DETECTION OF 2.93 MS PULSATIONS IN SCO X-1

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ABSTRACT/RESUME

Scorpius X-1 is an x-ray binary in the class exhibiting quasi-periodic oscillations or QPO. Models for QPO sources involve a neutron star with low magnetic field and high spin rate in orbit with a low mass stellar companion. Here is reported that high frequency coherent pulsations have been detected during an observation of Sco X-1. The observation was taken with a balloon-borne phoswich detector sensitive to X-rays in the 18 to 120 keV energy band. The pulsations are interpreted as the spin period of the neutron star.

Keywords: Sco X-1, pulsations, neutron stars, X-rays

1. INTRODUCTION

The bright X-ray source Scorpius X-1 has been observed many times since its discovery as the first non-solar X-ray source in 1962 (Ref. 1). Despite its early discovery and the many observations of this source, little is known about the physical nature of the X-ray emission. Sco X-1 is the optical variable V818 Scorpii with a blue magnitude of 12.5. The distance to Sco X-1 is poorly known, although it is believed to be (Ref. 2) at 1-2 kpc, so that it belongs to the class of galactic bulge sources with X-ray luminosities near the Eddington limit. Optical photometry (Ref. 3) has given an orbital period for Sco X-1 of $0^d.787$. The lack of eclipses and the correlated flaring at X-ray and optical wavelengths (Ref. 4) indicates that Sco X-1 has a low mass companion with the optical light coming from an accretion disk and that the orbit is nearly pole-on (Ref. 2). More recently Sco X-1 has been discovered as a QPO source (Ref. 5), clearly placing it in the category of other near-Eddington luminosity galactic bulge X-ray sources such as GX5-1, Cyg X-2, and GX 349+2.

Limits on any coherent pulsations in the X-ray flux from EXOSAT observations of Sco X-1 are (Ref. 5) less than 0.8% for frequencies less than 250 Hz. Analysis (Ref. 6) of a 1969 rocket flight observation gave less than 1% upper limits for periods from 3 to 300 milliseconds. Weaker limits were obtained in an earlier analysis (Ref. 7) of the phoswich detector data which is the data analyzed for the result reported here. The long term variability of Sco X-1 in X-rays from the Ariel V all-sky monitor data on has been reported (Ref. 8) in a search for orbital variations.

2. OBSERVATIONS

The data under analysis here were taken during a Dec. 18, 1984 balloon flight of a phoswich scintillator X-ray telescope (Ref. 9) conducted from Hyderabad, India. The detector consisted of four 5 inch diameter 3 mm NaI(Tl)-25mm CsI(Na) scintillator sandwiches bonded to photomultiplier tubes, each with a $5^\circ \times 5^\circ$ brass collimator surrounded by a graded shield of lead, tin, and copper. The nominal energy range for detection of X-rays was 20 to 120 keV. Pulse height, pulse width and event time, with 0.04 ms resolution, for each event, as well as house-keeping data were telemetered to the ground for recording on magnetic tape. The telemetry rate gave a 5.12 ms frame rate (one frame consisted of 32 8-bit words of data). A 14 bit frame counter was used to determine frame time, a 7 bit counter to determine time within a frame. 2195 s of continuous Sco X-1 on-source data were obtained starting at 04:12:30 UT.

3. DATA ANALYSIS

The initial analysis (Ref. 7) showed that Sco X-1 was detected only in the energy range 18-60 keV, with a strong signal only in the 18 to 40 keV range. That analysis was limited to searching for pulsations for periods greater than 5.12 ms and showed no coherent pulsations. The data in 18-40 keV band binned on 30s timebins is shown in Figure 1. The mean count rate was 7.48 s^{-1} including source and background, the total number of events was 16429. A separate background pointing gave a count rate in the

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18-40 keV band of 5.51 s^{-1}, giving a net source rate of 1.97 s^{-1}.

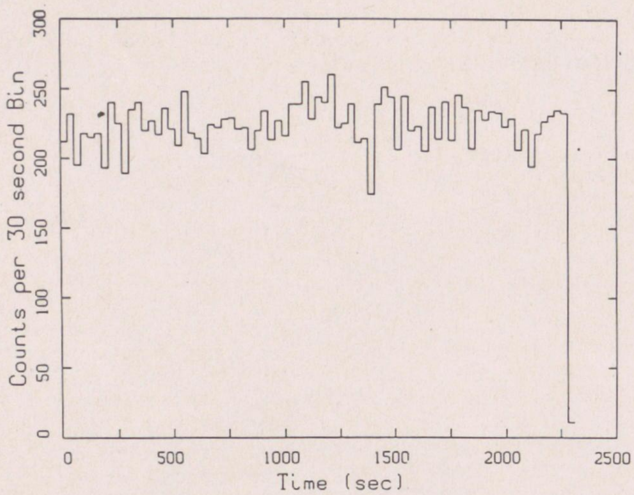

Fig.1 Observed counts in 30 s time bins for 2195s observation of Sco X-1 in 18-40 keV X-rays.

The Fast Fourier Transform (FFT) algorithm (Ref. 10) was used to search for pulsations. A 2^{22} bin FFT was run on the data covering the frequency range 4.39 x 10^{-4} to 920 Hz (see Fig. 2). The units of power were scaled as χ^2, giving a 90% threshold power of 33.4. The only power above threshold was at a frequency of f=340.9017 Hz (i.e. 2.933396 ms) with a power of 35.6. The calculated 90% confidence threshold of this FFT was A=6.9% where a signal of the form: R (1 + A cos(2πft)) is assumed. The power of 35.6 corresponds to a confidence level of 96.1%. No peak in the power spectrum was seen in 517 s of background data taken immediately before the Sco X-1 data or in 5804 s of data taken after. Neither were pulsations detected in an FFT on data taken during the on-source pointing with the energy range was restricted to 60 - 120 keV.

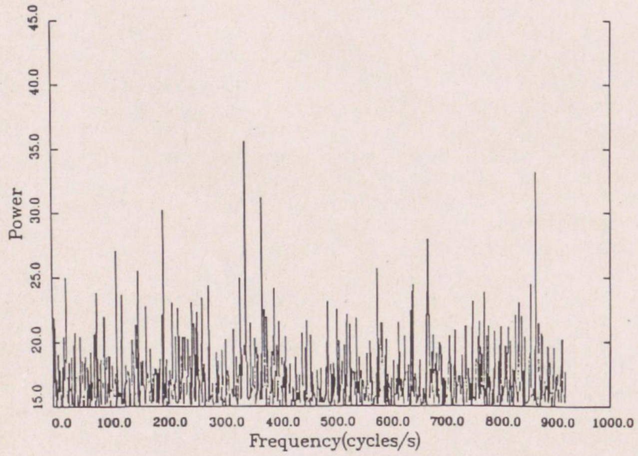

Fig.2 Power spectrum of 18-40 keV observation of Sco X-1 from a Fast Fourier Transform with 2^{22} time bins. Only powers above 15.0 are plotted.

Epoch folding was performed on the data set for 40 periods between 2.933376 and 2.933415 ms on both source and background data. The χ^2 vs. period plot for the source data is shown in **Figure 3a** for epoch folding with 8 phase bins. There is a peak χ^2 of 33.6 at 2.933396 ms corresponding to a single trial chance probability of 2.0 x 10^{-5} or 8.0 x 10^{-4} for 40 periods (99.92% confidence). This χ^2 is equivalent (Ref. 10) to a sinusoidal amplitude of 5.8%. The folded light curve (see Fig. 3b) has roughly a sinusoidal shape. No pulsations were seen when the 18-40 keV off-source data or the 60-120 keV on source data were epoch folded at periods near the 2.933396 ms period.

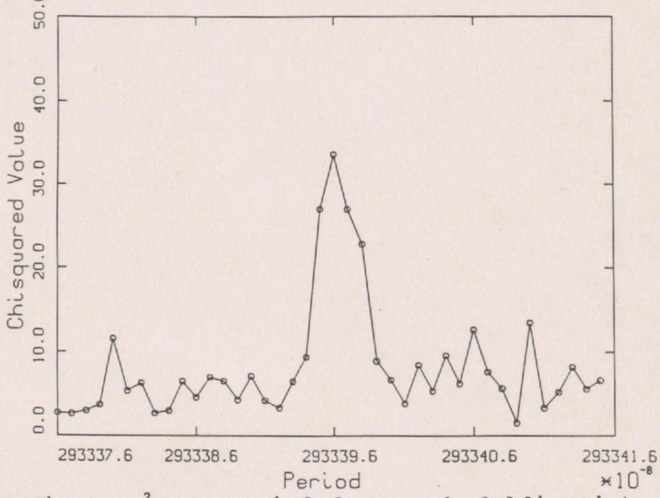

Fig.3a χ^2 vs. period for epoch folding into 8 phase bins of the 2195 s 18-40 keV observation of Sco X-1.

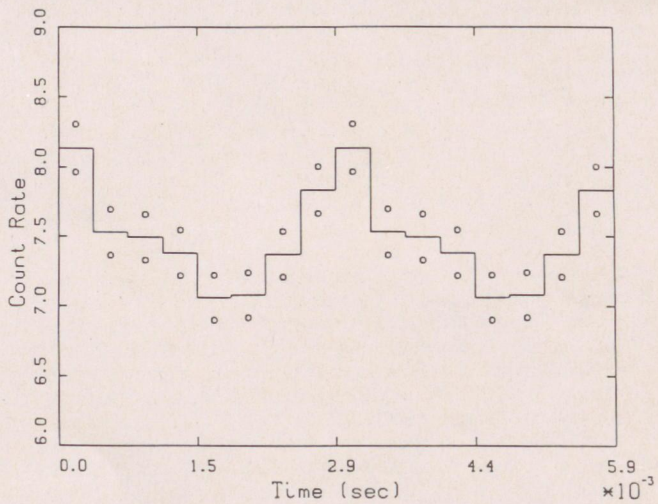

Fig.3b Folded light curve for a period of 2.933396 ms for 2195 s of 18-40 keV data.

The 18-40 keV on-source data was split into two 1097.5 s halves which were epoch folded over 20 periods covering the same period range as above. The 2.933396 ms period was seen in the first half with χ^2 of 37.1 with the same phase for the peak and the same shape of light curve as the epoch folded full data set. This χ^2 corresponds to a single trial probability of 4.5 x 10^{-6} and a 99.99% confidence level. No statistically significant peak in χ^2 was seen for the second half. The first half was further subdivided into 2 548.75 s quarters. Epoch folding on these gave peak χ^2 of 21.2 at 2.933396 ms and 25.2 at 2.933392 ms, so that the signal is present throughout the first half of the observation. The data was separated into 2 energy bands, 18-25 keV (count rate 2.60 s^{-1}) and 25-40 keV (count rate 4.84 s^{-1}). Epoch folding on each showed the pulsations with similar amplitude and the same phase in both energy bands. Epoch folding was also done with 16 phase bins, however no evidence for any significant difference in pulse shape from that of Fig. 3b was seen.

To determine the period and sinusoidal amplitude and their errors more accurately the technique of fitting to the χ^2 vs period curve (Ref. 11) was used. The results were P = 2.9333964 (.0000013) ms and A = 0.056 (0.012) with 1σ limits in brackets. Correcting for the earth's motion yields a barycentric period of 2.9334923 ms. Expressed as a modulation of source rather than total count rate, the amplitude is 0.22 (0.05).

Recent observations by EXOSAT have shown (Ref. 5) Sco X-1 to be a QPO source with a QPO peak containing approximately 5% of the flux and with low frequency noise (LFN) in the power spectrum containing 2 to 3% of the flux. A search for LFN and QPO was carried out using low resolution FFTs. 27 FFTs on 81.92s data segments were summed, as well as 278 FFTs on 8.192 s data segments. Neither showed any powers above the 90% confidence threshold. Both showed distributed power with 54 and 556 degrees of freedom, resp. The calculated 90% confidence limits on amplitude of coherent pulsations of these summed FFTs were 0.091 and 0.149 for the frequency ranges 0.0123 to 504 Hz and 0.123 to 50.4 Hz, respectively. Averages of power were done over 1 Hz wide and 10 Hz wide bands in these and in the original (high resolution) power spectrum for frequencies from 0 to 50 Hz (excluding power at the zero frequency). The averages in no case differed by as much as 2 times the root of the expected variance for the sums. This was calculated as the square root of the expected variance of the power (54, 556 and 2 for the 3 FFTs, resp.) divided by the square root of the number of powers in the average. The 2σ limits on LFN and on QPO obtained in this way were 4.2% of total flux, which increases to 16% expressed as a percentage of source flux.

4. DISCUSSION

The 2.93 ms period observed here is constant over the 1100s first half of the data. However the X-ray source motion should cause a period shift during the observation. Radial velocities have been measured for various optical emission lines. A sine wave fit (Ref. 3) at the orbital period gave K = 20±10 km s^{-1}, while K = 72±5 km s^{-1} and K = 58±3 were obtained (Ref. 2) from H_β, H_γ and H_δ lines and from He 4686. Orbital smearing of the pulse frequency is given by: $\Delta f/f = \Delta V_r/c$ with ΔV_r the change in radial velocity over the observation period. For the worst case K = 72 km s^{-1}, and the X-ray source has the same velocity as the optical source. Then for a circular orbit and the source at conjunction one has a maximum frequency smearing: ΔV_r = 15 km s^{-1}, $\Delta f/f = 5 \times 10^{-5}$. For the source at quadrature, ΔV_r = 1.6 km s^{-1} , $\Delta f/f = 5 \times 10^{-6}$. These are larger than the observed limits from FFT or epoch folding of $\Delta f/f < 2.6 \times 10^{-6}$. However the observed limit on smearing is consistent with either a K value less than 35 km s^{-1} or with the X-ray source moving less than half as fast as the optical source.

It is important to verify the pulsation period with other observations. However such pulsations have not been found in the existing data from the Einstein Monitor Proportional Counter (MPC) (private communication, R.F Elsner). The period from this work (reported in IAUC 4485) was not seen in EXOSAT data (IAUC 4489). However the EXOSAT time resolution was only 0.98 ms and high energy photons only comprise a small fraction of the total number of events. The occurence of pulsations is most likely a transient event, since it was seen in only part of our data, making verification more difficult. The short observation here (pulsations detected in the first 1100 of 2200 s) does not allow any study of the binary orbit or of intrinsic changes in neutron star spin period.

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