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The unusual 2006 dwarf nova outburst of GK Persei

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ABSTRACT

The 2006 outburst of GK Persei differed significantly at optical and ultraviolet (UV) wavelengths from typical outbursts of this object. We present multiwavelength (X-ray, UV and optical) *Swift* and AAVSO data, giving unprecedented broad-band coverage of the outburst, allowing us to follow the evolution of the longer-than-normal 2006 outburst across these wavelengths. In the optical and UV we see a triple-peaked morphology with maximum brightness ∼1.5 mag lower than in previous years. In contrast, the peak hard X-ray flux is the same as in previous outbursts. We resolve this dichotomy by demonstrating that the hard X-ray flux only accounts for a small fraction of the total energy liberated during accretion, and interpret the optical/UV outburst profile as arising from a series of heating and cooling waves traversing the disc, caused by its variable density profile.

Key words: accretion, accretion discs – stars: individual: GK Per – novae, cataclysmic variables – X-rays: binaries.

1 INTRODUCTION

The magnetic cataclysmic variable (CV) star GK Persei (GK Per) underwent an unusual dwarf-nova-like outburst in 2006–2007. This system, which is not a typical CV as it has a red dwarf secondary and a 2-d orbital period (Crampton, Cowley & Fisher 1986; Morales-Rueda et al. 2002), has been observed to undergo outbursts roughly every 3 years (e.g. Sabbadin & Bianchini 1983; Simon 2002). Its long orbital period and the fact that it is an intermediate polar (IP; i.e. the white dwarf primary has a moderately strong magnetic field which truncates the inner accretion disc; Watson, King & Osborne 1985) make GK Per different from most dwarf novae (DNe). The outbursts are still believed to be analogous to normal DN outbursts, i.e. they are thought to be caused by enhanced mass transfer through the accretion disc due to thermal instability therein (e.g. Bianchini, Sabbadin & Hamzaoglu 1982; Simon 2002; Bianchini et al. 2003).

GK Per has been well studied in quiescence and outburst. Its X-ray emission is modulated at the 351-s white dwarf rotational period (Watson et al. 1985) in quiescence and outburst. In outburst the modulation is strong and single peaked, whereas in quiescence it is weak and double peaked (Watson et al. 1985; Norton, Watson & King 1988; Hellier, Harmer & Beardmore 2004). Modulation at this period has also been seen in optical spectroscopy (Morales-Rueda, Still & Roche 1999) and photometry (Patterson 1991). The American Association of Variable Star Observers (AAVSO)[1] archive contains data extending back to 1904, with frequent observations beginning in 1919. From 1954 onwards the light curve shows regular outbursts, peaking typically around 10th magnitude. In Fig. 1, we show the AAVSO light curve of every outburst found in a visual inspection of the data set. As can be immediately seen, the 2006 outburst is fainter than most and shows an unusual morphology. It is, however, similar to the 1967 outburst.

The coverage of GK Per at X-ray and ultraviolet (UV) wavelengths is not as extensive as in the optical; however, it has been observed in quiescence and outburst in both bands. Observations with *Ginga* (Ishida et al. 1992) and *EXOSAT* (Watson et al. 1985; Norton et al. 1988) show that in hard X-rays (∼2–10 keV) the typical outburst flux is ∼10 times the quiescent flux. These and *RXTE* observations (Hellier et al. 2004) show the typical outburst 2–10 keV flux to be $\sim 2.5 \times 10^{-10}$ erg cm^{-2} s^{-1}. GK Per is 470 pc away (McLaughlin 1960), thus $L_X \sim 6 \times 10^{33}$ erg s^{-1}. *International Ultraviolet Explorer* (*IUE*) observed GK Per in both quiescence (Bianchini & Sabbadin 1983) and outburst (Rosino, Bianchini & Rafanelli 1982) and saw a flux ratio of ∼30 between the two observations at 2600 Å.

The 2006 outburst of GK Per was announced by Brat et al. (2006) on 2006 December 18. Examination of the AAVSO light curve shows the outburst to have begun on December 11; hereafter we use 2006 December 11 at 00:00 UT (= JD 245 4080.5, *Swift* MET 187 488 001.6 s) as the start time of the outburst (hereafter 'T0').

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[1] http://www.aavso.org

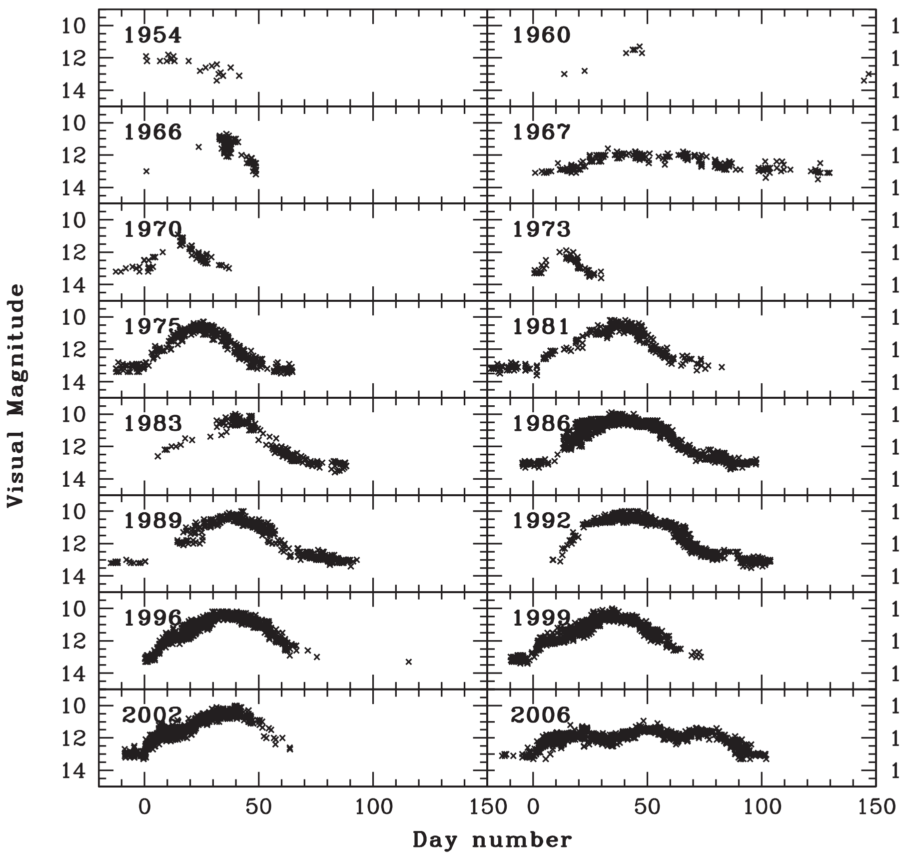

Figure 1. AAVSO light curves of all outbursts of GK Per which can be identified in the complete AAVSO data set. Day zero is estimated by eye.

We obtained Target of Opportunity observations with *Swift* (Gehrels et al. 2004) which began on 2006 December 20 and were repeated regularly throughout the outburst.

2 OBSERVATIONS AND DATA ANALYSIS

For the first 6 weeks of the outburst, *Swift* observed GK Per for 6 ks once a week. Each observation was spread over three snapshots (one snapshot per 96-min *Swift* orbit) as *Swift* is in a low-Earth orbit. The X-ray telescope (XRT; Burrows et al. 2005) was in its automatic state, able to choose its operating mode for itself based on the source count rate (Hill et al. 2005); it remained in photon-counting mode for every observation. The UV/optical telescope (UVOT; Roming et al. 2005) was operating in event mode. We requested the *uvw1* filter (with a central wavelength of 2600 Å and full width at half-maximum of 693 Å; Poole et al. 2008), so that our results would be comparable with the *XMM–Newton* observations taken during the optical rise phase of the 2002 outburst (Vrielmann, Ness & Schmitt 2005).[2] Based on Vrielmann et al. (2005), we anticipated a UVOT count rate of ∼30 counts s^{-1}, well below the level at which coincidence loss becomes an issue.

Swift data are available within a few hours of the observations taking place, and it became immediately apparent that the UVOT count rate was much higher than anticipated and showed large variations. Three of the first four observations had a coincidence loss corrected count rate of ∼115 counts s^{-1}, while one of them was at ∼160 counts s^{-1}. Within the individual observations no variations of this magnitude were seen. To better sample this variability, we extended our observing campaign to twice weekly from 2007 January 30 (T0+50 d), the additional observation being ∼4 ks in duration each time. A summary of each observation is given in Table 1. By the time of the final observation GK Per had almost returned to quiescence. Unfortunately, it was not possible to continue observing with *Swift* after this point as GK Per was within 45° of the Sun – *Swift*'s observing limit.

The data were analysed using the *Swift* software.[3] The data reduction was performed using version 28 of the *Swift* software. XRT light curves and spectra of each observation were built using the software presented by Evans et al. (2009). We created light curves with 30-s bins. UVOT light curves were built following the standard approach: the ATTCORRJUMP tool was used to correct the spacecraft attitude file and COORDINATOR to create sky coordinates for each UVOT event. The UVOTSCREEN task was called to remove bad events before UVOTEVTLC was used to produce a light curve with 5-s bins. This task takes source and background regions and performs background subtraction and coincidence-loss correction. The final, calibrated source brightness is provided as a count rate, magnitude and flux density. Since the UVOT data were not astrometrically

[2] The *XMM* observations included the optical monitor (OM) using the *uvw1* filter and the band pass of the filter is the same as for the *Swift*–UVOT, although the latter has ∼10 per cent more effective area in this filter than the *XMM*–OM.

[3] Part of the LHEASOFT package: http://heasarc.gsfc.nasa.gov/lheasoft/

Table 1. Summary of the *Swift* observations of GK Per. The spin amplitude is defined as $(max - min)/(max + min)$. Observation 020 was taken in quiescence, 6 months after the outburst finished, and has no UVOT data.

Obs. segment	Date and time start (UT)	XRT exposure (s)	Mean XRT rate (s^{-1})	XRT spin amplitude[a] (per cent)	UVOT exposure (s)	Mean UVOT rate (s^{-1})	UVOT spin amplitude[b] (per cent)
001	2006-12-20 at 16:14	3946	1.58	39	3989	117	5.8
002	2006-12-26 at 02:29	4510	1.65	30	4539	155	4.7
003	2007-01-02 at 12:46	4697	1.98	21	4735	114	5.6
004	2007-01-09 at 08:35	4821	1.65	46	4838	99	7.9
005	2007-01-17 at 03:14	6017	2.02	27	5861	116	5.8
006	2007-01-23 at 02:12	5776	1.77	42	5798	198	5.6
007	2007-01-30 at 01:40	734	1.5	57	748	200	16.7
008	2007-02-04 at 14:52	3936	1.78	29	3978	197	3.8
009	2007-02-08 at 03:49	5250	2.24	42	5270	138	4.7
011	2007-02-12 at 02:20	2967	1.69	52	3023	113	11.2
012	2007-02-16 at 02:42	6155	2.06	35	6237	129	4.9
013	2007-02-19 at 14:30	2798	1.38	43	2808	206	9.6
014	2007-02-23 at 00:10	3239	1.48	40	3243	199	4.8
015	2007-02-26 at 00:29	6368	1.76	39	6418	188	3.5
016	2007-03-03 at 12:08	3144	1.46	47	3288	160	7.7
017	2007-03-06 at 04:42	7796	2.21	26	7848	86	5.2
018	2007-03-09 at 00:18	4201	1.73	25	4229	50	7.2
019	2007-03-13 at 00:32	5892	1.22	22	5981	35	4.4
020	2007-09-27 at 14:07	2473	0.12	<30			

[a]Typical uncertainties ∼3 per cent.
[b]Typical uncertainties ∼0.5 per cent.

corrected, we examined each observation individually and produced a unique source region for each snapshot.

We barycentrically corrected the data, using a single barycentric correction per observation segment, since this varied by ∼1 s per observation. We also folded each observation on the 351-s spin period, using the same zero-point (in the barycentric frame) for each observation. The spin-period modulation was clearly detected in X-rays and the UV in all outburst observations; the pulse fraction is given in Table 1.

3 RESULTS

In Fig. 2 we show the AAVSO optical light curve of the 2006 outburst with the X-ray and UV light curves The optical light curve peaks ∼1.5 mag fainter than most recent outbursts. The shape of the light curve, rather than having a smooth 'hump', shows a series of three humps. Note that the 2002 outburst showed a pause during the rise to maximum and was very similar to the 2006 outburst for the first ∼20 d; however, thereafter the 2002 outburst returned to the 'normal' behaviour.

Since the 2006 and 1967 outbursts appear longer than the others, as well as fainter, we measured the optical fluence of each outburst (i.e. the flux integrated over the outburst). These are shown in Fig. 3. Generally, as one would expect, outburst fluence is correlated with duration. The exceptions are the 2006 and 1967 outbursts, which are long but of low fluence.

The UV light curve of the 2006 outburst is unique in its coverage and thus cannot be compared to previous outbursts. However, the ratio of the maximum flux to that in the final observation (approximately quiescence; the AAVSO magnitude was ∼0.2 mag above the quiescent level) is ∼7.5 (=2.2 mag) whereas the ratio of the *IUE* flux at 2600 Å between outburst and quiescence was ∼28 (=3.6 mag; Rosino et al. 1982; Bianchini & Sabbadin 1983). The amplitude of the UV outburst is thus around 1.5 mag less than expected from

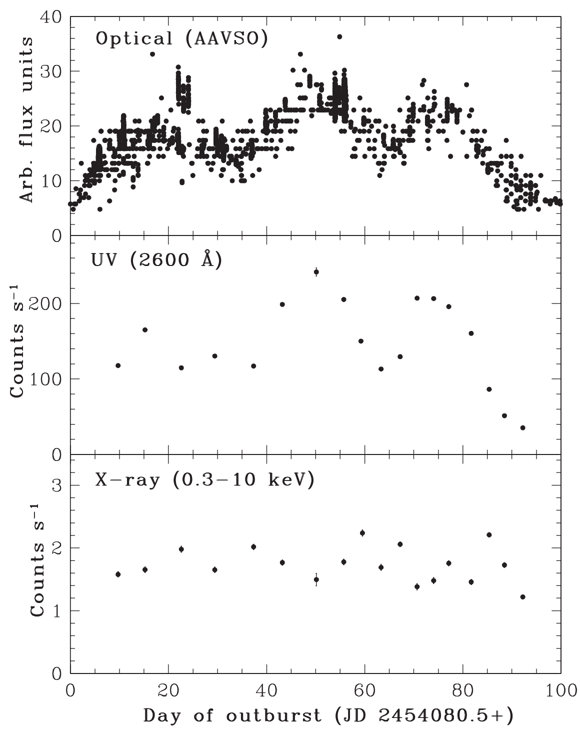

Figure 2. The AAVSO, *Swift*-UV (2600 Å) and *Swift*-X-ray (0.3–10 keV) light curves of the 2006 outburst of GK Per. The AAVSO data have been converted to (arbitrary) linear units for comparison with the *Swift* data. The *Swift* data are binned to one point per observation.

the previous data, as has already been noted for the optical data. By analogy with the optical data, we assume this implies a lower outburst flux rather than increased quiescent flux. This is a surprising result, since the typical UVOT count rate was nearly an order

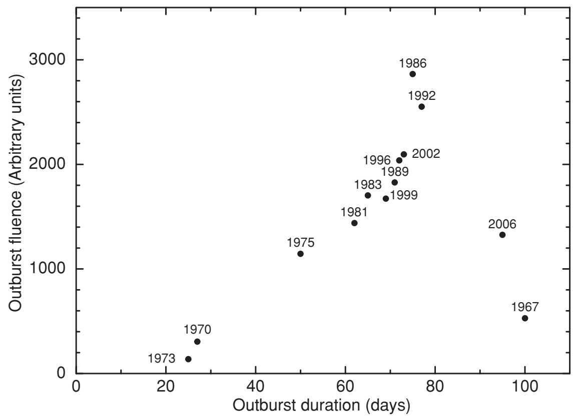

Figure 3. Optical outburst fluence plotted against the duration.

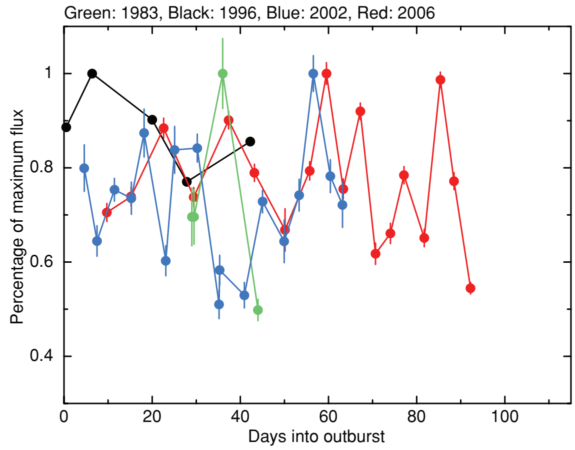

Figure 4. A comparison of recent outbursts of GK Per in the X-rays. The *y*-axis shows the count rate as a proportion of the maximum count rate observed (to normalize the different detectors). Green: 2–10 keV *EXOSAT* data from 1983 (Watson et al. 1985). Black: 2–15 keV *RXTE* data from 1996 (Hellier et al. 2004). Blue: 2–15 keV *RXTE* data from 2002. Red: 0.3–10 keV *Swift* data (this paper).

of magnitude higher than that reported by Vrielmann et al. (2005). To investigate, we downloaded the pipeline *XMM*–OM products from the *XMM* Science Archive and examined the *uvw1* data (Obs ID 0154550201). We found the count rate to be much higher than claimed by Vrielmann et al. (2005) and comparable to or higher than in our *Swift* data. Given that the *XMM* data were taken on the rise of the outburst, not the peak, we conclude that *XMM*–OM data are consistent with the idea that the UV emission in the 2006 outburst was fainter than in previous outbursts. We also searched the OM data for evidence of spin-period modulation, since this is clearly seen in our *Swift*–UVOT data but was reported as absent by Vrielmann et al. (2005). There is weak evidence for spin-period modulation in the OM data, with an amplitude $\lesssim 3$ per cent. The presence of spin-period modulation in the UV emission is thus not peculiar to the 2006 outburst.

While the UV light curve is clearly correlated with the optical one, the X-ray light curve is not. By eye, some possible anticorrelation or time-delayed correlation with the UVOT data seems possible. We thus performed a discrete correlation function analysis between the UVOT and XRT data; however, no correlation was found above the 1.8σ level.

The 1983, 1996 and 2002 outbursts of GK Per were all monitored in the X-rays with different satellites (Watson et al. 1985; Hellier et al. 2004). The most extensive data set prior to that presented here is unpublished *RXTE* monitoring of the 2002 outburst. In Fig. 4 we show the X-ray flux evolution from these three outbursts in addition to the *Swift* data from 2006. As can be seen, there is no systematic X-ray evolution seen during outbursts, unlike in the optical. The 2006 outburst is, however, fairly typical in its relative flux evolution. The 2–10 keV flux during *Swift* observation 009 (the observation during which the X-ray flux was greatest) was 3.3×10^{-10} erg cm^{-2} s^{-1} ($L_X = 8.7 \times 10^{33}$ erg s^{-1}), which is consistent with the peak hard X-ray fluxes seen in previous outbursts (e.g. 1983, Watson et al. 1985; 1989, Ishida et al. 1992; 1996, Hellier et al. 2004). In 2007 September *Swift*-XRT observed GK Per in quiescence for calibration purposes (unfortunately, the UVOT was not in operation). The 2–10 keV flux in this observation was 2.3×10^{-11} erg cm^{-2} s^{-1} ($L_X = 6.1 \times 10^{32}$ erg s^{-1}), i.e. a factor of 14 lower than in outburst. This is similar to the 2–10 keV quiescent fluxes of 4.5×10^{-11} and 2.7×10^{-11} erg cm^{-2} s^{-1} reported by Norton et al. (1988). Thus, unlike the optical and UV, both the peak 2–10 keV flux and the outburst/quiescence 2–10 keV flux ratio seen in this outburst are consistent with measurements from previous outbursts.

3.1 X-ray spectroscopy

We created X-ray spectra for each observation of GK Per and modelled them in XSPEC 12.4. We first used the GRPPHA tool to ensure that there was at least one count per spectral bin and performed fitting using the *C*-statistic (this is more reliable than the χ^2 statistic; see e.g. Humphrey, Liu & Buote 2009).

The hard X-ray emission in IPs is believed to come from a dense, post-shock plasma cooling via bremsstrahlung emission (e.g. Aizu 1973; Cropper et al. 1999), which we fitted with the physical model of this developed by Cropper et al. (1999). A simple photoelectric absorber and two partial covering absorbers were necessary to obtain a good fit to the hard X-ray data, as previously found (e.g. Ishida et al. 1992).

There were still significant residuals seen at soft energies. A number of IPs show evidence for a soft (∼30–100 eV) blackbody component in their X-ray spectra (e.g. de Martino et al. 2004; Evans & Hellier 2007; Anzolin et al. 2008), as did GK Per during the 2002 outburst (Vrielmann et al. 2005; Evans & Hellier 2007). We thus added a blackbody component. We also added narrow Gaussian lines at 0.423, 0.557 and 0.907 keV to reproduce the lines from the nova shell; the energies, widths and normalizations of these lines were taken from Balman (2005).

In IPs it is often assumed that most of the accretion luminosity is emitted as hard X-rays (e.g. Evans & Hellier 2007 showed the bolometric luminosity of the soft component to be $\lesssim 0.1$ of the bolometric luminosity of the hard component); however, since the 0.3–10 keV bandpass of the XRT (and the EPIC instruments on *XMM*) covers only the hard tail of the blackbody component, the details of the soft emission are not particularly well constrained. To remedy this we created a spectral point from the UVOT data for observation 009 (the X-ray brightest observation) using the UVOT2PHA tool and fitted the combined UVOT and XRT data for this observation. The (unabsorbed) bolometric flux from the blackbody component in this fit far exceeded the hard X-ray flux; however, at $D = 470$ pc, it also exceeded the Eddington luminosity by more than an order of magnitude (assuming a 0.87 $M_\odot$ white dwarf; Morales-Rueda et al. 2002). Thus, there cannot be a single spectral component, powered

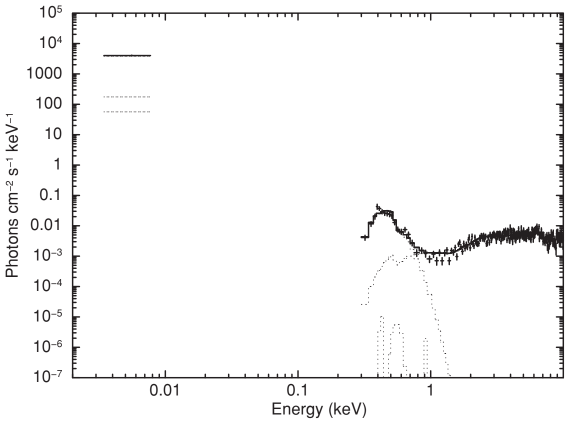

Figure 5. The spectrum obtained from the observation 009 data, with the best-fitting model applied. For fitting, the data were grouped to contain at least one count per spectral bin; however, for plotting purposes the data have been binned such that each point is significant at at least the 5σ level. The best-fitting model parameters are detailed in Table 2.

by accretion energy, spanning the UV to soft X-ray wavelength range.

A potential contributor to the UV emission is the inner disc. Frank, King & Raine (2002) give the temperature of the disc at radius R as

$$T(R) = \left(\frac{3GM\dot{M}}{8\pi R^3\sigma}\left[1-\left(\frac{R_{\rm wd}}{R}\right)^{1/2}\right]\right)^{1/4}. \quad (1)$$

Using $M_{\rm WD} = 0.87\,{\rm M}_{\odot}$ (Morales-Rueda et al. 2002), the white dwarf mass–radius relation of Nauenberg (1972), and assuming[4] $\dot{M} \geq 5 \times 10^{16}$ g s^{-1}, we find the disc temperature at the co-rotation radius (=7 × 10^9 cm) to be $T_{\rm corot} \geq 12\,400$ K, which corresponds to a blackbody peak wavelength of $\lambda_{\rm corot} \leq 2360$ Å; towards the centre of the *uvw2* filter bandpass. Thus, we expect the inner disc to make a significant contribution to the UVOT flux.

We therefore modified our model further, adding a second blackbody with the peak wavelength fixed at 2360 Å (with only a single UV spectral point we cannot leave this parameter free). This blackbody was absorbed only by a TBABS component (which includes the effects of dust), with $N_{\rm H}$ tied to that of the PHABS component acting on the harder emission. The best-fitting spectrum is shown in Fig. 5 and the parameters are tabulated in Table 2. In this fit, only ∼1 per cent of the combined flux of the harder blackbody and thermal plasma components – i.e. those expected to radiate the majority of the liberated accretion energy – is emitted in the 2–10 keV band, suggesting that the hard X-ray flux is a poor proxy for accretion rate. This 1 per cent figure should be seen as a poorly constrained lower limit due to the limitations of this model fit: the harder blackbody component is affected by the softer one, whose temperature is fixed at that determined assuming that the 2–10 keV flux comprises 100 per cent of the accretion flux. However, the fit shows that this is not the case, i.e. the approach is not self-consistent. However, a self-consistent model is not readily attainable. In order to properly constrain the spectrum and hence the wavelengths at which the accretion energy is radiated, we need simultaneous X-ray and UV (preferably broad-band UV) spectroscopy, which we do not have; none the less, it is clear that a significant portion of the accretion energy can be radiated below the 2–10 keV band.

[4] By taking $L_{\rm X,2-10} = GM\dot{M}/R_{\rm wd}$: this is a lower limit since it assumes that all of the liberated accretion energy was radiated in the 2–10 keV band.

3.2 Spectral evolution through the outburst

While some variation in best-fitting spectral parameters was seen between observations, the uncertainties were too large to determine whether there was any spectral evolution taking place during the outburst. We tried combining several observations to give a total of five spectra for the outburst: 'plateau 1' (observations 001–005), 'hump 1' (observations 006–008); 'plateau 2' (009–012), 'hump 2' (013–016) and 'fading' (017–018). The only parameter which showed significant variation between these regions was the column density of the less dense of the two partial covering absorbers, this was ∼(8.4 ± ∼0.7) × 10^{22} cm^{-2} during the 'humps' and ∼(4.5 ± ∼0.5) × 10^{22} cm^{-2} during the 'plateaux'.

3.3 Spin-period modulation

One of the signatures of IPs is that their emission is modulated on the white dwarf spin period. For GK Per this is 351 s (Watson et al. 1985; Mauche 2004). We folded the X-ray and UV data for each observation on this period – using the same arbitrary zero-point (T0+52.65 s, in the barycentric frame) each time. The resultant folds are shown in Fig. 6.

As can be seen, the shape, magnitude and phase of spin minimum changes from observation to observation. This behaviour has been seen in quiescence, both in X-rays (Norton et al. 1988) and in the *V*/*R* ratios of the Hα and Hδ Balmer lines (Garlick et al. 1994).

In some cases the shape of the profile is the same in both wavebands, and in others they differ (for example, observation 001 has a roughly saw-toothed profile in each band whereas the UV profile in observation 009 is much more symmetric than the X-ray profile).

Unfortunately, the individual observations contain too few counts for a meaningful phase-resolved spectroscopic analysis. We are reluctant to combine observations for this purpose because of the pulse-profile evolution. Instead we created hardness ratios and folded these on the spin period. Because the source is so heavily absorbed, it was necessary to use the 4–10/0.3–4 keV hardness ratio in order to have sufficient counts in the 'soft' band; however, even with this ratio the rate in that band is so low that large bins and hence low time resolution is necessary. The hardness ratio spin folds are shown in Fig. 7. Little significant modulation is seen; however, this is not entirely surprising: the spin-period modulation is thought to be an absorption effect (Hellier et al. 2004; Vrielmann et al. 2005), and our hardness ratio is not especially sensitive to absorption.

An ∼5000-s quasi-periodic oscillation (QPO) has been previously reported in GK Per outburst observations (e.g. Watson et al. 1985; Hellier et al. 2004). Unfortunately, the orbital period of *Swift* is close to this; we thus do not consider the QPO further in this paper.

4 DISCUSSION

4.1 Interpreting the outburst profile

We have presented a high-quality multiwavelength data set covering the 2006 outburst of GK Per, which shows that this was an atypical event. Lasting 20–30 d longer than a typical outburst, the optical brightness peaked 1.5 mag below that seen in most previous events. The ∼2600-Å UV flux is similarly reduced compared to previous

Table 2. The best-fitting parameters for the *Swift*–UVOT and XRT spectrum of observation 009.

Component	Parameters	Units	Value (error, 90 per cent confidence)
tbabs	N_{H}	10^{22} cm^{-2}	0.25 (+0.05, −0.07)
Blackbody	kT	eV	5.25 (frozen)
	Normalization		2.49 (+0.03, −0.05)
phabs	N_{H}	10^{22} cm^{-2}	tied to that of the tbabs
Part. Cvr. Abs.	N_{H}	10^{22} cm^{-2}	4.6 (+0.3, −0.4)
	Cvf. Frc		0.951 (+0.012, −0.001)
Part. Cvr. Abs.	N_{H}	10^{22} cm^{-2}	48 (+4, −13)
	Cvf. Frc		0.76 (+0.02, −0.03)
Blackbody	kT	eV	57 (+3, −2)
	Normalization		0.43 (+0.17, −0.09)
'Cropper'	$\dot{M}$	g s^{-2} cm^{-2}	0.51 (+18.1, −0.05)
	Normalization		1.10×10^{-4} (+18.9, -2.7×10^{-5})

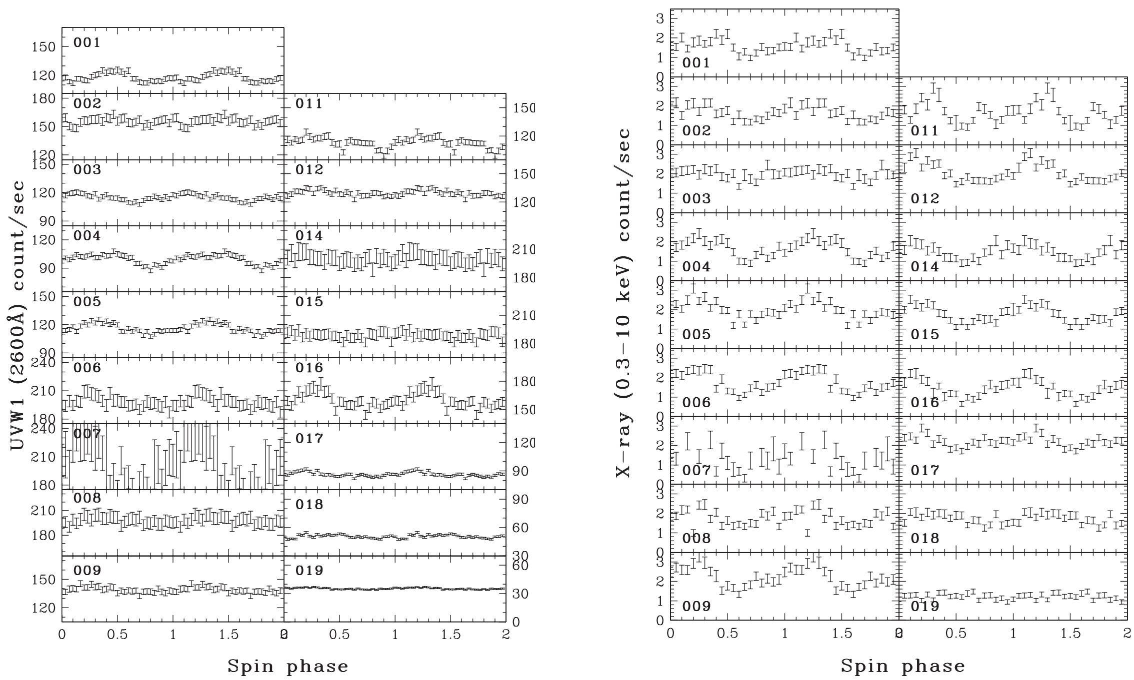

Figure 6. UV (2600 Å) and X-ray (0.3–10 keV) spin-folded light curves of GK Per. All of the plots have the same (arbitrary) zero-point in the barycentric reference frame. Note that the UV panels have different *y*-axis since the emission was so variable; however, each has a range of 70 counts s^{-1}.

outbursts. In contrast, the hard X-ray flux is consistent with that seen in the previous outbursts.

At first glance these statements seem paradoxical. The optical flux tracks the disc brightness. This brightness indicates the extent of the region of the disc which is in outburst. Thus, the lower luminosity seen in 2006 suggests that less of the disc was in outburst than in previous years, hence less mass was transferred through the disc. This is further supported by Fig. 3, which showed the optical fluence of the 2006 outburst to be abnormally low. In contrast, the hard X-ray flux in IPs is often assumed to track the rate of accretion on to the white dwarf. The typical outburst X-ray flux seen in 2006, combined with the long duration of this outburst, therefore implies that more mass was accreted in 2006 than during typical outbursts. Both these inferences cannot be true.

A resolution of this apparent inconsistency lies in the joint X-ray and UV spectral fit (Section 3.1). This revealed that the proportion of the accretion flux emitted in the 2–10 keV band could be as little as 1 per cent of the total radiated accretion flux: the flux in this energy range is clearly not a good proxy for the accretion rate.

In order to understand the unusual nature of the 2006 outburst, we must consider the accretion disc, since DN outbursts are thought to be disc-instability events (e.g. Lasota 2001). GK Per is an atypical DN as it is an IP, thus the inner disc is missing. Although this may have an effect on the shape and duration of outbursts in GK Per compared to other DNe, it is unlikely to be the cause of the unusual nature of the 2006 outburst, since the magnetic field of the white dwarf should affect all outbursts in a similar way. GK Per is also atypical due to its long (2-d) orbital period, meaning the system contains a much larger disc than most CVs. Warner (1995) gives the outer disc radius as

$$R_{\mathrm{d}} = \frac{0.6}{1+q}, \tag{2}$$

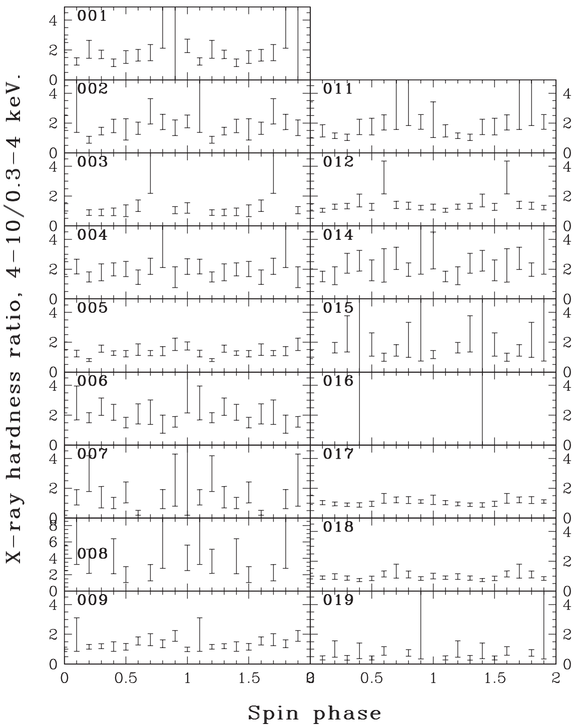

Figure 7. X-ray hardness ratios (4–10/0.3–4 keV) of GK Per folded on the 351-s spin period. The zero-point is the same as for Fig. 6.

which for GK Per evaluates to $R_d = 2 \times 10^{11}$ cm, assuming the masses of the white dwarf and secondary to be 0.87 and 0.48 $M_{\odot}$, respectively (Morales-Rueda et al. 2002). The viscous time-scale of the disc will thus also be much longer than is typical for CVs. The viscous time-scale at radius R is given by

$$\tau_v = \frac{R^2}{\alpha c_s H}, \qquad (3)$$

where α is the dimensionless viscosity parameter ($\alpha \sim 0.1$ during outburst and at least a factor of 10 lower in quiescence), c_s is the sound speed in the disc ($\sim 10^6$ cm s^{-1}) and H is the scaleheight of the disc ($\sim 0.05R$). The cold-state (i.e. quiescent) viscous time-scale at the outer edge of the disc is thus $\tau_{q,R_d} \sim 4600$ d, which is longer than the typical inter-outburst time of $\sim$1100 d. We also note that this time-scale is only a factor of $\sim$3 different from the delay between the 1967 outburst and the 2006 outburst, i.e. the large disc is capable of producing variations on the approximate time-scale on which the outburst morphology is showing variation.

A typical outburst lasts $\sim$70 d (Fig. 3). Interpreting this as a viscous decay time-scale, inverting equation (3) shows that such outbursts extend to a disc radius $R \sim 3 \times 10^{10}$ cm, i.e. about 10 per cent of the disc (by radius) is involved in a typical outburst.

The above numbers demonstrate that the disc in GK Per can retain a 'memory' of its state which is not erased either by outbursts or during the quiescent inter-outburst period. This is because the cold-state viscous time-scale is longer than the inter-outburst interval for a significant fraction of the disc. Thus if there were, for example, long-term variations in the mass transfer rate from the secondary (e.g. caused by magnetic activity on the star), these would be reflected in the disc-density profile for many years. Further, the disc configuration before and after any given outburst will vary. The fact that the 2006 outburst was different from previous events is thus not surprising: it is entirely possible that long-term changes in the mass transfer rate are embedded in the disc-density profile and hence outburst light curves. That many outbursts are similar to each other (and even the 2006 outburst follows a 'typical' outburst pattern for the first 10–15 d) is still consistent with this idea: the outburst is triggered when the surface density somewhere in the disc reaches the (radius-dependent) critical value. If each outburst begins at around the same place then by definition the disc state at this point must be approximately the same at the start of each outburst, hence the outbursts will appear similar at early times. As the heating wave propagates outwards to radii where the disc state can differ from outburst to outburst, it becomes possible to observe variation in the outburst profile.

In general terms, this idea allows for long-term variations in the outburst profile, we consider now the detailed shape of the 2006 outburst and how this can be explained.

The shape of the optical and UV outburst light curve (Fig. 2) is suggestive of three short, faint outbursts running into each other (e.g. each reminiscent of the 1970 outburst). A possible interpretation is thus that a series of heating and cooling waves passed through the disc giving a mini outburst which is twice rekindled. This could be achieved if the heating wave is triggered at the inner disc but encounters a lower density which halts its progress. At this point, as is usual for the end out DN outbursts, a cooling wave is launched (Lasota 2001). This wave travels inwards, reducing the amount of the disc which is in the hot state. However, this short time is less than the viscous time-scale at the outburst triggering radius so the outburst in the inner regions of the disc is not extinguished. The cooling wave is reflected back as a heating wave and the outburst is rekindled. We suggest that this sequence of events happens twice, giving rise to the triple-peaked optical/UV outburst profile.

If this idea is correct, i.e the outburst profile is determined by the disc-density structure, then the similarity between the 1967 and 2006 outbursts suggests that the next outburst will be shorter and less luminous than normal, akin to the 1970 outburst.

4.2 The spin-period modulation

The origin of the X-ray spin-period pulsations in GK Per was discussed extensively by Hellier et al. (2004) and Vrielmann et al. (2005). They proposed that the modulation is caused by varying absorption as the 'accretion curtains' of magnetically confined material pass through our line-of-sight to the emitting regions, although the specific geometric details differ between those two papers. If this is correct we would expect the hardness ratio to show a maximum of hardness at spin minimum (i.e. when absorption is at its greatest). Figs 6 and 7 appear to support this, although the errors on the hardness ratio are too large to make a definitive statement. The *XMM* spin-pulse profile and hardness ratio from the 2002 outburst (Evans & Hellier 2005), however, clearly show this correlation.

The phasing and shape of the X-ray (and UV) spin-period modulation vary during the outburst (Fig. 6). Norton et al. (1988) reported a similar effect in quiescent X-ray data. They noted that in quiescence the accretion rate is barely enough to overcome the magnetospheric boundary and produce stable accretion, so the accretion may be time dependent and thus the accretion geometry will be variable, explaining the changing pulse profiles. Clearly in outburst the accretion rate is much higher and away from this limit, however, the multiwavelength light curves (Fig. 2) show a significant amount of variability from observation to observation, suggesting that the accretion rate is not stable. This in turn means that the disc–magnetosphere interaction region will be constantly changing, thus an unvarying spin-pulse profile is not expected.

5 CONCLUSIONS

We have presented a unique, multiwavelength, high-cadence data set monitoring the evolution of the 2006 outburst of GK Per at optical, UV and X-ray wavelengths. The optical outburst profile is unusual, showing three weak peaks, rather than the typical single, bright peak; it is also ∼30 per cent longer than a typical outburst. The UV data follow the optical evolution. The X-ray data, in contrast, appear entirely consistent with previous outbursts. This presents a significant challenge to existing disc outburst models.

We have shown that the large disc in GK Per is able to maintain a long-term 'memory' of its state (and hence the mass transfer rate from the secondary) which is not erased by outbursts or by quiescent accretion during the inter-outburst period. This is expected to produce long-term variation in outburst morphology. Within this context, we interpret the 2006 outburst as a short outburst which is thrice suppressed by low-density regions of the disc, and twice rekindled by the high-density inner regions. We also suggest that the next outburst, expected around 2009–2010, will be shorted than normal, similar to the 1970 outburst.

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GK Per has recently undergone another outburst which, as predicted in this paper, was shorter (∼30 d) and fainter (peaking around $V \sim 12.5$ mag) than typical outbursts. We thank Wolfgang Renz for drawing this to our attention.

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