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X-ray flux and pulse frequency changes of three high mass X-ray binary pulsars: Vela X-1, GX 301-2 and OAO 1657-415

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Abstract. Using archival BATSE (Burst and Transient Source Experiment) 20–60 keV band X-ray flux and pulse frequency time series, we look for correlations between torque, luminosity and specific angular momentum for three high mass X-ray binary pulsars Vela X-1, GX 301-2 and OAO 1657-415. Our results show that there is no correlation between pulse frequency derivative and flux which may be an indication of the absence of stable prograde accretion disk. From the strong correlation of specific angular momentum and torque, we conclude that the accretion geometry changes continuously as suggested by the hydrodynamic simulations (Blondin et al. 1990).

Key words: X-rays: stars – accretion, accretion disks – stars: pulsars: individual: OAO 1657-415 – stars: pulsars: individual: GX 301-2 – stars: pulsars: individual: Vela X1

1. Introduction

Observations of accretion powered pulsars began with the discovery of periodic X-ray pulsations from Cen X-3 by *Uhuru* (Giacconi et al. 1971; Schreier et al. 1972). Qualitative understanding of accretion powered pulsars was achieved in the 1970s (Pringle & Rees 1972; Davidson & Ostriker 1973; Lamb et al. 1973). Ghosh & Lamb presented an accretion disk theory to address the accretion powered pulsar observations in the 1970s in terms of a fastness parameter, material and magnetic torques in the case of a stable prograde accretion disk (Ghosh & Lamb 1979a,b). In the absence of a stable accretion disk, numerical simulations were used to probe the nature of accretion (Anzer et al. 1987; Taam & Fryxell 1988a, 1988b, 1989; Blondin et al. 1990).

Observations of pulse frequency changes in accretion powered pulsars are direct signs of torques exerted on the pulsar. These torques can originate either outside or inside the star (Lamb et al. 1978; Baykal & Ögelman 1993). Internal torques depend on the coupling between interior components, in particular the core superfluid, and the solid outer crust (Baykal et al. 1991). External torques depend on the magnetic field strength of the neutron star and on the type of accretion flow to the neutron star.

If the neutron star accretes mass from an accretion disk, torques are produced either by the angular momentum transfer of the plasma to the magnetic field in the magnetospheric radius via interaction of the inner boundary of the disk and the magnetic field lines (causing material torques) or by the interaction of the disk and the magnetic field (causing magnetic torques) (Ghosh & Lamb 1979a,b). If the accretion results from Roche lobe overflow of the companion, a persistent prograde Keplerian accretion disk forms and the disk creates material and magnetic torques causing the neutron star to spin-up or spin-down. For such a configuration, material torques can only give spin-up contribution to the net torque, while magnetic torques may give either spin-up or spin-down contribution.

If the companion does not fill its Roche lobe, then the neutron star may still accrete mass from its companion's wind. From the hydrodynamic simulations, it is seen that the stellar wind is disrupted in the vicinity of a compact X-ray source (the neutron star for our case) which causes plasma to lose its homogeneity. The interaction of the incident flow with the shock fronts around the neutron star can produce retrograde and prograde temporary accretion disks (Anzer et al. 1987, Taam & Fryxell 1988a, 1988b, 1989; Blondin et al. 1990).

The relations between X-ray luminosity, torque and specific angular momentum may lead to important clues about the accretion process. If the neutron star accretes mass from a stable prograde accretion disk, we expect a positive correlation between X-ray flux and torque (Ghosh & Lamb 1979a,b). For the case of continuous changes in accretion geometry, we can expect a correlation between specific angular momentum and torque which may be the sign of significant torque changes while the luminosity does not vary significantly (Taam & Fryxell 1988a, 1988b, 1989; Blondin et al. 1990).

In this paper, we use BATSE (Burst and Transient Source Experiment) 20–60 keV band X-ray flux and pulse frequency time series of three high mass systems (Vela X-1, GX 301-2, and OAO 1657-415). This database is a part of the flux and pulse frequency database for accretion powered pulsars which was discussed before by Bildsten et al. (1997). Using these time series, we investigate the correlations of torque, X-ray luminosity and specific angular momentum. Detailed studies on torque and X-ray luminosity using the BATSE X-ray flux and pulse frequency data were presented before for GX 1+4 (Chakrabarty

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1996, 1997) and OAO 1657-415 (Baykal 1997). Baykal (1997) also discussed correlations of specific angular momentum with torque and X-ray luminosity for OAO 1657-415.

GX 1+4, which was continuously spinning-up in the 1970's, later exhibited a continuous spin-down trend with an anticorrelation of torque and X-ray luminosity, i.e. the spin-down rate is increased with increasing X-ray luminosity (Chakrabarty 1996, 1997). This spin-down episode was interpreted as evidence for a retrograde Keplerian accretion disk (Nelson et al. 1997) which may originate from the slow wind of a red giant (Murray et al. 1998). Other explanations for this spin-down episode were the radially advective sub-Keplerian disk (Yi et al. 1997) and warped disk (Van Kerkwijk et al. 1998) models.

X-ray luminosity, torque and specific angular momentum correlations for OAO 1657-415 were studied earlier (Baykal 1997). That work employed a flux and pulse frequency data string covering a ∼30% shorter time interval compared to the content of the OAO 1657-415 data studied in the present paper. In that paper, correlations of pulse frequency derivative (proportional to torque exerted on the neutron star), pulse frequency derivative over flux (proportional to specific angular momentum of the accreted plasma) and flux (proportional to luminosity) were discussed. It was found that the most natural explanation of the observed X-ray flux and pulse frequency derivative fluctuations is the formation of temporary accretion disks in the case of stellar wind accretion. The present paper extends the analysis on OAO 1657-415 to cover a larger data string. We also present the results of a similar analysis in two other pulsars, Vela X-1 and GX 301-2.

In the next section, database is introduced, and pulse frequency, pulse frequency derivative and flux time series are presented. A discussion of the results and conclusions are given in Sect. 3.

2. Database and results

BATSE is made up of eight detector modules located at the corners of CGRO (Compton Gamma Ray Observatory). These detectors have enabled continuous all sky monitoring for both pulsed and unpulsed sources above 20 keV since 1991. BATSE daily monitors the pulse frequency and X-ray flux of three low mass binaries, five high mass binaries and seven previously known transients. It has also discovered new transients (Bildsten et al. 1997).

This paper is based on orbitally corrected BATSE 20–60 keV band X-ray flux and pulse frequency time series of Vela X-1, GX 301-2 and OAO 1657-415 which are obtained from the ftp site "ftp.cossc.gsfc.nasa.gov". In this paper, we assume that time variation of the 20–60 keV band flux represents the time variation of the bolometric X-ray flux. It should be noted that the flux time series, reported in Figs. 1, 4, and 7 might not be representative of the time variation of the bolometric X-ray flux. Pulse frequency and flux time series are binned by considering that measurement errors dominate in short time lags or high frequencies in the pulse frequency derivative power spectrum (Bildsten et al. 1997). We choose our bin sizes to the extent that the measurement errors do not dominate on pulse frequency derivatives. Bin sizes are 45 days, 30 days and 16 days for Vela X-1, GX 301-2 and OAO 1657-415 respectively. Pulse frequency derivatives are found by averaging left and right derivatives of pulse frequency values so that each pulse frequency derivative corresponds to a single flux and time value. We present X-ray flux, pulse frequency and pulse frequency derivative time series in Figs. 1,4 and 7. In Figs. 2, 5 and 8, we present the plot of pulse frequency derivative and flux values corresponding to the same time value. Since pulse frequency derivative and X-ray flux are directly proportional to torque and X-ray luminosity, these figures show the relation between torque and X-ray luminosity. Pulse frequency derivative over flux is directly proportional to the specific angular momentum of the plasma ($l = I\dot{\Omega}/\dot{M}$ where l is the specific angular momentum, $\dot{\Omega}$ is the frequency derivative and $\dot{M}$ is the mass accretion rate). Figs. 3, 6, 9 which are plots of pulse frequency derivative over flux and pulse frequency derivative show the relation between specific angular momentum and torque. Pulse frequency derivative over flux time series are created by dividing each pulse frequency derivative value with the flux value corresponding to the same time.

2.1. *Vela X-1*

283s pulsations from Vela X-1 were discovered by *SAS-3* in 1975 (McClintock et al. 1976). It is the brightest persistent accretion powered pulsar in the 20–60 keV energy band (Bildsten et al. 1997). Optical companion of Vela X-1 is the B0.5 Ib supergiant HD77581 (Vidal et al. 1973). This system is an eclipsing binary with eccentricity of $\simeq 0.126$ and period of 8.96 days (Rappaport et al. 1976).

X-ray flux, pulse frequency and pulse frequency derivative values of Vela X-1 cover the interval between 48371 MJD and 50580 MJD (Fig. 1). In Fig. 2, pulse frequency derivative and corresponding X-ray flux data were plotted. No correlation between frequency derivative and flux is found. From Fig. 3, it is seen that there is a correlation between pulse frequency derivative over flux and frequency derivative.

2.2. *GX 301-2*

700s pulsations from GX 301-2 (4U 1223-62) were discovered by Ariel 5 in 1975 (White et al. 1976). GX 301-2 was, on average, neither spinning up nor spinning down between 1975 and 1985. After 1985, a spin-up episode began (Nagase 1989), reaching the current pulsar spin period of $\sim 676s$. GX 301-2, being in a 41.5 day eccentric orbit ($e = 0.47$), is an accreting pulsar with the supergiant companion Wray 977 (Sato et al. 1986). This source exhibited two rapid spin-up episodes at ~ 48450 MJD and ~ 49250 MJD. These two spin-up episodes suggest the existence of a long-lived (≈ 30days) accretion disk (Koh et al. 1997).

X-ray flux, pulse frequency and pulse frequency derivative values of GX 301-2 cover the interval between 48371 MJD and 50577 MJD (Fig. 4). Fig. 5 is the plot of pulse frequency derivative and corresponding X-ray flux values. No correlation be-

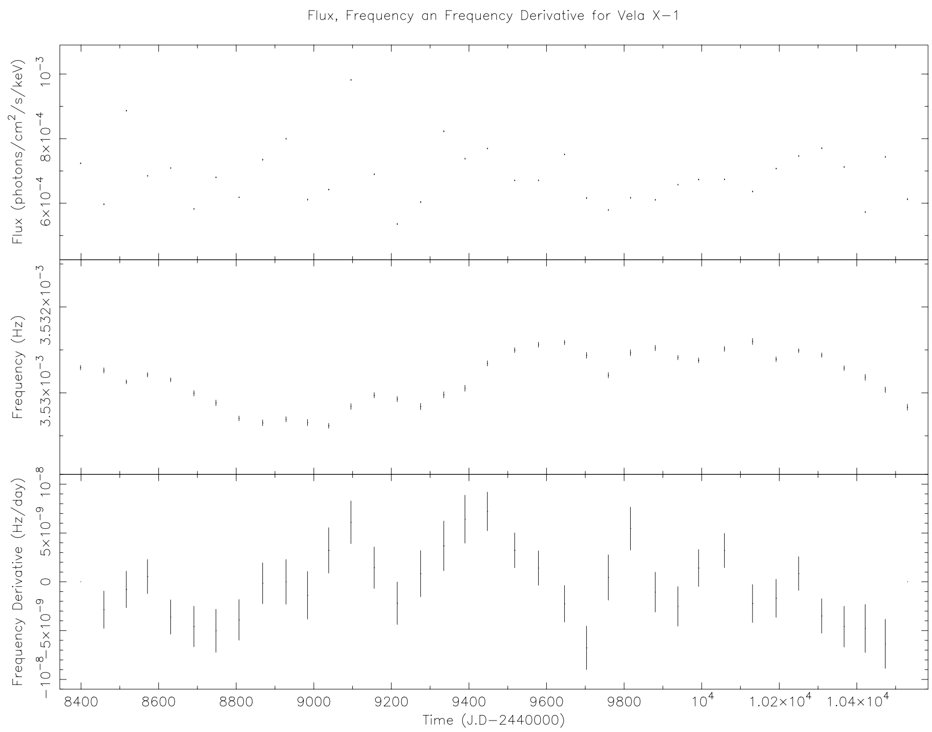

Fig. 1. Flux, pulse frequency and pulse frequency derivative time series of Vela X-1. Data points were obtained by making bins each covering 45 days from the original data. Errors are in 1σ level.

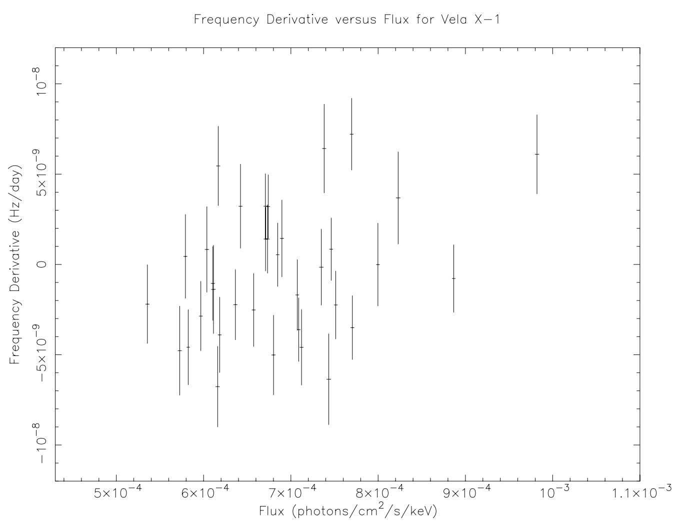

Fig. 2. Pulse frequency derivative versus flux for Vela X-1. Errors are in 1σ level.

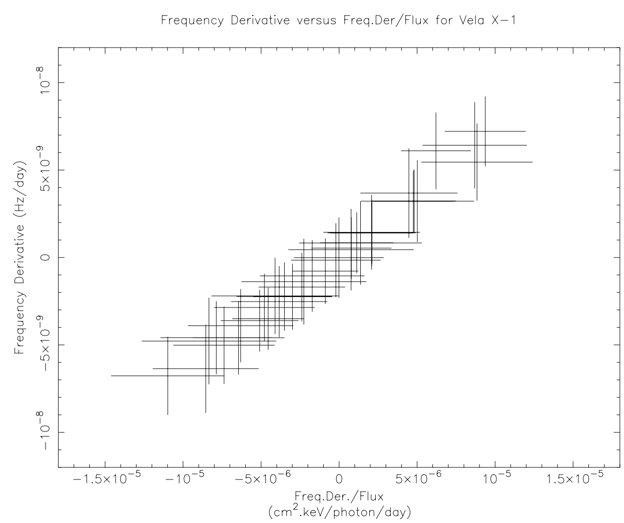

Fig. 3. Pulse frequency derivative versus pulse frequency derivative over flux for Vela X-1. Errors are in 1σ level.

tween pulse frequency derivative and flux is found. From Fig. 6, we see that there is a correlation between pulse frequency derivative over flux and pulse frequency derivative. In Figs. 5 and 6, there exist two points with pulse frequency derivative values greater than 10^{-7} Hz/day. These points correspond to two rapid spin-up episodes which was interpreted as a sign of transient prograde accretion disk (Koh et al. 1997).

2.3. *OAO 1657-415*

OAO 1657-415 was first detected by the Copernicus satellite (Polidan et al. 1978). 38.22s pulsations from OAO 1657-415 were found in 1978 from HEAO 1 observations (White et al. 1979). The optical companion of OAO 1657-415 is probably a OB type star. Its binary orbit period with an eccentricity of ~ 0.10 was found to be 10.4 days from the eclipse due to its companion from timing observations of this source with the BATSE observations (Chakrabarty 1993). Detailed studies on X-ray flux and pulse frequency derivative changes were performed earlier on a less extensive BATSE 20–60 keV X-ray flux and pulse frequency data string (Baykal 1997). In the current data string, X-ray flux and pulse frequency and pulse frequency derivative values of OAO 1657-415 cover the interval between 48372 MJD and 50302 MJD (Fig. 7).

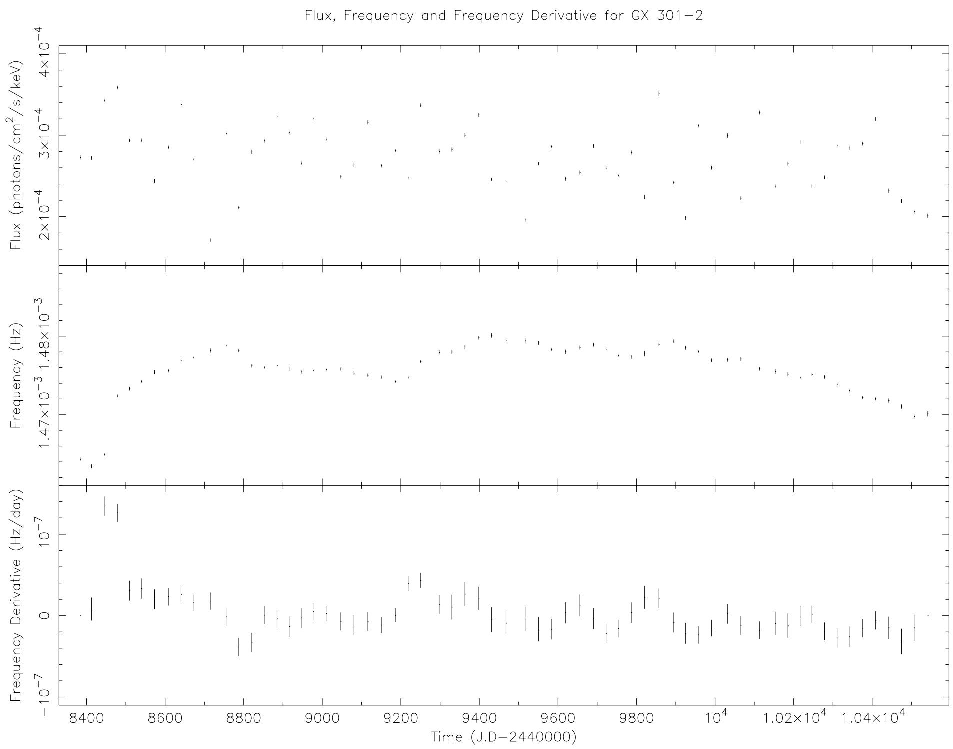

Fig. 4. Flux, pulse frequency and pulse frequency derivative time series of GX 301-2. Data points were obtained by making bins each covering 30 days from the original data. Errors are in 1σ level.

Fig. 8 presents pulse frequency derivative and corresponding X-ray flux time series. No correlation between pulse frequency derivative and flux is found. There is a correlation between pulse frequency derivative over flux and pulse frequency derivative as seen from Fig. 9.

3. Discussion and conclusion

The torque on the neutron star can be expressed in terms of the specific angular momentum (l) added to the neutron star by the accreted plasma and the mass accretion rate ($\dot{M}$):

$$N = I\dot{\Omega} = \dot{M}l. \tag{1}$$

where $\dot{\Omega}$ is the spin frequency derivative and I is the moment of inertia of the neutron star.

This equation is a general expression which is valid for both accretion from a Keplerian disk and accretion from the stellar wind. In the case of accretion from a Keplerian disk (Ghosh & Lamb 1979b) we have,

$$I\dot{\Omega} = n(\omega_s)\dot{M}l, \tag{2}$$

and

$$l = (GMr_0)^{1/2}, \tag{3}$$

where ω_s is the fastness parameter and $n(\omega_s)$, the dimensionless torque, represents the ratio of the total (magnetic plus material) torque to the material torque. r_0 is the radius of the inner edge of the disk, which can be written as $r_0 \simeq 0.5(2GM)^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$ where μ is the magnetic moment of the neutron star. Dimensionless torque can approximately be written as

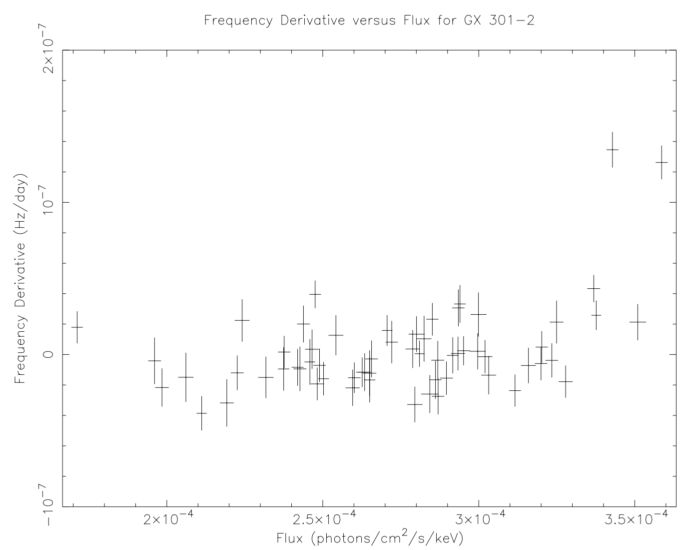

Fig. 5. Pulse frequency derivative versus flux for GX 301-2. Two points with pulse frequency derivative values greater than 10^{-7} Hz/day, correspond to two rapid spin-up episodes discussed by Koh et al. (1997). Errors are in 1σ level.

$$n(\omega_s) = 1.4\frac{1-\omega_s/\omega_c}{1-\omega_s}, \tag{4}$$

where ω_c is a critical value for the fastness parameter which defines the boundary between spin-up and net spin-down phases. Dimensionless torque may be positive or negative depending on the fastness parameter ω_s which is defined as

$$\omega_s = \frac{\Omega_s}{\Omega_{K_0}}, \tag{5}$$

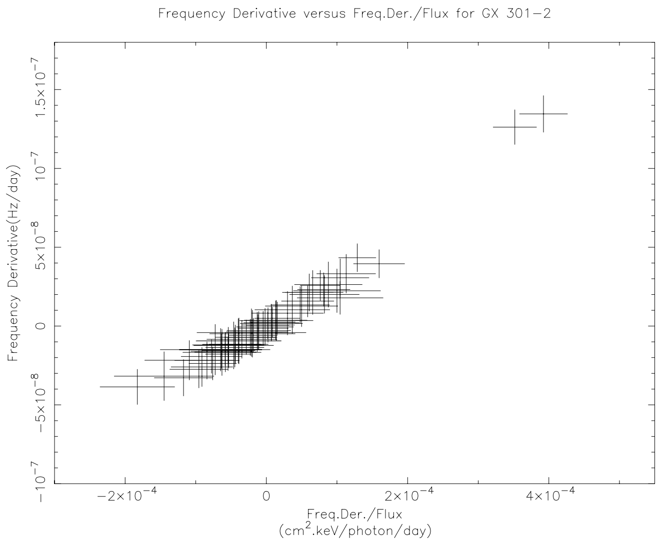

Fig. 6. Pulse frequency derivative versus pulse frequency derivative over flux for GX 301-2.Two points with pulse frequency derivative values greater than 10^{-7} Hz/day, correspond to two rapid spin-up episodes discussed by Koh et al. (1997). Errors are in 1σ level.

where Ω_s is the neutron star's spin angular velocity and Ω_{K_0} is the angular velocity corresponding to the Keplerian velocity at the magnetospheric radius. For a slowly rotating neutron star for which $\omega_s < \omega_c \simeq 0.35 - 0.95$ (Ghosh & Lamb 1979b; Wang 1995; Li & Wang 1996, 1999), we expect a spin-up torque and for a very fast rotating neutron star ($\omega_s >> \omega_c$), we expect a spin-down torque. We also expect to see positive correlation between torque and mass accretion rate if the disk is prograde. For a disk formed from Roche Lobe overflow of the companion we expect the plasma to carry positive specific angular momentum, so a prograde disk should be formed. The total torque exerted on the neutron star is proportional to the material torque for a given fastness parameter. Since the specific angular momentum weakly depends on mass accretion rate ($l \propto \dot{M}^{-1/7}$), the net torque becomes proportional to the mass accretion rate ($\dot{M}$). The bolometric X-ray luminosity is also correlated with the mass accretion rate ($L = GM\dot{M}/R$ where R is the radius of the neutron star). Thus, we expect a correlation between torque and X-ray luminosity for the sources accreting from prograde accretion disks (torques are positive). For the similar reasons, an anticorrelation between torque and X-ray luminosity is expected from a retrograde accretion disk (torques are negative). However, for the pulsars we have considered, we see no correlation of pulse frequency derivative and flux (Figs. 2, 5, 8). Moreover, there are several transitions from spin-up and spin-down. These results suggest that we do not have stable accretion disks for these sources.

There is a model which does not exclude the possibility of a stable Keplerian accretion disk (Anzer & Börner 1995). This model is proposed to explain the torque reversals in Vela X-1 suggesting the existence of a stable accretion disk lying just outside the magnetosphere mass of which exhibits small variations. It is found that change of the disk's mass in a random way can produce variations of torque in Vela X-1. However, the authors have not identified a specific physical process which is responsible for such random mass fluctuations.

Alternatively, we can think of the existence of accretion geometry changes around the neutron star. We can, in general, write the variation of torque (δN) as

$$\delta N = I\delta\dot{\Omega} = \delta\dot{M}l + \dot{M}\delta l \tag{6}$$

where I is the moment of inertia of the neutron star, l is the specific angular momentum of the accreting matter, $\delta\dot{\Omega}$, $\delta\dot{M}$, and δl are the variations of spin frequency derivative, mass accretion rate (proportional to X-ray flux) and specific angular momentum (proportional to pulse frequency derivative over flux) respectively. When the variations of torques for the three pulsars are concerned, we have considerable changes and transitions from negative values to positive values and vice versa. For the case of an accretion from the wind, numerical simulations show that the changes in the sign of specific angular momentum is possible (Anzer et al. 1987; Taam & Fryxell 1988a, 1988b, 1989; Blondin et al. 1990, Murray et al. 1998). So, we can observe transitions from spin-up to spin-down or vice versa even if there is not a significant change in mass accretion rate. For wind accreting sources, continuous change in accretion geometry rules out the existence of a stable accretion disk. Thus, it is unlikely to see a correlation between torque and X-ray luminosity which is the case for our sources as well. For such sources, a correlation between specific angular momentum and torque shows that there are considerable changes in torque while there are not very considerable changes in X-ray luminosity. This indicates changes in accretion geometry. The correlation between specific angular momentum and torque exists for all of the three sources (Figs. 3, 6 and 9).

There are recent developments which explain the torque reversals in accretion powered pulsars. Negative torques may come from a retrograde Keplerian accretion disk (Nelson et al. 1997) which may, for instance, originate from a red giant (Murray et al. 1998). These spin-down torques may be the result of an advection dominated sub-Keplerian disk for which the fastness parameter should be higher than that of a corresponding Keplerian disk causing a net spin-down (Yi et al. 1997) or the warping of the disk so that the inner disk is tilted by more than 90 degrees (van Kerkwijk et al. 1998). Torque and X-ray luminosity correlation is expected from these models which is not found for our sources. Moreover, in these models timescales for torque reversals are either not certain or of the order of years. So, these ideas about torque reversals are not supported by the behaviour of the three pulsars we have considered.

Our considerations about correlations between pulse frequency derivative, flux and specific angular momentum give insights about the physics of the plasma flow in the vicinity of the neutron stars accreting from the winds' of their companions. We had similar conclusions for all three sources. We found that it is unlikely for these sources to have stable prograde Keplerian accretion disks since they show both spin-up and spin-down episodes and they do not show correlation between torque and luminosity. Correlation between specific angular momentum

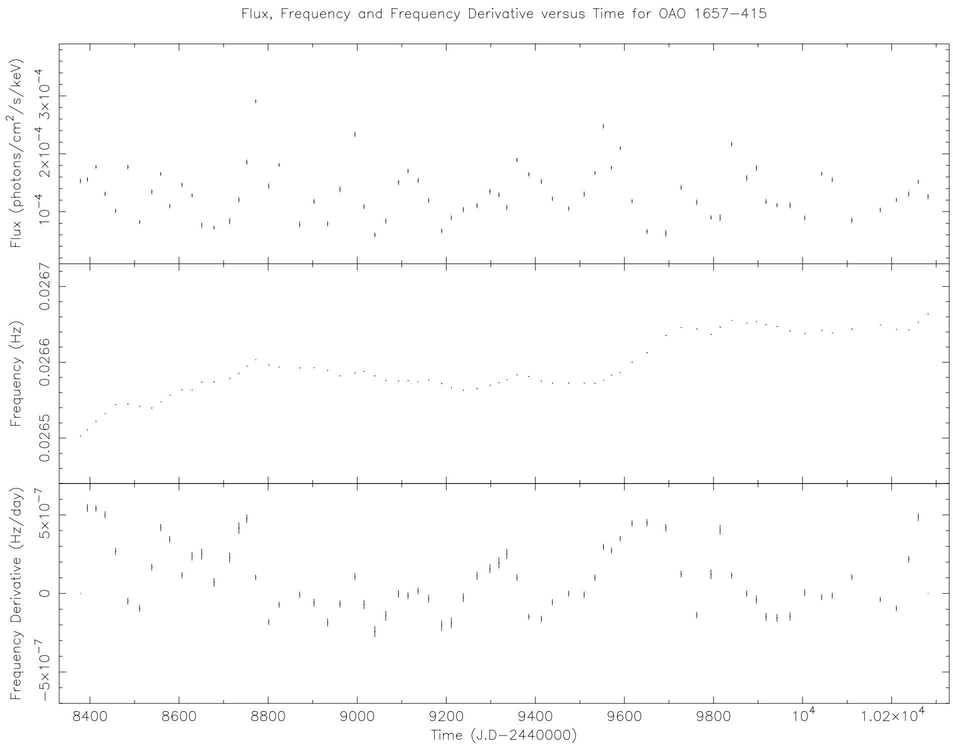

Fig. 7. Flux, pulse frequency and pulse frequency derivative time series of OAO 1657-415. Data points were obtained by making bins each covering 16 days from the original data. Errors are in 1σ level.

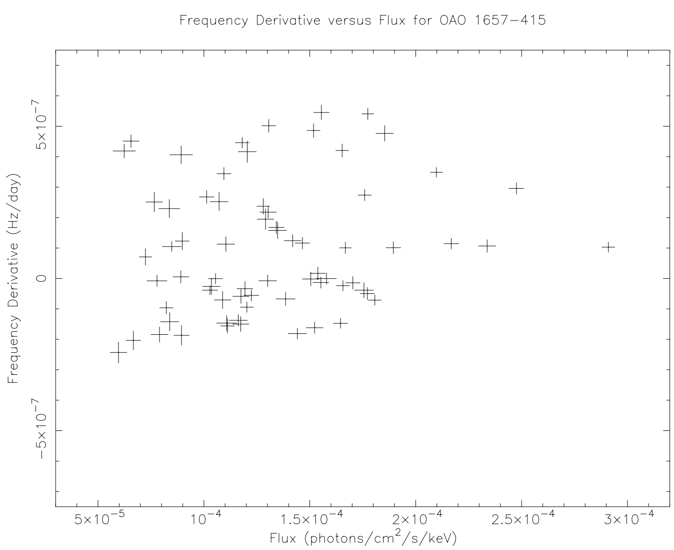

Fig. 8. Pulse frequency derivative versus flux for OAO 1657-415. Data points were obtained by making bins each covering 16 days from the original data. Errors are in 1σ level.

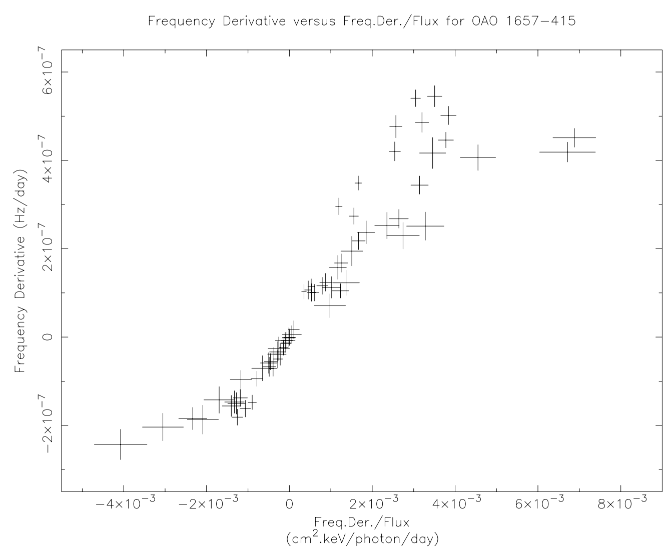

Fig. 9. Pulse frequency derivative versus pulse frequency derivative over flux for OAO 1657-415. Errors are in 1σ level.

and torque for these sources may indicate the continuous change in accretion geometry. This shows the possibility of temporary prograde and retrograde accretion disk formation. It would be also possible to have stronger idea about the accretion geometry if we had measurements of the pulse frequency derivative with a time resolution of the order of hours, which is a typical time scale of accretion geometry changes for these systems (Taam & Fryxell 1988a, 1988b, 1989; Blondin et al. 1990). For such a case, we would allow a better comparison of the changes in flux and specific angular momentum and it would be interesting to detect both high flux and low specific angular momentum points corresponding to the radial flow cases and to see low flux and high specific angular momentum points corresponding to the accretion from prograde (high positive specific angular momentum) or retrograde (high negative specific angular momentum) accretion disks.

Our flux and pulse frequency time series are found using the X-ray flux and pulse frequency between 20–60 keV. Observatories with higher time resolution and capable of detecting photons from a wider energy band will be useful to observe the torque, X-ray luminosity and specific angular momentum changes for these pulsars. An encouraging example is given by RXTE (Rossi X-ray Timing Explorer) observations of the accretion powered pulsar 4U 1907+09. Dipping activity in the X-ray intensity was found which was interpreted as a consequence of inhomogeneity of the wind from the companion (In'T Zand et al. 1997), and more recently, it was shown from the RXTE observations that 4U 1907+09 exhibited transient ~ 18s QPO oscillations during a flare which was superposed on long term spin-down rate. This was interpreted as a sign of transient retrograde accretion disk (In'T Zand et al. 1998a,b). RXTE observations of Vela X-1, GX 301-2, and OAO 1657-415 may provide more understanding on the nature of accretion flow through tests on flux and frequency time series at higher resolution.

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