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著者(和文)	篠田 浩一
Authors	K. Shinoda, T. Kii, K. Mitsuda, F. Nagase, Y. Tanaka
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## Discovery of the Quasi-Periodic Oscillations from the X-Ray Pulsar X1627–673

Koichi SHINODA, Tsuneo KII, Kazuhisa MITSUDA,  
Fumiaki NAGASE, and Yasuo TANAKA

*Institute of Space and Astronautical Science,  
1-1, Yoshinodai 3-chome, Sagamihara, Kanagawa 229*

Kazuo MAKISHIMA

*Department of Physics, Faculty of Science, The University of Tokyo,  
Bunkyo-ku, Tokyo 113*

and

Noriaki SHIBAZAKI

*Department of Physics, Rikkyo University,  
Nishi-Ikebukuro 3-chome, Toshima-ku, Tokyo 171*

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### Abstract

Quasi-periodic oscillations (QPO) with a centroid frequency of 0.04 Hz were detected in the X-ray flux from a low-mass binary X-ray pulsar, X1627–673. The FWHM of the QPO peak in the power spectrum was 0.02 Hz. Though the QPO were observed over the entire energy range, 2 – 22 keV, they were most prominent in the energy band 14 – 18 keV. The QPO frequency is consistent with the beat frequency between the neutron star rotation and Keplerian motion at the Alfvén radius of the accretion disk. This is, however, not consistent with the theoretical model of the accretion torque which is widely accepted for interpreting the steady spin-up trend of this source.

Key words: Quasi-periodic oscillations; X-ray binaries; X-ray pulsars.

### 1. Introduction

X1627–673 is an X-ray pulsar with a period of 7.7 s. It is considered to have a low-mass companion star and to be powered by an accretion disk. The 7.7-s X-ray

pulsations were first discovered by Rappaport et al. (1977) and have been intensively monitored for a long time [e.g., Nagase (1989), and references therein]. The pulse-period history of this source shows a stable spin-up with a constant rate of  $\dot{P}/P \sim -2 \times 10^{-4} \text{ yr}^{-1}$ . In spite of extensive Doppler analyses of pulse arrival times, evidence of binary motion from the X-ray data has not yet been obtained. A faint ( $m_V \sim 18.5$ ) blue star, KZ TrA, was identified as the optical counterpart by McClintock et al. (1977). Most of the optical emission was considered to arise from the reprocessing of X-ray radiation, supported by a subsequent detection of 7.7-s optical pulsations by Ilovaisky et al. (1978). From an optical-pulsation analysis Middleditch et al. (1981) found a weak side lobe frequency, which they interpreted as arising from X-ray reprocessing in the secondary star. A combination of this result with a strong upper limit of  $\sim 10$  m lt-s for the projected semi-major axis of the neutron star leads to a very low secondary mass of  $0.1 M_{\odot}$  (Levine et al. 1988). The X-ray luminosity is  $1 \times 10^{37} \text{ erg s}^{-1}$  (White et al. 1983) for an assumed source distance of 8 kpc. It is most likely that an accretion disk is present (Roche lobe geometry). Pravdo et al. (1979) found a hump structure around 20 keV in the energy spectrum of this source. From this they estimated the surface magnetic field of the neutron star to be  $1.5 - 6 \times 10^{12} \text{ G}$ . Kii et al. (1986) proposed a somewhat larger value of  $8 \times 10^{12} \text{ G}$  from the energy dependence of the X-ray pulse profile.

Quasi-periodic oscillations (QPO) at frequencies 5–100 Hz have been observed in the X-ray flux from more than ten low-mass X-ray binaries [LMXRB's, see Lewin et al. (1988) for a review]. Recently, broad peak structures were discovered in the power spectrum of two X-ray pulsars, Cen X-3 (Tennant 1988) and the transient EXO 2030 + 375 (Angelini et al. 1990). We observed X1627–673 with the Ginga satellite and detected a broad peak structure at a frequency of about 0.04 Hz. Since X1627–673 shows a very stable spin-up, and is certainly an accretion powered X-ray pulsar, the present observations provide us with an ideal test for some of the models of QPO and accretion torque.

## 2. Observations and Results

Ginga observations of X1627–673 were performed for about three days from 1988 July 27, 07:09 (UT) to 1988 July 30, 00:20 (UT). The X-ray intensity was fairly stable during the observations with an average intensity of 30 mCrab, except for some recurrent flares with intensity increases by a factor of 2 and durations of  $\sim 1000$  s. We obtained a heliocentric pulse period of  $7.6625685 \pm 0.000003 \text{ s}$  at JD 2447400.8, which is consistent with the spin-up trend previously observed. The energy dependence of the pulse profiles and the phase-resolved energy spectra are both similar with those seen in previous observations (Pravdo et al. 1979; Kii et al. 1986; Levine et al. 1988). We obtained no evidence for binary motion from the pulse arrival time analyses: the upper limit for the projected semimajor axis of the X-ray star is  $a_x \sin i < 0.008 \text{ lt-s}$  ( $3\sigma$ ).

About 20000 s of data which have a time resolution better than 0.5 s [the MPC-2 and MPC-3 modes with high and medium bit-rates, Makino and the ASTRO-C team (1987)] were analyzed in order to obtain Fourier power spectra of the source. All of the data were rebinned to 0.5 second bins and Fourier-transformed every 2048 bins. Then,

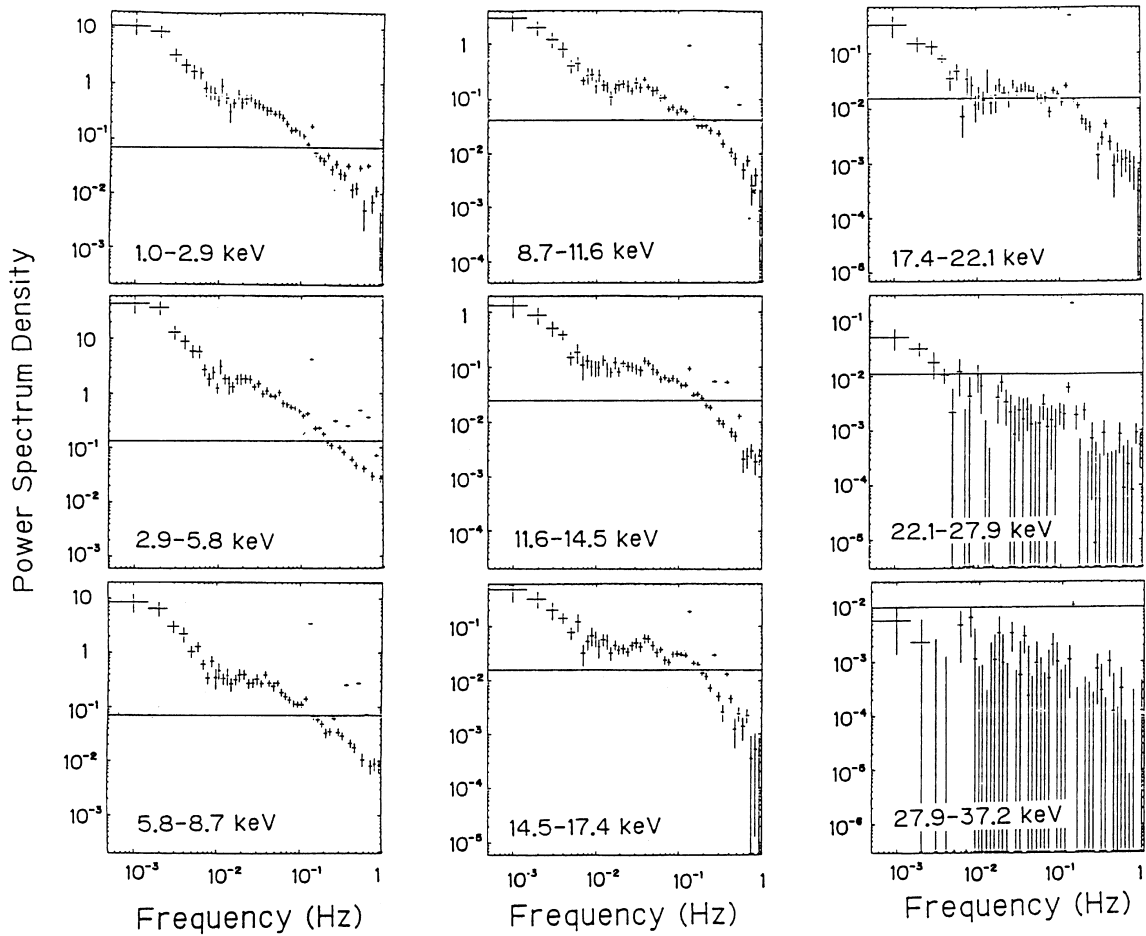


Fig. 1. Average power spectra of X1627-673 observed with Ginga in July 1988 in nine different energy bands. The Poisson noise component in the power spectra has already been subtracted. The vertical bars show the  $1\text{-}\sigma$  statistical uncertainty, which is estimated from a standard deviation of 13 ensembles of the power spectra.

13 such ensembles of power spectra were averaged. In figure 1, we show the power spectra, thus obtained, in nine different energy bands. All of the power spectra show a shoulder-like feature in the range 0.01–0.1 Hz, which looks similar to the low-frequency noise (LFN) seen in non-pulsating LMXRB's (e.g., Lewin et al. 1988). One can also see a broad hump near 0.04 Hz. This broad peak is most prominent in the energy range 14.5–17.4 keV. In order to test the statistical significance of the broad hump at about 0.04 Hz, the power spectrum of the 14.5–17.4 keV band was fitted with a model which does not include a broad peak structure. We employed a model which consists of a power-law function for the noise component which increases towards the lower frequency (similar to the very low-frequency noise, VLFN, in LMXB's), a Lorentzian function for the LFN-like component, and functions for coherent pulsations and their higher harmonics. The result of the fit is shown in figure 2a. The resultant reduced  $\chi^2$  value was 1.73 with 42 degrees of freedom. The chance probability of obtaining such a large  $\chi^2$  value is less than 0.5%. We, then, added another Lorentzian function to

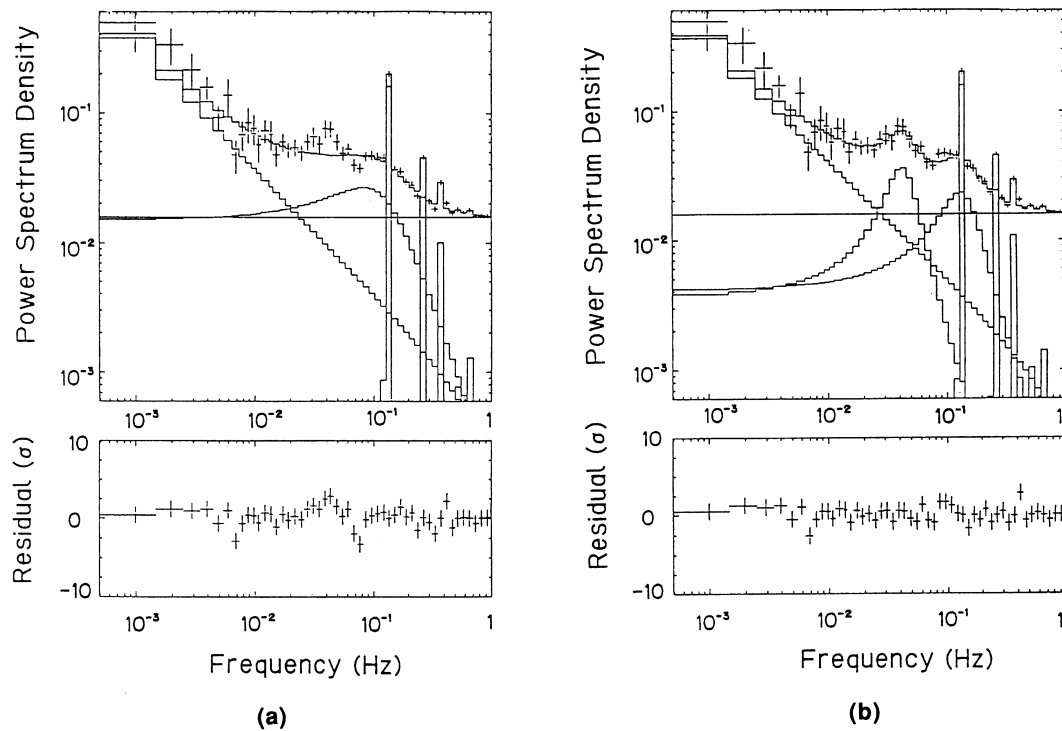


Fig. 2. Model fits of the power spectrum in the 14.7 – 17.4 keV band; (a) a model consisting of a power-law function representing the noise component which increases toward the lower frequency, a Lorentzian profile for the shoulder-like structure, and 0.131-Hz coherent pulse and its higher harmonics; (b) same as (a) but with another Lorentzian function for the QPO component included. In the upper panels, the observed power spectrum and the best-fit model function are shown by crosses and step functions, respectively. In the lower panels, the residuals of the fits are shown.

represent the peak feature at about 0.04 Hz. Figure 2b shows the fit with this model. This fit was acceptable with a reduced  $\chi^2$  of 1.08 for 39 degrees of freedom. From the F-test of the two reduced  $\chi^2$  values we find that the possibility that this peak accidentally results from statistical fluctuations is less than 1%. The peak feature is, therefore, considered to be intrinsic to the source in this statistical limit. The best-fit value of the centroid frequency is  $0.041 \pm 0.003$  Hz, and the width (FWHM) is  $0.017 \pm 0.012$  Hz (90% errors).

Although X1627–673 exhibited flares with intensity increases by a factor of two, we were at the moment unable to test the correlation between the QPO frequencies and X-ray intensities because of the statistical limitation.

### 3. Discussion

More than ten different models have been proposed so far for the QPO (e.g., Lewin et al. 1988). The mechanism which determines the frequency of the QPO in most of the QPO models may be grouped into three different categories: the Keplerian frequency (e.g., van der Klis et al. 1987), the beat frequency between the Keplerian

motion and the neutron star rotation (Alpar and Shaham 1985), and accretion flow instabilities (e.g., Fortner et al. 1989; Lamb 1990). The last mechanism has been proposed for the 6 Hz normal-branch QPO in z-type sources (Hasinger and van der Klis 1989) and implies an X-ray luminosity close to the Eddington limit. Since the luminosity of X1627–673 is far below the Eddington limit, we need not consider the third possibility.

We first consider the Keplerian motion at the Alfvén radius, since X1627–673 is a disk-fed X-ray pulsar. If we assume that the QPO frequency is equal to the Keplerian frequency at the Alfvén radius, this leads to the conclusion that the Keplerian frequency at the Alfvén radius is smaller than the rotation frequency of the neutron star. This is very unlikely because in this case most of the inflowing matter cannot fall into the neutron star surface by the propeller effect (Davidson and Ostriker 1973).

We next consider the beat frequency between the Keplerian motion at the Alfvén radius and the rotation of the neutron star. From the pulse and QPO frequencies,  $\nu_{\text{pulse}}$  and  $\nu_{\text{QPO}}$ , the Keplerian frequency at the magnetosphere boundary is estimated to be

$$\nu_{\text{K}} = \nu_{\text{pulse}} + \nu_{\text{QPO}} = 0.13 + 0.04 = 0.17 \text{ Hz.} \quad (1)$$

On the other hand, from the accretion disk model (Ghosh and Lamb 1979), the Keplerian frequency at the magnetosphere boundary is estimated to be

$$\nu_{\text{K}} = 0.74 \mu_{30}^{-6/7} L_{37}^{3/7} \text{ Hz,} \quad (2)$$

where  $\mu_{30}$  is the magnetic dipole moment of the neutron star in units of  $10^{30} \text{ G cm}^3$  and  $L_{37}$  the accretion luminosity in units of  $10^{37} \text{ erg s}^{-1}$ . Adopting  $\nu_{\text{K}} = 0.17$  and  $L_{37} = 1$ , this equation leads to  $\mu_{30} = 6$ , consistent with an estimate based on the shape of the hard X-ray spectrum (see section 1).

Finally, we examine the accretion torque on this pulsar. The torque is most conveniently expressed as a function of the fastness parameter, which is the ratio of the spin frequency  $\nu_{\text{pulse}}$  of the neutron star to the Keplerian frequency  $\nu_{\text{K}}$  at the Alfvén radius. The value of this parameter is 0.76 in this case. Ghosh and Lamb (1979) give a critical value of fastness parameter above which the torque on the neutron star caused by the accretion matter becomes negative. In other words, with a fastness parameter larger than the critical value, spin down is expected. The critical value they give depends on the azimuthal pitch of the magnetic field lines in the boundary layer near the Alfvén radius. Since a steady spin-up has been observed for more than 10 years, the critical value of the fastness parameter should be larger than 0.76. Within the range of the azimuthal pitch of the magnetic field lines Ghosh and Lamb (1979) employed, the critical fastness is at most 0.65. From a simple extrapolation of their results, the magnetic pitch can be estimated to be  $\sim 30$  for a critical fastness of 0.76. This value of the magnetic pitch is far larger than the value widely accepted in the most torque theories ( $\sim 1$ ), which leads to a critical fastness of 0.35.

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