Supergiant, fast, but not so transient 4U 1907+09

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ABSTRACT

We have investigated the dipping activity observed in the high-mass X-ray binary 4U 1907+09 and shown that the source continues to pulsate in the “off” state, noting that the transition between the “on” and “off” states may be either dip-like or flare-like. This behavior may be explained in the framework of the “gated accretion” scenario proposed to explain the flares in supergiant fast X-ray transients (SFXTs). We conclude that 4U 1907+09 might prove to be a missing link between the SFXTs and ordinary accreting pulsars.

Key words. stars: neutron – pulsars: individual: 4U 1907+09 – X-rays: binaries

1. Introduction

The persistently active high-mass X-ray binary system 4U 1907+09, discovered in the third *Uhuru* survey (Giacconi et al. 1971), consists of an X-ray pulsar with a spin period of ~ 437.5 (Makishima et al. 1984) and a highly reddened companion in an eccentric $e \sim 0.28$ orbit with a period of $P \sim 8.3753$ d (in 't Zand et al. 1998). Optical and infrared observations (Cox et al. 2005; Nespoli et al. 2008) suggest an O8–O9 Ia type supergiant donor with $L \sim 5 \times 10^5 L_{\odot}$ and a mass-loss rate of about $7 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. The supergiant nature of the companion and the strong X-ray variability indicate that accretion most likely proceeds from a stellar wind. The distance to the source is estimated to be between 2 and 6 kpc (Cox et al. 2005; Nespoli et al. 2008), therefore, the X-ray luminosity of the source is uncertain. Assuming a compromise distance of 4 kpc, the observed persistent flux of $\sim 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (in 't Zand et al. 1998) implies a luminosity of about $10^{36} \text{ erg s}^{-1}$.

The broadband X-ray spectrum of 4U 1907+09, similar to other accreting pulsars, can be modeled with an absorbed cut-off power law. Based on *Ginga* data, Mihara (1995) reported a cyclotron resonance scattering feature (CRSF) at 19 keV, which was later confirmed with *BeppoSAX* (Cusumano et al. 1998), who also reported a harmonic at ~ 39 keV and a narrow iron emission line at 6.4 keV. The CRSF harmonic, however, was not detected either in RXTE (in 't Zand et al. 1998) and *Suzaku* (Rivers et al. 2010) observations.

One signature feature of 4U 1907+09 is its dipping activity. During the dips, the X-ray flux drops abruptly by a decade or more for a period of few minutes to several hours (in 't Zand et al. 1998; Roberts et al. 2001; Rivers et al. 2010). Similar behavior has been reported for other HMXBs, notably Vela X–1 (Kreykenbohm et al. 2008; Doroshenko et al. 2011) and GX 301–2 (Gögüş et al. 2011). However, 4U 1907+09 spends a substantial fraction of time (up to 60%, Şahiner et al. 2012) in the “off” state, whereas dips are rare events in other systems. Unlike Vela X–1 and GX 301–2, no pulsations were detected during the short dips of 4U 1907+09 observed with RXTE (in 't Zand et al. 1998). Roberts et al. (2001) were able to detect pulsed emission during an extended low-flux episode observed with ASCA. Two scenarios have been invoked to explain the dips: 1) obscuration of the neutron star by a dense wind

clump, and 2) cessation of the accretion owing a wind density drop. Several authors have suggested that in most cases there is no evidence of an increase in the absorption column during the dips (in 't Zand et al. 1998; Roberts et al. 2001; Rivers et al. 2010), so the former scenario is unlikely.

In this study, we have examined the nature of the dips in the lightcurve of 4U 1907+09 in great detail, using recent *Suzaku* and RXTE observations. First, we compared the flaring behavior of the source with the one of other HMXBs, and then we attempted to link the observed phenomenology with the flaring activity typical of the SFXTs. We affirm that similarities of 4U 1907+09 between both normal wind accreting pulsars and SFXTs suggest the source might constitute a missing link between the two classes.

2. Observations and facts

Pulsations during the “off”-states. For a deeper understanding of the nature of the source, it is essential to clarify whether the residual X-ray emission of the “off”-states is pulsed or not. This is indeed the case for Vela X–1 (Doroshenko et al. 2011) and GX 301–2 (Gögüş et al. 2011). As already mentioned, in 't Zand et al. (1998) did not detect pulsations during the dips of 4U 1907+09 using RXTE observations, however, the source lies close to the galactic ridge, and therefore systematic effects related to a stronger background might affect observations with collimating instruments. On the other hand, ASCA observations hint at the pulsations during the two 10 ks-long extended low-flux episodes (Roberts et al. 2001) when the source flux was comparable to the “off”-states. It is unclear, however, whether the pulsations were significant and whether such a low-flux episode could be caused by the same mechanism as the short dips. To clarify this, we analyzed a 123 ks *Suzaku* observation (ID 401057010 from May 2006) of the source. We repeated the analysis carried out by Rivers et al. (2010) who used this observation to study the behavior of the source in the normal flux state, focusing, however, exclusively on the source properties during the “off”-states.

Suzaku is equipped with two instruments: the X-ray spectrometer (XIS), consisting of focusing four units and a collimating hard X-ray detector (HXD). To increase the signal-to-noise ratio, we only used XIS data, combining all four units for timing

Fig. 1. Observation-long XIS lightcurve (background-subtracted with 4 XIS units combined) and close-up of some of the “off” states, all of which are marked with red points in the lightcurve.

Fig. 2. Count-rate distribution in the background-subtracted XIS lightcurve (44 s bin size). Two roughly log-normally distributed peaks corresponding to “off” and “on” states can be identified.

analysis. For data reduction, we used the HEASOFT 6.11 analysis package, and the set of calibration files v.20111109. The XIS lightcurve of the entire observation is presented in Fig. 1. Several dip episodes are observed throughout the entire observation. Similar to Vela X-1 (Doroshenko et al. 2011), the observed count rate roughly follows a log-normal distribution for both the “on” and “off” states, with different mean values as is also evident from the lightcurve (see Fig. 2). Here we define “off”-states as the abrupt flux drops to a level of ~ 1 cts/s per XIS unit for at least one spin cycle of the pulsar. Note, that it is expected to find that the “off”-states contribute to the *tail* of the “on” flux distribution rather than forming a separate *peak*, should they come from random fluctuations in wind density or velocity.

For the timing analysis, the lightcurve was corrected for the orbital motion in the solar and in the binary system using the orbital parameters by in ’t Zand et al. (1998). Phase-coherent timing analysis, using the XIS and HXD lightcurves, yielded a constant pulse period of $P = 441.10(5)$ s, consistent with the value reported by Rivers et al. (2010).

A blind search for significant pulsations in the “off” lightcurve is challenging because it only contains a few pulse cycles separated by many gaps of various lengths, which alias with the intrinsic variability and result in very noisy periodograms if conventional algorithms are used. On the other hand, folding the “off” lightcurve with the period found from “on” lightcurve produces a pulse profile with a similar shape (see Fig. 3), which is also similar to the ASCA folded lightcurve for the extended low-flux episode (see Fig. 5 of Roberts et al. 2001). To justify the significance of the pulsations one can estimate the probability of getting the observed deviation from a constant over the pulse

Fig. 3. Background subtracted “on” (top) and “off” (bottom) XIS pulse profiles in 1–10 keV energy range folded with the same parameters.

Fig. 4. Distribution of squared deviations in the synthetic pulse profiles from the constant (black) and the best-fit probability density function to the distribution (red). Dashed line indicates the observed squared deviation for the “off” pulse profile.

profile by chance (for known pulse-period and pulse shape). To do this we simulated 10^4 modified “off” lightcurves with flux randomly distributed with the same average value and dispersion as the observed “off” flux. We then folded the simulated lightcurves with observed period and calculated the deviation of the resulting pulse profile from a constant. These turn out to be distributed log-normally, so one can estimate the probability of getting the deviation equal to or larger than observed. We find that it is fairly low at $P_0 \sim 6 \times 10^{-8}$ as summarized in Fig. 4, i.e. the observed pulsation is significant.

“Interdips” or flares. It is interesting to observe that the fraction of time the source spends in the “off” state is so long that occasionally two consecutive dips are separated by just a short

Fig. 5. Two SFXT-like flares observed by RXTE and centered respectively at $\sim$ MJD 55 169.5 and $\sim$ MJD 51 074.49. In the latter case the source remains “off” after a gap in the data for $\sim$ 3 h.

“on” interval of a comparable length to that of the dips. This interval would be considered a transient flaring episode, should only the part of the lightcurve shown in the third upper panel of Fig. 1 be observed. We searched for similar events in the source lightcurves in RXTE archive, that had extensively monitored the source. Searching for uninterrupted pointings, which fully covered intervals between consecutive dips, we found the two cases presented in Fig. 5. We would like to emphasize that the sharp transition between the “off” and “on” states produces distinct flare-like events in the lightcurve.

Out of the RXTE archival data (Şahiner et al. 2012) another relevant observational fact emerges: the probability of observing the source in the “off”-state depends on the orbital phase and is significantly lower at periastron.

3. Discussion

The discussion section begins with a short summary of the observed phenomenology:

- 4U 1907+09 exhibits a dipping activity associated with sudden drops in flux by an order of magnitude or more on a timescale that is comparable to the spin period. Dips last several minutes to several hours before the flux recovers to the “on” value on a similar timescale.
- 4U 1907+09 is not unique and a similar behavior has been observed in other HMXBs, notably Vela X–1 and GX 301–2.
- In the “off” state, accretion does not cease completely, forming a distinct peak in the flux distribution while the source continues to pulsate.
- The pulse profile changes significantly during the “off”-state.
- The probability of observing the source in the “off” state depends on the orbital phase and is lower at periastron.
- The fraction of time 4U 1907+09 spends in the “off”-state is long enough to make inter-dip intervals occasionally appear as flares.

First, emphasis should be placed on the phenomenological similarity between 4U 1907+09 and the SFXTs. The inter-dips or flares shown in Fig. 5 exhibit timescales and amplitudes similar to the smaller flares observed from the SFXTs. Indeed, we have measured an average unabsorbed flux of $\sim 4.5 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$ and $\sim 4.5 \times 10^{-10}$ erg cm $^{-2}$ s $^{-1}$ for the “off” and “on” fluxes respectively, implying $L_x \approx 8.6 \times 10^{34-35}$ erg s $^{-1}$

for an assumed distance of 4 kpc, so is comparable to values observed during the flaring periods in SFXTs (Sguera et al. 2008; Bozzo et al. 2008).

On the other hand, 4U 1907+09 in “off” state is brighter than the SFXTs in deep quiescence, and it has shorter “off” duty cycle. The latter depends, however, on the orbital phase, hence on the distance from the companion. One could anticipate, therefore, that the source would remain “off” longer should the system be wider. On the other hand, the duty cycle of SFXTs is also known to depend on the orbital phase, and some of them leave the deep quiescence and only start to flare in the vicinity of the periastron (Sidoli 2011). Making such a system more compact would extend the flaring period and prevent it from going to deep quiescence, thus making it similar to the 4U 1907+09 with its relatively bright “off” states and lower dynamical range than the prototypical SFXTs. Luminosity-related changes of the pulse profiles similar to ones in 4U 1907+09 have also been observed in SFXT, at least in one case (Romano et al. 2009). 4U 1907+09 seems to exhibit, therefore, properties that are intermediate between the SFXTs and the persistent systems.

The dipping activity in 4U 1907+09 is not unique among wind-accreting pulsars. As discussed by Kreykenbohm et al. (2008) for Vela X–1, the drop in X-ray flux must be intrinsic rather than due to eclipses by a wind clump obscuring the neutron star. Since no “off” flux was known to emerge from Vela X–1 and 4U 1907+09, Kreykenbohm et al. (2008) and Şahiner et al. (2012) have suggested that the centrifugal inhibition might be responsible for the cessation of emission. However, residual pulsed flux has been detected in Vela X–1 (Doroshenko et al. 2011), suggesting that a change in the accretion regime might be responsible for the flux drop. Following Burnard et al. (1983) and Bozzo et al. (2008), Doroshenko et al. (2011) proposed for Vela X–1 that, while normally the accretion proceeds via Rayleigh-Taylor instability (RTI), this switches off during the dips, and Kelvin-Helmholtz instabilities (KHI) become relevant. Note that the switch between two accretion regimes naturally explains the observed bimodal flux distribution. The same scenario may also apply to 4U 1907+09.

It is interesting to discuss why just a few X-ray pulsars do switch “off”. For SFXTs Bozzo et al. (2008) argue that a strong magnetic field is required to explain the observed luminosity swings and the characteristic accretion rates in different accretion regimes. They estimate that RTIs become inefficient for mass-loss rates of the optical companion below:

$$\dot{M}_{-6} \leq 280 P_{s3}^{-3} a_{10d}^2 \nu_8 R_{M10}^{5/2} [1 + 16 R_{G10}/(5 R_{M10})]^{-3/2} \quad (1)$$

here, R_{G10} and R_{M10} are the capture and magnetosphere radius, respectively, in units of 10^{10} cm; $a_{10d} = P_{10d}^{2/3} M_{30}^{1/3}$ is function of the orbital period and of the total mass of the system; ν_8 is the relative velocity between the wind and the neutron star in units of 10^8 cm s $^{-1}$; and P_{s3} is the spin period in units of 1000 s. Assuming for 4U 1907+09 the parameters reported by Cox et al. (2005), we obtain an upper limit for the magnetosphere size of $R_{M10} \leq 0.6$. Routinely observed regime transitions imply, however, that the R_{M10} is close to this value, i.e. large as well.

Bozzo et al. (2008) also provide an estimate for the leak rate and the corresponding X-ray luminosity if plasma enters the magnetosphere via KHI. For 4U 1907+09 the estimate is

$$\begin{aligned} L_{KH} &\approx GM_{NS} \dot{M}_{KH} / R_{NS} \\ &\approx 10^{35} \eta_{KH} R_{M10}^3 (1 + 16 R_{G10}/(5 R_{M10}))^{3/2} \frac{\sqrt{\rho_i / \rho_e}}{1 + \rho_i / \rho_e} \text{ erg s}^{-1} \end{aligned}$$

where $\rho_{i,e}$ are the densities within and outside of the magnetosphere. According to [Bozzo et al. \(2008\)](#), $\eta_{KH} \sim 0.1$, and the density ratio is estimated to be between

$$\frac{\sqrt{\rho_i/\rho_e}}{1 + \rho_i/\rho_e} = \begin{cases} 0.3\eta_{KH}h^{-1}R_{M10}^{3/2}P_{s3}^{-1} \\ 0.1\eta_{KH}h^{-1}R_{M10}^{1/2}v_8 \end{cases}$$

where h is the fractional height of the area where the plasma and the magnetic field coexist, in units of the total thickness of the KHI unstable layer ([Burnard et al. 1983](#)). In the case of 4U 1907+09, for the observed “off-state” luminosity of $\sim 8 \times 10^{34}$ erg s $^{-1}$, $R_{M10} \geq 0.25$ can be estimated if the KHI unstable layer is relatively thin ($h \sim 0.05$), or $R_{M10} \geq 0.55$, if $h \sim 1$, as suggested by [Burnard et al. \(1983\)](#). The latter is in good agreement with the value deduced from stability criteria. For the observed X-ray luminosity, this implies a magnetized neutron star with $B \sim 10^{13}$ G.

[Kreykenbohm et al. \(2008\)](#) proposed that the magnetosphere might grow enough to inhibit the accretion even for moderately magnetized neutron star if the wind density in the vicinity of the neutron star drops by factor of ~ 1000 . This would allow reconciliation of the “off”-states with a magnetic field intensity of $B \approx 2 \times 10^{12}$ G like the one deduced from the observed CRSF energy. The winds of young supergiants are known to be structured, and hydrodynamical simulations have predicted a wind density contrast as high as 10^4 ([Oskinova et al. 2007](#)). These predictions are not confirmed by observations, however, because the observed X-ray flux typically varies at most by a factor of 10. Moreover, the “off-state” duty cycle of 4U 1907+09 depends on the orbital phase ([Şahiner et al. 2012](#)); i.e., the fluctuations in wind density which trigger the “off”-states must be comparable to the ones associated with the orbital motion. The average wind density in 4U 1907+09 is expected in the CAK model ([Castor et al. 1975](#)) to vary just by a factor of ~ 5 along the orbit, which is consistent with the observed orbital lightcurve. The “off”-states in 4U 1907+09 are therefore most likely triggered by minor fluctuations in wind density, so a large magnetosphere would imply a magnetic field for the neutron star of $B \sim 10^{13}$ G. Such a strong magnetic field might help also in explaining the long spin-period of 4U 1907+09, although its complicated evolution definitively deserves a dedicated study.

The observed CRSF energy in 4U 1907+09 implies, however, an order of magnitude weaker field $B \sim 1.5 \times 10^{12}$ G in the line-forming region. Considering that the details of the magnetosphere-plasma interaction are far from being fully understood, and that there is significant uncertainty in the distance to the source (which reflects in the estimate of the accretion rate and consequently of the magnetosphere radius), it may well be that the scenario outlined above will also hold for a weaker field. However, 4U 1907+09 is a very unusual HMXB, and we tend to believe that there is something distinctive behind its dipping behavior, and the strong magnetic field of the neutron star is a natural candidate. As previously discussed for the case of Vela X–1 and GX 301–2, the CRSF energy provides an estimate for the magnetic field in a line-forming region, and if the line forms far above surface of the neutron star, it might underestimate the surface field by orders of magnitude. The dipole component of the field changes with $\sim R^{-3}$, so scattering in the upper parts of the accretion column, or in the accretion stream at heights comparable to the neutron star radius atop the polar caps may help explain the observed CRSF energies even for magnetar-like surface fields. Note, that the complicated observed shapes of the pulse profiles in bright accreting pulsars cannot be explained with the direct emission from compact polar caps ([Kraus et al. 2003](#)), and

this possibility should be considered irrespectively of the surface field.

In 4U 1907+09, the luminosity is probably too low to form an extended accretion column ([Lyubarsky & Sunyaev 1988](#)), however, scattering of X-ray photons from the polar caps in the upper accretion stream may be important. This was discussed by [Kraus et al. \(2003\)](#), who find that scattering in the upper accretion flow might affect the formation of the pulse-profile and spectra in a major way and, in fact, be responsible for the majority of the hard photons coming from the source. The magnetic field in scattering region might already be compatible with the one estimated from the observed CRSF energy. [Nishimura \(2008\)](#) consider the CRSF formation in an accretion column with a height of several kilometers and suggest that line-like features are still present in the spectrum. As we discussed for GX 301–2 ([Doroshenko et al. 2010](#)), the orientation of the emission region with respect to the observer will also affect line formation because only part of the emission or scattering region will be visible.

Another scenario that could explain the difference between SFXTs and normal HMXBs, invokes properties of the stellar wind. Recently, [Ikhsanov & Finger \(2012\)](#) have suggested that the picture of interaction of the accretion flow and the magnetosphere outlined by [Bozzo et al. \(2008\)](#) should be altered if the wind plasma itself is magnetized, and this might help explain the long pulse periods in some pulsars. We note here that the wind magnetic field might also affect the stability of the accretion, although how still needs to be clarified. In this scenario the strong magnetic field of the *optical* companion could, in principle, be responsible for the difference between the ordinary HMXBs, the intermediate systems like 4U 1907+09, and the SFXTs. Such a scenario requires further theoretical investigation, while systematic survey of the magnetic fields of the primaries of different source classes may be carried out already now to verify whether they differ significantly.

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