Spectral and temporal changes associated with flux enhancement in 4U 1626−67

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ABSTRACT
4U 1626−67 is an accretion powered X-ray pulsar that shows remarkably stable X-ray luminosity above a time-scale of hours and gradual intensity variation on a time-scale of a few years. Unlike the other high magnetic field binary X-ray pulsars, the spin-up or spin-down rate of the neutron star is also very stable on time-scales up to several years. Here, we report a significant increase in the X-ray intensity in the long-term Rossi X-ray Timing Explorer (RXTE) All Sky Monitor light curve of 4U 1626−67. Similar enhancement in the X-ray flux has also been detected in the Swift Burst Alert Telescope light curve. The increase in the X-ray flux took place over a long period of about 100 d and there appear to be two episodes of flux enhancement. We have investigated the spectral and timing features of 4U 1626−67 during its current state of enhanced flux emission with data obtained from the Proportional Counter Array and the High-Energy X-ray Timing Explorer on board RXTE. We report the detection of a torque reversal to spin-up in 4U 1626−67. The source has entered a new spin-up phase with a spin-up rate of 4.02(5) × 10−13 Hz s−1. The present spin-up rate is almost half of the earlier spin-up and spin-down trends. A significant excess in soft X-ray photon emission is observed during the enhanced flux state, which is similar to the energy spectrum obtained during the spin-up era of the pulsar before 1990. 4U 1626−67 is a unique accretion powered X-ray pulsar in which quasi-periodic oscillations have been consistently observed over the past ~20 years. During the recent observations, however, we did not detect a quasi-periodic oscillation at frequencies as seen in earlier observations. Instead, we report detection of a significant broadening in the wings of the 130 mHz peak and a change in the shape of the continuum of the power spectrum. These results indicate that the flux enhancement is not a simple case of increased mass accretion rate, but there is also a change in the accretion geometry in the vicinity of the neutron star.

Key words: pulsars: individual: 4U 1626−67 – X-rays: binaries – X-rays: stars.

1 INTRODUCTION
4U 1626−67 is an accretion powered X-ray pulsar which was discovered with the Uhuru satellite in 1972 (Giacconi et al. 1972). The 7.7 s X-ray pulsations were discovered by Rappaport et al. (1977) during SAS3 observations and have been extensively monitored since then. Initially, the pulsar was found to be spinning up with a characteristic time-scale of ~5000 yr. It underwent an abrupt torque reversal in 1990 and has been steadily spinning down since then (Chakrabarty et al. 1997; Krauss et al. 2007). The optical counterpart of the pulsar was identified as KZ TrA, a faint blue star with little reddening (McClintock et al. 1977; Bradt & McClintock 1983). Pulsations at 130 mHz have also been detected from the reprocessed optical emission (Middleditch et al. 1981). Multiple sidebands separated by about 0.4 mHz are present in the power spectrum of the optical light curve, which was interpreted as the signature of an orbital period of ~42 min (Middleditch et al. 1981; Chakrabarty et al. 2001). Despite extensive searches, however, an orbital motion of the neutron star (usually observed in binary pulsars in the form of a Doppler shift in the pulse period or delay in the pulse arrival time) has never been detected in this source (Rappaport et al. 1977; Levine et al. 1988; Jain et al. 2007). It is believed that the neutron star, most probably, has a low mass binary companion and is in a nearly face-on orbit.

The X-ray spectrum of 4U 1626−67 was first studied in detail with the ASCA spectrometers (Angelini et al. 1995) and later with instruments on board Beppo-SAX (Owens, Oosterbroek & Parmar...
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2 OBSERVATIONS AND ANALYSIS

4U 1626–67 is a medium-intensity persistent X-ray source among the few hundred bright X-ray sources regularly monitored by the All Sky Monitor (ASM) on board RXTE. Fig. 1 (thin line) shows the long-term 1.5–12 keV ASM light curve of 4U 1626–67, binned with 30 d. The data used here covered the time range between MJD 50088 and MJD 54909. The X-ray intensity was gradually decreasing until MJD 54500, when an increase in the X-ray flux was noticed. The inset in Fig. 1 shows the expanded view near the onset of the flux enhancement. There seem to be two episodes of X-ray flux enhancement, both on time-scales of ~100 d.

4U 1626–67 was also regularly monitored by the Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the Swift observatory (Gehrels et al. 2004). The long-term 15–50 keV Swift-BAT light curve, binned with 30 d, is also shown in Fig. 1 (thick line) along with the ASM light curve. The observations covered the time range from MJD 53414 to MJD 54920. A sudden increase in the X-ray flux was first reported by Krimm et al. (2008). The inset in Fig. 1 (thick line) shows the expanded view (in the same units) near the onset of the flux enhancement. The flux change on time-scales of ~100 d is also clear in the Swift-BAT light curve.

We have also analysed data obtained from the Proportional Counter Array (PCA) and the High-Energy X-ray Timing Explorer (HEXTE) on board the RXTE. The PCA consists of five xenon/methane proportional counter units (PCUs) and is sensitive in the energy range of 2–60 keV with an effective area of 1300–6500 cm², depending on the number of PCUs ON (Jahoda et al. 1996). The HEXTE operates in the energy range 15–250 keV and consists of two clusters of phoswich scintillation detectors, each having a collecting area of 800 cm² (Gruber et al. 1996).

Table 1 gives a log of the RXTE observations used for the present analysis. We have studied the temporal and spectral variations in

| Year | Observation ID | Number of pointings | Total exposure (ks) |
|------|----------------|---------------------|---------------------|
| 1996 | P10101         | 3                   | 153                 |
|      | P10144         | 1                   | 10                  |
|      | P20146         | 2                   | 2                   |
| 1997 | P20146         | 12                  | 7                   |
| 1998 | P30058         | 2                   | 40                  |
|      | P30060         | 7                   | 53                  |
| 2008 | P93431         | 2                   | 7                   |
| 2009 | P94423         | 3                   | 9                   |

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4U 1626−67 using data collected in the Standard-1 and the Standard-2 mode of the RXTE-PCA, respectively. The archive mode data of the HEXTE were used for the spectral analysis.

2.1 Timing analysis

We searched for pulsations using data obtained in the Standard-1 mode of the RXTE-PCA. The background counts were simulated using the ftool—runpcabackest and subtracted from the source light curve. The photon arrival times were converted to the Solar system barycentre using the ftool—fbar. We searched for the spin period of the neutron star using the efsearch tool of the HEASOFT analysis package, ftools ver 6.5.1. This tool folds the light curve with a large number of trial periods around an approximate period and determines the best period by the $\chi^2$ maximization technique. Using this method, we determined a pulse period of $7.67941(1)$ s at MJD 54530.4, $7.67945(7)$ s at MJD 54538.1 and $7.67848(2)$ at MJD 54984.5 (Jain & Paul 2009). This gives a spin-up rate of $4.02(5)$ mHz.

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2.2 Spectral analysis

The pulse-phase averaged spectra of 4U 1626−67 were generated from the data collected in the Standard-1 mode of the RXTE-PCA and the archive mode of the RXTE-HEXTE. The background counts for the PCA data were simulated using the ftool—runpcabackest and subtracted from the source spectrum. In case of the HEXTE data, the source and the background spectra were generated using the ftool—hxtback. These were then corrected for the detector dead time using the ftool—hxtdead. In order to bring out the significant evolution in the X-ray spectrum, we have generated the spectrum from one of the 1996 observations (Obs ID 10101-01-01-00) and the 2008 observation (Obs ID 93431-01-01-00).

Fig. 4 shows the power spectrum generated from the 2008 observations (Obs ID 93431-01-01-00; Fig. 3, panel 9) overlaid with a typical power spectrum from a 1996 observation (Obs ID 10101-01-01-00; Fig. 3, panel 1). In the 2008 power spectrum, the absence of a QPO at $\sim 48$ mHz is clearly seen. One more feature that stands out is the substantial broadening of the wings of the pulse peak in the power spectrum during the 2008 observation. The rms variability in the low-frequency noise component of the power spectrum was 14.6 per cent, whereas the rms variability in the broad wings of the fundamental pulse peak and the fundamental pulse peak itself was 6.9 and 5.2 per cent, respectively. This broad feature at $\sim 130$ mHz has never been detected before and hence provides the first instance of a strong coupling between the aperiodic and periodic X-ray variability in the source.
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Figure 3. Some representative X-ray power spectra of 4U 1626–67 generated from the RXTE-PCA observations. The date of observation is mentioned in each panel above the respective observation ID.

Figure 4. X-ray power spectra of 4U 1626–67 from the RXTE observations of 1996 and 2008. The upper, dotted curve is the X-ray spectrum of the 1996 observation (Obs ID 10101-01-01-00; Fig. 3 – panel 1) and the lower, solid curve is from the 2008 observation (Obs ID 93431-01-01-00; Fig. 3 – panel 9).

with HEAO-1 (Pravdo et al. 1979) and the X-ray astronomy satellite Tenma (Kii et al. 1986) during the earlier spin-up phase of 4U 1626–67 also showed a similar energy spectrum.

Fig. 7 shows the evolution of the 3–50 keV X-ray spectrum from the 1996 observation to the 2008 observation. In the figure, the best-

Figure 5. The X-ray spectrum of the 1996 RXTE-PCA and RXTE-HXTE observations of 4U 1626–67. The model components are intrinsic absorption, a power law, a Gaussian and a high-energy cut-off. The bottom panel shows the residual of the fit.
The best-fitting spectrum of 4U 1626 obtained from the RXTE-PCA observations. The bottom panel shows the ratio of the two spectra. It is clear that there is an excess soft-photon emission in the spectrum generated from the 2008 observations. The power-law photon index has also increased during the recent observation.

### Table 2. Best-fitting spectral parameters of 4U 1626−67, obtained from the RXTE-PCA and RXTE-HEXTE observations.

| Parameter                  | Value 1996 | Value 2008 |
|----------------------------|------------|------------|
| $N_H$ (10$^{22}$ cm$^{-2}$) | 0.65       | 0.82       |
| Photon index ($\Gamma$)    | 0.59(4)    | 0.74(7)    |
| Norm (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) | 0.0079(6)  | 0.012(2)   |
| Gaussian line (keV)        | 6.56(40)   | 6.33(39)   |
| Gaussian width (keV)       | 1.15(21)   | 1.43(38)   |
| Gaussian norm (photons cm$^{-2}$ s$^{-1}$) | 0.00054(32) | 0.0019(18) |
| Blackbody, $kT$ (keV)      | –          | 0.66(12)   |
| Blackbody, norm (km$^2$ kpc$^{-2}$) | –          | 44(7)      |
| Cut-off E (keV)            | 6.45775(95)| 17.7(8)    |
| Fold E (keV)               | 32(5)      | 26(12)     |
| Energy(CRF) (keV)          | 39.5(1.8)  | 40.3(1.2)  |
| Width(CRF) (keV)           | 13.8(3.0)  | 4.8(4.5)   |
| Depth(CRF)                 | 2.02(28)   | 2.9(1.7)   |
| Reduced $\chi^2$ (d.o.f.) | 0.59(57)   | 0.61(43)   |

#### Figure 6. Energy spectrum of 4U 1626−67 obtained from the 2008 RXTE-PCA observations. The model consists of a blackbody, a power law and a Gaussian component.

#### Figure 7. The best-fitting spectrum of 4U 1626−67, generated from the 1996 (dotted line) and 2008 (solid line) RXTE observations. The bottom panel shows the ratio of the two spectra.

### 3 DISCUSSION

4U 1626−67 is a unique system in which the X-ray flux has been gradually decreasing over the past ~30 years. Since the discovery of X-ray pulsations in 1977, the source has shown a smooth spin evolution history. Initially, it was found to be spinning up with a characteristic time-scale of 5000 yr, but after an abrupt torque reversal, the neutron star started spinning down at about the same rate (Chakrabarty et al. 1997; Krauss et al. 2007). The recent flux enhancement has opened up many questions regarding the stability of the accretion disc. We have found a sudden increase in the X-ray flux of 4U 1626−67, which could have also caused significant changes in the geometry of the accretion column.

The power spectra of X-ray pulsars consist of narrow peaks originating from the periodic signal and its harmonic lines which are often accompanied with aperiodic features like broad bumps, wiggles and steep low-frequency excess (Wijnands & van der Klis 1999). The periodic variabilities arise due to the rotation-induced motion of the accretion column, through which the infalling matter is funnelled towards the magnetic poles of the neutron star, whereas any instability in the emissivity of the accretion column can give rise to an aperiodic variability (Burderi et al. 1997). If the inhomogeneities occur far away from the surface of the neutron star, then the periodic and aperiodic variations occur independently of each other (Angelini et al. 1989). If the aperiodic variability occurs near the accretion column, however, then they are modulated at the pulsar spin frequency (Makishima 1988). Lazzati & Stella (1997) found a significant coupling between the aperiodic and periodic variabilities in Vela X-1 and 4U 1145−62. A significant coupling was also reported in the accretion-powered millisecond binary pulsar SAX J1808.4−3658 (Menna et al. 2003), Her X-1 (Moon & Eikenberry 2001) and Cen X-3 (Raichur & Paul 2008). The coupling between the aperiodic and periodic variations is expected to alter the shape of the power spectrum because of the convolution of the two signals (Burderi, Robba & Cusumano 1993). The coupling results in a broadening of the base of the power spectrum peaks as if the peaks are riding on a QPO.

The X-ray spectrum and rapid X-ray variability of accreting compact objects have a common origin and are therefore expected to be correlated. In the case of 4U 1626−67, Yi & Vishniac (1999) had found that the torque reversal in 1990 was accompanied by spectral transition and a change in the luminosity. During the spin-up phase of 4U 1626−67, the phase-averaged spectrum was well fitted by a blackbody temperature $kT$ of ~0.6 and a power-law photon index of ~1 (Pravdo et al. 1979; Kii et al. 1986). Vaughan & Kitamoto...
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found that the spin transition had a significant effect on the 2–10 keV energy spectrum. The power-law photon index changed from 1.6 (Pravdo et al. 1979) to ~0.6 (Owens et al. 1997). The blackbody temperature also decreased from ~0.6 to ~0.3 keV. We have found similar spectral transition in the present high flux state of the source. The spectral parameters derived during the present high flux state are similar to those determined during the earlier spin-up phase.

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