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Evolution of Spin and Superorbital Modulation in 4U 0114+650

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We report on a systematic analysis of the spin and superorbital modulations of the high-mass X-ray binary 4U 0114+650, which consists of the slowest spinning neutron star known. Utilizing dynamic power spectra, we found that the spin period varied dramatically during the *RXTE* ASM and *Swift* BAT observations. This variation consists of a long-term spin-up trend, and two ~1,000 day and one ~600 day random walk epochs previously, MJD 51,000, ~MJD 51,400-52,000, and ~MJD 55,100-56,100. We further found that the events appear together with depressions of superorbital modulation amplitude. This provides evidence of the existence of an accretion disk, although the physical mechanism of superorbital modulation remains unclear. Furthermore, the decrease of the superorbital modulation amplitude may be associated with the decrease of mass accretion rate from the disk, and may distribute the accretion torque of the neutron star randomly in time.

Keywords: accretion, accretion disks, 4U 0114+650, X-ray binaries

1. INTRODUCTION

4U 0114+650 is a high-mass X-ray binary system showing properties of both Be star X-ray binaries (Koenigsberger et al. 1983) and supergiant X-ray binaries (Crampton et al. 1985; Reig et al. 1996). The compact object in this system is one of the slowest known rotating pulsars, with a spin period of ~2.7 hours (Finley et al. 1992; Hall et al. 2000). The spin period increases with time at a spin-up rate of $\frac{\dot{P}}{P}$ =-2×10^{-3} year^{-1} (Hall et al. 2000). This value was revised by many investigations and the spin-up rate seems to be accelerating (Wang 2011). The spin period was determined using the first 4.5 years of *RXTE* ASM data, and was found to vary dramatically on a short timescale (Wen et al. 2006). Therefore, the spin period evolution of 4U 0114+650 may exhibit stochastic variability and a long-term spin-up trend. With the help of *Swift* BAT hard X-ray monitoring data, we investigated the full evolutionary track of the spin period (Hu et al. 2016, in preparation).

The orbital period of this system was first determined via radial velocity measurement of its companion LS I +65°010; the period was found to be 11.558(3) days (Crampton et al. 1985) and was then revised to 11.5983(6) days (Grundstrom et al. 2007). The orbital modulation can also be seen in the X-ray band as an eclipse-like feature and a sawtooth modulation profile (Corbet et al. 1999). However, Farrell et al. (2008) argued that 4U 0114+650 does not exhibit eclipsing binary behavior. To interpret the spectral variability, they proposed another scenario in which the neutron star passes through a heavily absorbing region close to the base of the stellar wind.

4U 0114+650 exhibits long-term modulation with a period of 30.7 days. This superorbital modulation was first determined by Farrell et al. (2006) using *RXTE* ASM data. The stability of the superorbital modulation was then characterized by Kotze & Charles (2012); the star was found to have a stable period with alternating stronger and weaker signals in the dynamic power spectrum. The superorbital modulation period is unlikely to be caused by the precession of a radiation-induced warp disk or the precession of the spin axis of the neutron star; the origin of this modulation is still controversial.

In this research, we used all-sky monitoring data from *RXTE* ASM and *Swift* BAT to investigate the variability of the spin period and the stability of superorbital modulations in 4U 0114+650.

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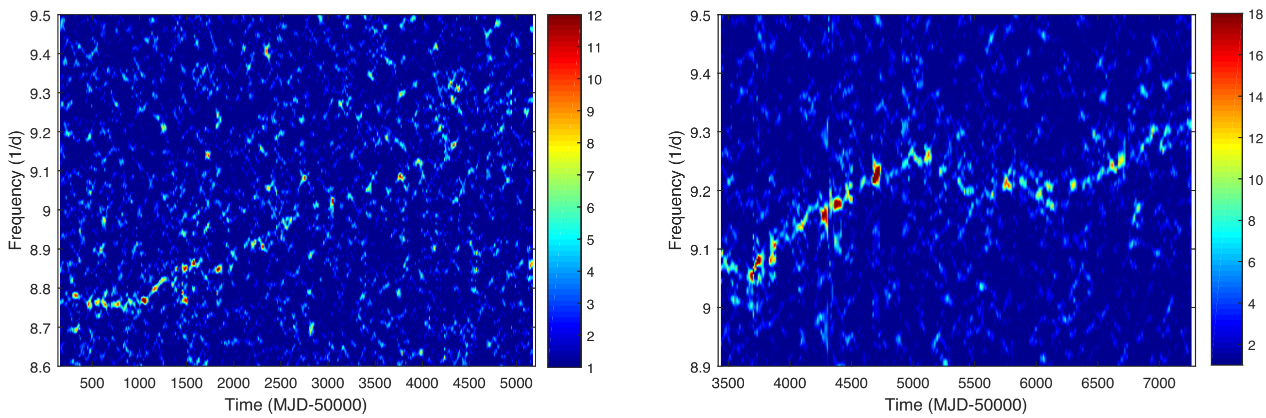

Fig. 1. Dynamic power spectra of ASM (left) and BAT (right) light curves in the frequency range of the spin period. The color map shows the Lomb-Scargle power.

2. DATA COLLECTION

From its launch in 1996 to its decommissioning in 2012, the ASM onboard the *RXTE* monitored the entire sky every 90 minutes. The energy range of the ASM was 1.5-12 keV. We used the dwell data between MJD 50,134 and MJD 55,200 in this research. Similar to the ASM onboard the *RXTE*, the BAT is a payload of the *Swift* observatory that has issued triggering alerts for γ-ray bursts since 2004. The energy range of the BAT is 15-150 keV, which is much higher than that of ASM. We used the "orbit" light curve of 4U 0114+650 provided by the hard X-ray transient monitor program (Krimm et al. 2013) in this research.

3. EVOLUTION OF SPIN PERIOD

Because the spin period is long and highly variable, to trace its evolution we applied the dynamic Lomb-Scargle periodogram (Clarkson et al. 2003) to both the ASM and the BAT light curves. We set the window size at 60 days and the moving step at 10 days. The dynamic power spectra are shown in Fig. 1. From the ASM results, we can clearly see a random walk behavior before MJD 51,000; this is then followed by a dramatic spin up. Between MJD 51,400 – MJD 52,000, there possibly existed another random walk epoch, but the signal is not clear. After MJD 52,000, a long increasing trend in spin frequency can be seen, although the signal can only be detected marginally.

For the dynamic power spectrum of the BAT light curve, the evolution of the spin frequency can be much more clearly detected by comparing it with the ASM light curve. It seems that there is a spin down epoch in the beginning, but it is too short to be confirmed. A long spin-up trend can be clearly observed before MJD 55,100. Then, a long random-walk epoch lasting ~1,000 days occurred and a fluctuation of the pulse period can be seen within this epoch. After MJD 56,100, another long spin-up epoch began. The overall spin-up rate is $\dot{P}$ = (-5.7±0.3)×10^{-7}s s^{-1}, but the fitting is poor. This poor fit is due to the presence of the random-walk epoch and the intrinsic short-term variability.

4. EVOLUTION OF SUPERORBITAL MODULATION

The presence of superorbital modulation may indicate the existence of an accretion disk, although the accretion mechanism of 4U 0114+650 is dominated by wind-fed accretion. Because the ASM and BAT light curves were extended to a much longer time baseline after the previous report by Farrell et al. (2006), we used the dynamic Lomb-Scargle technique to investigate the evolution of superorbital modulation.

Similar to the procedure in Section 3, we produced the dynamic power spectra of superorbital modulation for ASM and BAT datasets with a window size of 500 days and a moving step of 10 days (see Fig. 2). We noticed that the period is stable, but the significance is time-variable. There are several weakly detected epochs in the ASM dataset: before MJD 51,000, for MJD 51,700 – MJD 52,200, and after MJD 54,200. Because the signal can be easily seen in the BAT spectrum, the last one may be caused by the decrease of the X-ray flux instead of by the decrease of the signal strength. The dynamic power spectrum of the BAT light curve also shows an interesting break of the superorbital modulation period for ~MJD 55,300 – 56,200. Except for the last break epoch in the ASM light curve, all of the breaks coincide with the presence of random walk or spin-down epochs in the spin period evolution.

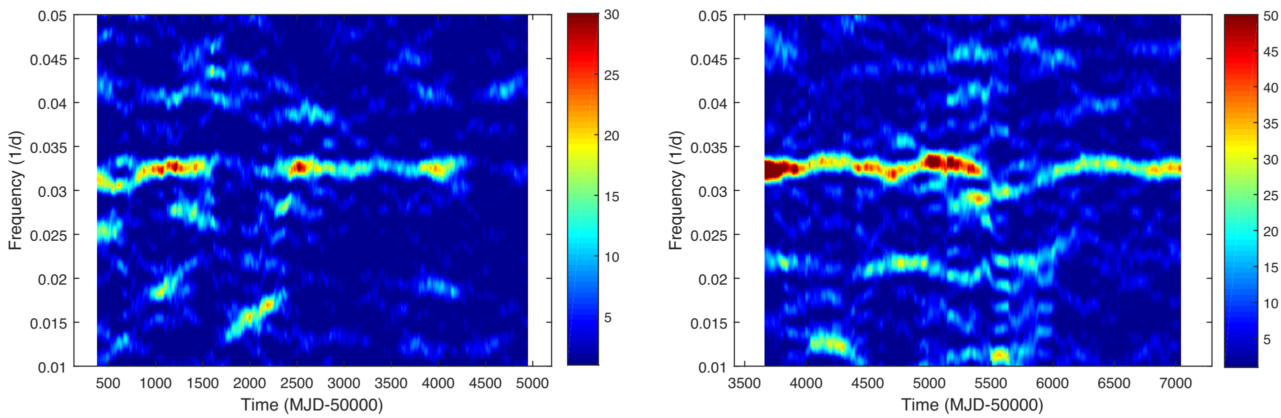

Fig. 2. Dynamic power spectra of ASM (left) and BAT (right) light curves in the frequency range of superorbital modulation. The color map shows the Lomb-Scargle power.

5. RELATIONSHIP BETWEEN SPIN AND SUPERORBITAL MODULATION

Long-term monitoring of accreting pulsars in the hard X-ray band was achieved by BATSE and *Fermi* GBM (Bildsten et al. 1997; Finger et al. 2009). The spin evolution of neutron stars in pure wind-fed HMXBs shows a random walk with no obvious trends of spin-up or spin-down. Vela X-1 is a typical case of a wind-fed accreting pulsar. Systems containing accretion disks, e.g., the disk-fed HMXB or LMXB systems, usually show persistent spin-up or spin-down trends, and sometimes exhibit torque reversal behavior. Some wind-fed HMXBs exhibit accretion disks and show both properties, i.e., random walk behavior on a long-term trend and possibly torque reversal. OAO 1657–415 and 4U 1538–52 belong to this class. The spin history of 4U 0114+650 can be classified as this class according to the spin period evolution.

Considering the dynamic power spectrum, the spin period evolution of 4U 0114+650 is highly variable. In contrast, the superorbital modulation period is relatively stable. Both of these characteristics are related to the presence of an accretion disk, although no clear connection between the accretion disk and these phenomena was found (Farrell et al. 2006). However, unlike the stable nature of superorbital modulation, the modulation profile and detection significance are highly variable. To investigate the relation between the spin period and the superorbital modulation profile, we calculated the RMS amplitude of the superorbital modulation. With the same analysis as was used for the dynamic power spectrum, we obtained the variation of RMS amplitude with time; results are shown in Fig. 3. We show the spin signal as determined by *RXTE* ASM only before ~53,000 because it cannot be clearly seen after that epoch due to the decrease of the X-ray intensity. The random walk epochs seem to be related to the low amplitude epochs of superorbital modulation. For the steady spin-up epochs, we argue that the accretion disk is obvious and that the torque is dominated by material from the disk. In the random walk epochs, the disk is not obvious and the torque is dominated by wind accretion.

6. SUMMARY

With the help of a dynamic power spectrum, we used *RXTE* ASM and *Swift* BAT data to investigate the complex

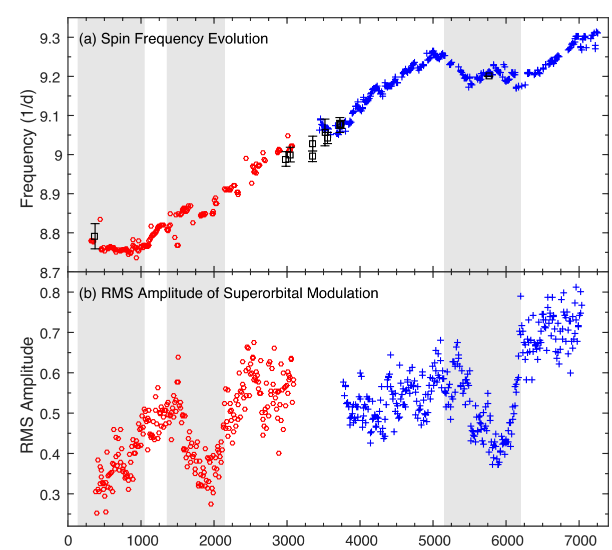

Fig. 3. (a) Evolution of spin frequency of 4U 0114+650. Black circles were obtained with *RXTE* ASM and the blue plus signs are from *Swift* BAT. Gray shaded areas denote the spin down epochs, while the spin frequency is spinning-up in other epochs. (b) Variation of the RMS amplitude of superorbital modulation profile obtained with *RXTE* ASM (red) and *Swift* BAT (blue).

variability of spin and superorbital modulation of 4U 0114+650. The evolution of spin period shows a long-term spin-up trend and at least three epochs with random-walk behavior. On the other hand, the superorbital modulation period is stable over the entire time baseline but the signal weakens in those three random walk epochs. With further calculation of the RMS amplitude of superorbital modulation, we found that the amplitude is low during these three epochs. We conclude that the torque contributed from the accretion disk is less dominant in these epochs. Hence, the spin period evolution is similar to the behavior of wind-fed accreting pulsars.

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