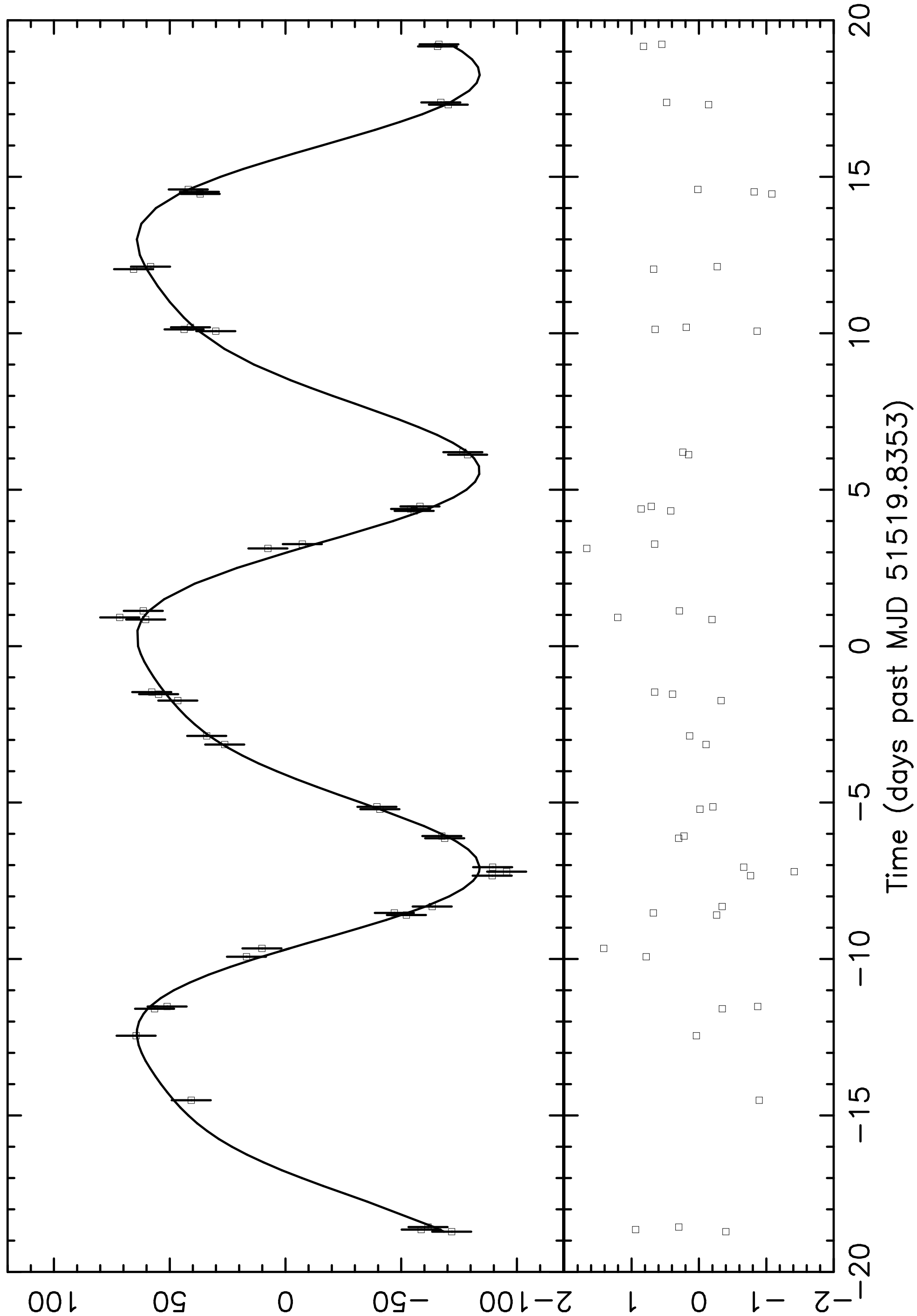
Table 1: Timing Solution of the transient X-ray pulsar SAX J2103.5+4545

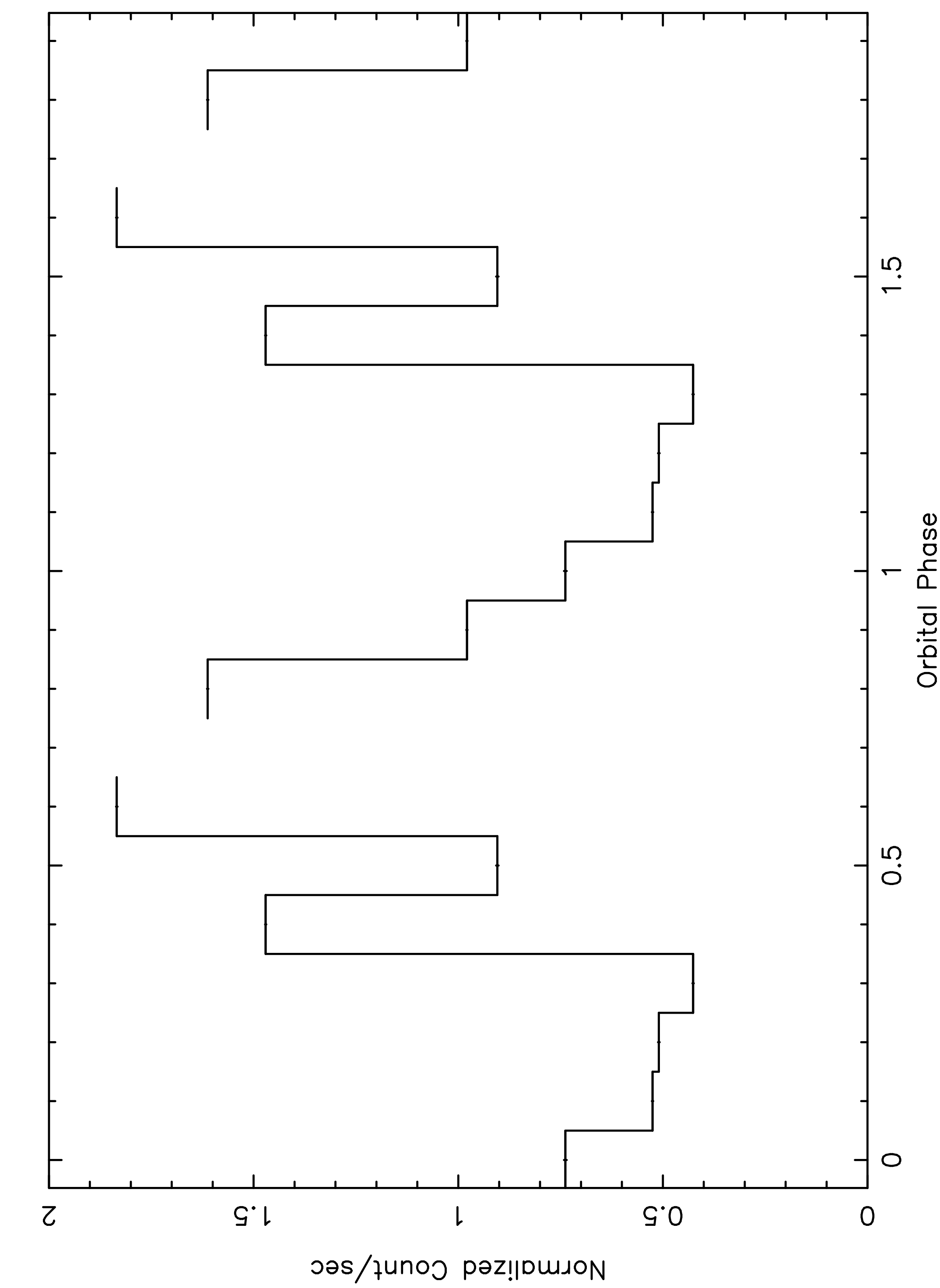
Epoch(MJD)	51519.8353(8)
Pulse Period (sec)	358.62171(88)
Derivative of the Pulse Period (sec $year^{-1}$)	-1.0(9)
Orbital Epoch (MJD)	51519.3(2)
P_{orb} (days)	12.68(25)
a_x sin i (lt-sec) (projected semimajor axis)	72(6)
e (eccentricity)	0.4(2)
w (longitude of periastron)	240(30)

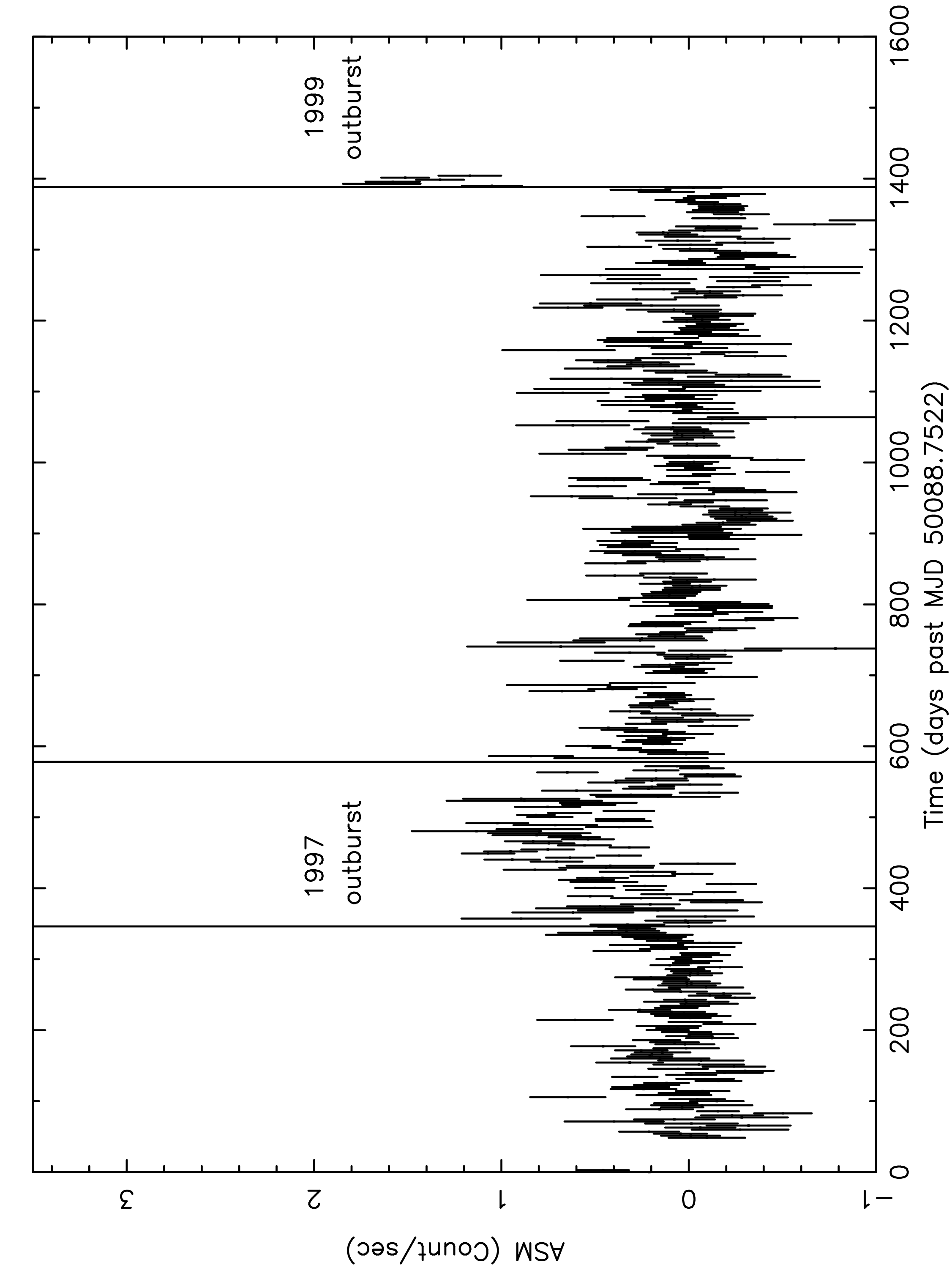

Time(days past MJD 51501.1846)
Count/Second
0
5
10
15
20
25
30
35
0
100
200
300

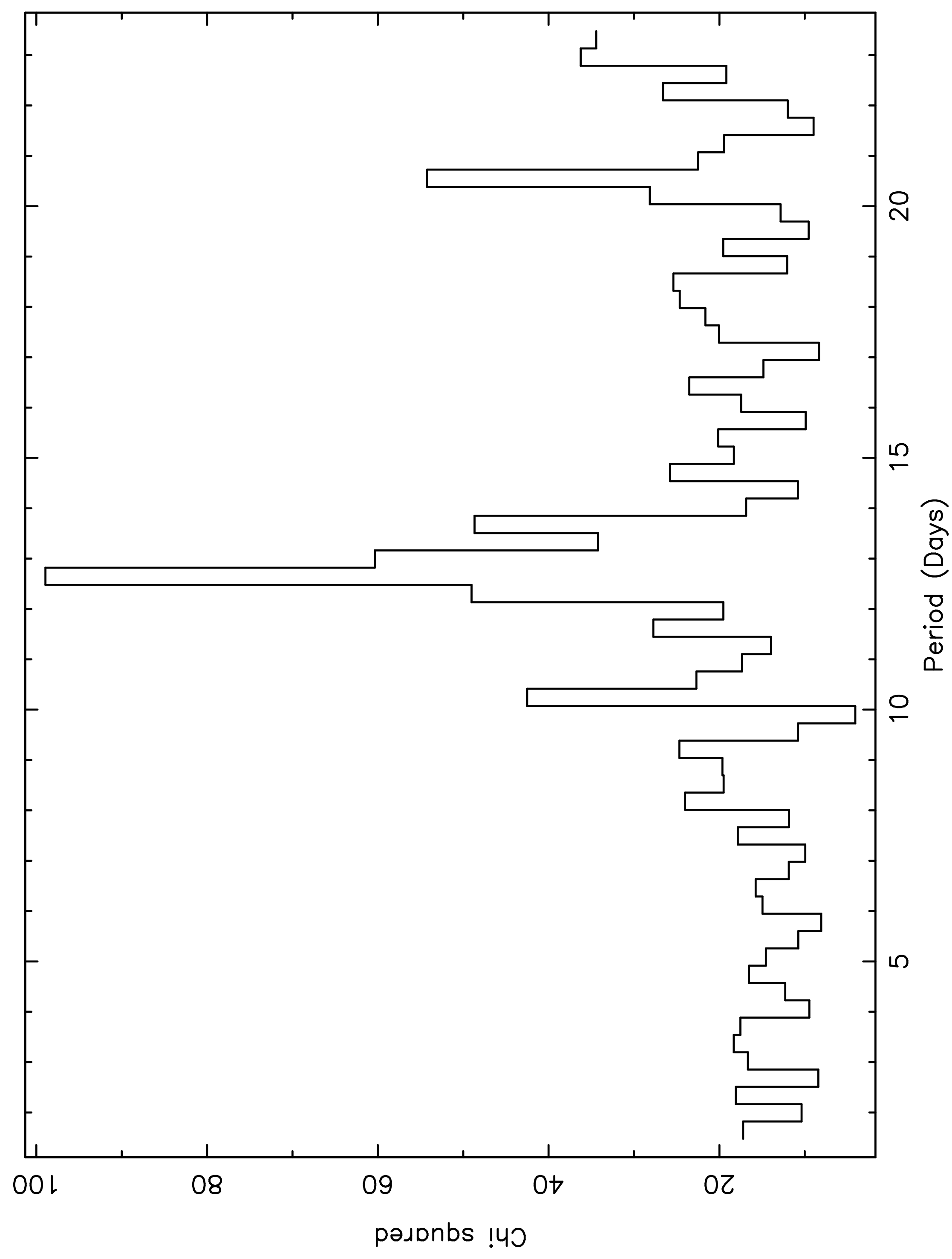

Pulse Phase
0.5
1
1.5
2
Normalized Count/sec
0.8
1
1.2
1.4


Time (days past MJD 51519.8353)
Pulse Arrival Time Delays (seconds)
−15
−10
−5
0
5
10
15
20
200
100
0
−100
−200

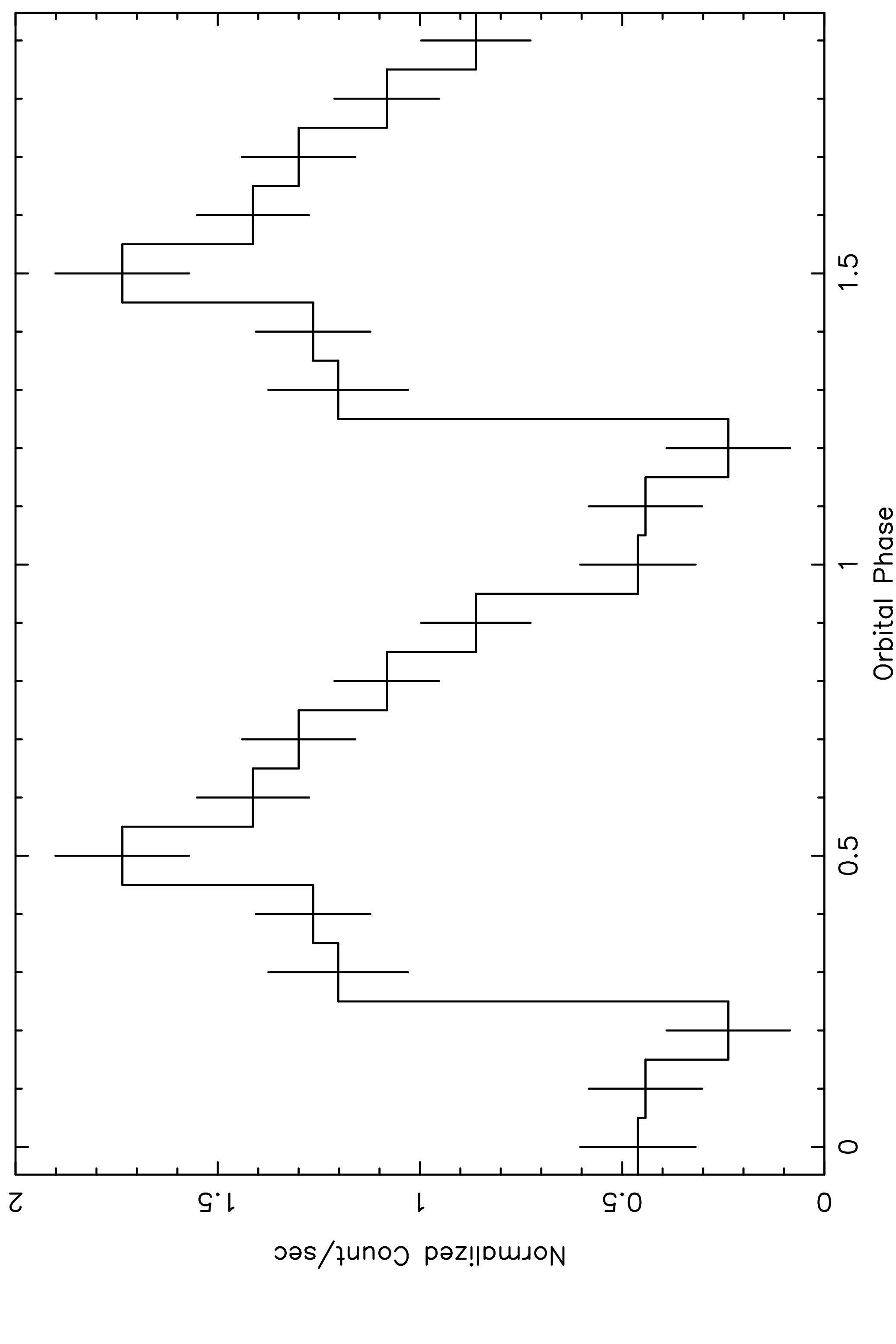

Pulse Arrival Times (sec)
Residuals (sigma)
Time (days past MJD 51519.8353)
100
50
0
−50
−100
2
1
0
−1
−2
−20
−15
−10
−5
0
5
10
15
20


Normalized Count/sec
0
0.5
1
1.5
2
Orbital Phase
0
0.5
1
1.5


1999
outburst
1997
outburst
Time (days past MJD 50088.7522)
ASM (Count/sec)
0
200
400
600
800
1000
1200
1400
1600
−1
0
1
2
3



Period (Days)
5
10
15
20
Chi squared
20
40
60
80
100


Orbital Phase
Normalized Count/sec
0
0.5
1
1.5
2