Recent phase changes in X Persei: optical, infrared and X-ray behaviour

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Received May 13, accepted September 2, 1992

Abstract. We present a set of optical and infrared photometric measurements which show the lightcurve of the Be/X-ray binary system X Persei over the last 25 yr. During this period, the Be star has undergone two extended faint, non-variable phases, the last of which (1990-present) has been shown to be related to the loss of the circumstellar shell associated with such systems. We show the relation between the presence of such a disk and the variability of the system. Spectroscopic data spanning the recent phase change narrows down the time changeover from emission to absorption to a period of about 6 months, and suggests that the Balmer emission faded gradually over a period in excess of 700 d. We discuss the similarity between this event and a previous extended low state seen in 1974–1977, where the star was again very faint, almost non-variable and had no near infrared excess. We propose that this was another disk-loss or near disk-loss event. Previously unpublished X-ray data from the Ariel 5 satellite are presented which show a steady decrease in the 2–10 keV flux of the system, which persists well beyond the end of this earlier extended low phase. It would thus appear that there is no relation between the optical and X-ray lightcurve after the 1974–1977 low.

Key words: stars: binaries: general – stars: emission – line, Be – stars: pulsars: general – infrared: stars – X-rays: stars

1. Introduction

X Persei (HD 24534) is the optical counterpart to the X-ray binary pulsar 4U0352 + 30 (Braes & Miley 1972; van den Bergh 1972; Brucato & Kristian 1972; Weisskopf et al. 1984). The primary is an O9.5IIIe star (Slettebak 1982; Fabregat et al. 1992), and the pulsed X-ray emission is thought to arise from accretion onto a magnetised neutron star companion. A pulse period of 835 s (X-ray) has been discovered (White et al. 1976; Robba & Warwick 1989) and a possible (spectroscopic) 580 d orbital period (Hutchings et al. 1974; Penrod & Vogt 1985) has been suggested, although this is still unconfirmed. The star is a known optical variable (V = 6.0 – 6.9) on timescales from seconds (Frohlich & Nevo 1974), and minutes (Campisi et al. 1976; Canizares et al. 1977; Sharma et al. 1983) to years (Mook et al. 1974; Gottlieb et al. 1975). X Per is a member of the Be/X-ray class of High-Mass X-ray Binaries, of which about 30 are currently known (Nagase 1989). The wide binary orbits in these systems are such that accretion is thought to occur by stellar wind losses alone, as the Be primary does not fill its Roche Lobe. Measurements of $v \sin i$ for X Per give values in the region of 150 km s$^{-1}$, suggesting that the geometry of the system is more pole-on than equator-on. The light curve is therefore expected to be affected more by disk emission than by disk absorption.

A previous paper (Norton et al. 1991) reported spectroscopic and infrared photometric observations which show that at some point between March 1988 and November 1990, X Per lost the circumstellar shell that is thought to exist in Be-type stars (Struve 1931). Due to a gap in the spectroscopic and infrared coverage, the disk-loss could have occurred anywhere between 10th March 1988 (JD 2447231) and 15th November 1990 (JD 2448211). The disk could therefore have been lost over a period of years, months or even days. It was not clear how the optical and infrared lightcurve had varied during this event, or how the stars $(B-V)$ and $(J-K)$ colours had altered. In order to better understand the nature and timescale of this event, an
extensive archive search was begun to obtain more data on the disk-loss. As a result, we have gathered together most of the previously published optical and infrared photometry from the last 25 yr, as well as data from X-ray observations. When combined with our own previously unpublished data and data from international amateur organisations, these allow very complete lightcurves of X Per to be presented for the first time. Full details of the sources of these data are given in Appendix 1. Additional spectroscopic data are also shown which limit the final changeover from Hz emission line to absorption line to a period of about 6 months during 1990.

This paper is therefore a review of the optical, infrared and X-ray behaviour of X Per over the past \(\approx 25\) yr and can be seen as a follow-up to the earlier papers by Mook et al. (1974) and Gottlieb et al. (1975) who accumulated long-term lightcurves of the star from photographic plate libraries. Using this multi-waveband coverage we have produced a summary of the known types of variability found in X Per at infrared and optical wavelengths, in the Hz line and in the X-ray region. By relating previously unconnected observations at different wavelengths we have investigated the recent changes in the system – special attention is paid to the extended low phases seen in 1974–1977 and 1990–present.

2. Optical photometry

X Per is generally classified as an irregular variable \((V = 6.0 – 6.9)\), showing several timescales of variability. These can be broadly classed as:

(i) Long-term variability on timescales of months or years (Mook et al. 1974; Gottlieb et al. 1975; Persi et al. 1977).

(ii) Short-term photometric variability on timescales of hours or less (Ferrari-Toniolo et al. 1977) and spectroscopically at the X-ray spin period of 835 s (Galkina 1978; Kaitchuk et al. 1980; Mazeh et al. 1982).

(iii) Transient, very short timescale \((\text{min or s})\) optical dips (Campisi et al. 1976; Canizares et al. 1977; Sharma et al. 1983) and Hz flux changes (Murdin et al. 1976). There has also been a report of rapid \((4 – 409\) s) “flickering” seen in \(V\) band photometry (Frohlich & Nevo 1974).

Many, if not most, Be-type stars show variations on timescales of 0.2 – 2 d (Stagg 1987; Percy 1987). We discuss below the various timescales of variability observed in X Per in the past, and the anomalous behaviour it displays during the extended optical low periods.

2.1. Long-term variability

Studies of the long-term variability of X Per show that the star undergoes periods of slow brightening/fading \((\text{i.e.} 300 – 500\) d rise/fall time), sometimes dropping to extreme low states. Mook et al. (1974) and Gottlieb et al. (1975) both report two decreases to \(V \approx 6.9\) in 1897 and 1902, although the exact nature of the \(V\) band is not specified as the measurements are made from archive photographic plates. Persi et al. (1977) and Ferrari-Toniolo et al. (1977), report a similar fading to \(V \approx 6.8\) in 1974–1977. Figure 1 shows the \(V\) band lightcurve of X Per over the last 27 yr, clearly showing the 1974–1977 extended low state, and the current low state that the star is in. It is interesting to note that the \(V\) band magnitude has been confined to a range of between 6.2 and 6.8 for at least the past 20 yr, whereas between 1903 and 1973 X Per was reported at magnitudes in the range \(V = 6.1 – 6.6\) (Mook et al. 1974). Unfortunately there is insufficient good quality photometry prior to the 1971–1974 optical fade to say whether or not earlier low states were actually brighter than those seen recently. However, it may well be that the extended low phase from 1974–1977 marked the beginning of a major change in the size and/or structure of the circumstellar disk, which resulted in deeper minima \((V \approx 6.8\) instead of \(\approx 6.6\)) following that period. If we associate optical lows with a thinning or shrinking of the disk, then the recent \((\text{i.e.} 1971\) to present) optical minima represent much more dramatic changes to the disk than were occurring between 1903 and 1971. A similar situation can be found in the long-term \((B\) band) photometric lightcurve of Gottlieb et al. (1975) —following the second of the deep optical lows \((\text{circa} 1902)\), the subsequent optical minima became progressively shallower until the next deep optical low in 1974. This may signify some period of stabilisation of the disk following the extreme changes that the extended optical lows indicate.

Figure 1 (and Mook et al. 1974) suggests a difference between the optical maxima prior to the 1974–1977 extended low and those that have occurred since. The brightest reported state of X Per \((V = 6.02,\) Brucato & Kristian 1972) occurs in 1972, but prior to this, peak \(V\) mag of around 6.1 appear to have been the norm, e.g. for 1965, \(V = 6.13\) (Mook et al. 1974); for 1956, \(V = 6.13\) (Harris 1956), \(V = 6.07\) (Hiltner 1956). Following the extremely bright state seen in 1972, subsequent maxima have not exceeded \(V \approx 6.25\). It may be that, prior to 1972, the circumstellar disk was larger \((\text{or more luminous})\) than it has been in the past 20 yr, and that this is somehow linked with the “hyper-extended” disk of 1972 and the subsequent disk-loss event.

In both recent extended low states it is clear that the star becomes almost non-variable \((\Delta V \leq 0.1\) in 1974–1977, \(\Delta V \leq 0.01\) in 1990–1992) but there is insufficient data from the earlier fadings \((1897, 1904)\) to say whether this is always the case. If we associate these extended optical lows with disk-loss \((\text{or near disk loss})\) events, then it would appear that the optical variability is due to the presence of the circumstellar material.

The associated \((B – V)\) colour changes that accompany these long-term variations are shown in Fig. 2. X Per now displays a \((B – V)\) colour consistent with a normal O9.5III star at a distance of \(1300 \pm 400\) pc (Norton et al. 1991; Fabregat et al. 1992), as it did during the 1974–1977 low
Fig. 1. \( V \) band lightcurve of X Per covering 1964-present (25 d means). The earlier low state contains evidence of some variability, but of a much lower amplitude than usual. The current low state was preceded by a long linear fade, and the period over which the Hz line switched from emission to absorption is indicated (the region marked “disk loss”).

state (Persi et al. 1977). As the star rapidly brightened following the 1974–1977 low, the \((B-V)\) colour became redder. It thus appears, as might be expected, that a high (bright) state is characterised by a red colour (more disk material present), and the low (faint) states are accompanied by a bluer colour (as we are seeing the unobscured O9.5 star beneath the shell). The rapid reddening episode immediately prior to the disk-loss may represent the final expulsion of the circumstellar material from the O9.5 star. This do suggest, however, that there is a definite colour change during these unusual lows, consistent with the model of complete or partial disk-loss episodes.

2.2. Short-term variability

Variations at the X-ray pulse period detected in Hz spectra have been reported by Galkina (1978), Kaitchuk et al. (1980) and Mazeh et al. (1982). Similarly, modulation of
emission from ionized material in the disk produced by absorption of X-rays from the neutron star. In all reported cases of spectroscopic variation at the pulse period in X Per, the amplitude of modulation has been low (e.g. around 2% from Mazeh et al. 1982). The general lack of optical photometric variability is thought to be linked to the low X-ray luminosity and \( L_x/L_{opt} \) ratio of X Per (e.g. \( L_x/L_{opt} = 10^{-3} \) from Margon et al. 1977).

As noted previously, most Be stars display variability on short timescales (0.2–2 d). X Per is therefore extremely unusual in its current extended low phase as it displays no significant photometric variations on any timescale to \( \Delta V \leq 0.01 \) mag (Percy 1992). During the 1974–1977 extended low, there was a similar lack of variation on short timescales, although there was a small brightening episode (rise of about 0.1 mag in \( V \) on a timescale of around 200 d and a fade over similar period) mid-way through this period.

### 2.3. Transient forms of variability

The third type of variability consists of apparently transient dips in the optical lightcurve of X Per, lasting from a few seconds to several minutes, and varying in depth to a maximum decrease of approx. 35% of the stars flux. Several observers have reported seeing such features (Campisi et al. 1976; Canizares et al. 1977; Sharma et al. 1983), generally in the \( U \) band. The longest of these dip features lasted almost 10 min and involved an intensity decrease of 30% in \( U \) (Campisi et al. 1976). A dip of similar depth and 4–5 min duration was observed by Canizares et al. but Sharma et al. saw three dips of about 15% decrease, each lasting 10–15 s. All these observers point out that there are long periods of quiescence in which the lightcurve is non-varying, interspersed with episodes of dipping behaviour. From our optical lightcurve of X Per (Fig. 1), it can be seen that all these observations occurred during...
optical minima, those of Campisi et al. and Canizares et al. during the 1974–1977 extended low, and Sharma et al. in the brief 1979 low. Other photometric runs by various observers at other times have not seen such features. No satisfactory explanation of this phenomenon has been proposed, but it may be significant that there are no reports of such features being seen when X Per is bright. Likewise, the only detection of coherent optical pulsations occurred during a minimum in 1985 (Latsyshyna & Lyutyj 1987) suggesting that significant changes occur in the disk structure whilst the star is in its low phase. Preliminary results from one of us (Percy 1992) suggest that no $U$ band dips have been observed during this current extended low period, although instrumental problems mean that only limited data are available. As noted, these events are transient, and the gaps in data coverage mean that we cannot rule out their occurrence.

Another case of short timescale, transient variability was found in a series of observations by Murdin et al. (1976). Simultaneously monitoring of the H$\alpha$ flux and the continuum showed a “rapid collapse” of the emission line on August 22nd, 1973 (JD 2441917). Observations over the rest of the night and for the following three nights failed to show a similar event again. They reported an almost simultaneous (30–50 s delay) rise in the continuum level, also seen in $B$ and $V$ band photometry taken concurrently from a distant site, that appears to have been anti-correlated with the H$\alpha$ collapse. The whole event lasted around 500 s, similar to the optical dips seen by Campisi et al. (1976). The sharp drop and gradual recovery of the H$\alpha$ flux is also very similar in shape to the $U$ band dips.

Murdin et al. (1976) suggested that the collapse of the H$\alpha$ flux that they observed (at the very beginning of the 1974–1977 low) and the $U$ band dips of Campisi et al. (1976) (actually seen a year later, but still during the same low phase) were caused by obscuration of the H$\alpha$ emitting region. They calculated the size of the obscuring body to be of the order of 1$R_\odot$ (assuming it was moving with an orbital velocity of 100–1000 km s$^{-1}$). The time delay between the H$\alpha$ collapse and the small continuum flare (30–50 s) implied that the H$\alpha$ emitting region and the flare region were no more than 50 lightseconds apart (approx. 25$R_\odot$) assuming a mean binary separation of around 200$R_\odot$ for the system, this placed both sites around either the Be primary or the neutron star. Since the H$\alpha$ emission is primarily associated with the circumstellar shell, the implication is therefore that this is the site of both the events. Their model suggested that the flare represented the “... collisional destruction of the kinetic energy of the same material which passed in front of and absorbed the Balmer emission region...”. In a model where the circumstellar material is dispersing or the disk itself is breaking up, as now seems likely, such a scenario seems feasible.

Frohlich & Nevo (1974) reported the detection of low amplitude, low frequency flickering during 2 out of 4 nights photometric observing in December 1972 (JDs 2441678–82). The timescales of these oscillations varied from 41 to 409 s (with 0.3% of the mean optical power) on JD 2441682 to between 4 and 120 s (with around 2% of the mean optical power) on JD 2441680. Again, these features appear to be transient, as the other two nights showed no evidence for this flickering behaviour. These observations were made shortly after the onset of the long optical fade that preceded the 1974–1977 low (when $V=6.23$). As with the optical dips, other photometric runs at different times (during optical maxima and minima) have not shown similar oscillations.

X Per thus displays a broad range of variability both in terms of amplitude and timescale. The shorter timescale variability seems to be associated with the optical low phases (and possibly with the periods of fading which precede them), and is of a transient nature.

2.4. The 580 day orbital period

Hutchings et al. (1974) reported the discovery of large-amplitude radial velocity variations in the higher Balmer lines of X Per, which they attributed to a binary period of 580.5 d. This gave a mass-function for the system which implied the unseen companion was too massive to be a neutron star, and led to models of X Per containing a black hole, or even a black hole/neutron star multiple system. Penrod & Vogt (1985) showed that these spectral features were in fact due to “asymmetric and variable emission components hiding in the absorption profiles”, caused by tidal distortion at the orbital period, and were not radial velocity variations. This removed the need for a massive unseen companion in the system. However, the 580 d period remains the best candidate for a binary orbital period, and various attempts have been made in the past to search for optical variations with this timescale.

We have searched our optical photometric lightcurve for the spectroscopic 580 d period claimed by Hutchings et al. (1974) using the one-dimensional CLEAN package developed by H. Lehto (Lehto 1989). The optical lightcurve, containing approx. 400 data points covering 1964–1991, shows no evidence for the spectroscopic period. Mook et al. (1974) and Gottlieb et al. (1975) similarly found no evidence for the 580 d period in their more extensive lightcurves (covering 70–80 yr of observations). Our data limits the amplitude of any variations at the 580 d period to $\Delta V < 0.02$ mag. The optical lightcurve does, however, suggest that there may be some characteristic timescale for the brightening/fading events in the region of 250–400 d.

3. Optical spectroscopy

Various observers have noted that the H$\alpha$ emission line in X Per is highly variable (i.e. Mendoza et al. 1983; Schuster & Alvarez 1983) and long-term studies of the H$\alpha$ emission line in X Per have noted changes on timescales of several
Table 1. Equivalent width measurements

<table>
<thead>
<tr>
<th>Local date</th>
<th>Julian date (UT)</th>
<th>Mean Hz EW (Å)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977 (mean)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Sept. 1983</td>
<td>2445606.01</td>
<td>-10.4</td>
<td>Optical maximum</td>
</tr>
<tr>
<td>9 Oct. 1983</td>
<td>2445617.95</td>
<td>-10.8</td>
<td></td>
</tr>
<tr>
<td>13 Oct. 1983</td>
<td>2445621.89</td>
<td>-9.6</td>
<td></td>
</tr>
<tr>
<td>14 Oct. 1983</td>
<td>2445622.89</td>
<td>-9.0</td>
<td></td>
</tr>
<tr>
<td>23 Dec. 1987</td>
<td>2447153.8</td>
<td>-8.9</td>
<td>Nearing optical maximum</td>
</tr>
<tr>
<td>30 Dec. 1987</td>
<td>2447160.7</td>
<td>-8.9</td>
<td></td>
</tr>
<tr>
<td>8 Mar. 1988</td>
<td>2447229.7</td>
<td>-13.2</td>
<td>Optical maximum</td>
</tr>
<tr>
<td>9 Mar. 1988</td>
<td>2447230.6</td>
<td>-14.1</td>
<td></td>
</tr>
<tr>
<td>10 Mar. 1988</td>
<td>2447231.7</td>
<td>-12.9</td>
<td></td>
</tr>
<tr>
<td>2 Feb. 1990</td>
<td>2447925.6</td>
<td>-1.3</td>
<td>Last emission line</td>
</tr>
<tr>
<td>2 Sept. 1990</td>
<td>2448137.6</td>
<td>+1.6</td>
<td>First absorption line</td>
</tr>
<tr>
<td>15 Nov. 1990</td>
<td>2448211.7</td>
<td>+2.1</td>
<td></td>
</tr>
<tr>
<td>27 Dec. 1990</td>
<td>2448253.6</td>
<td>+1.8</td>
<td>Optical minimum (extended)</td>
</tr>
<tr>
<td>28 Jan. 1991</td>
<td>2448285.5</td>
<td>+1.8</td>
<td></td>
</tr>
</tbody>
</table>

N.B. Error in Hz measurements is typically about 5–10%.

years. Hubert-Delplace & Hubert (1979) show that from 1953–1956, Hz was a strong, broad emission line. From 1957–1961, the emission strengthened, and remained strong until 1974. From 1974–1977 (i.e. during the extended optical low phase), only a moderate emission was seen, and then only in the Hz line. Co-ordinated photometric, spectroscopic and X-ray observations by de Loore et al. (1979) reported strange behaviour of the Balmer emission lines in 1977 (i.e. at the end of the 1974–1977 extended low phase). They comment that the “...lower X-ray emission may correspond to lower intensity of the Balmer emission lines, to a smaller Balmer excess and to a low photometric variability...”. They reported X Per to be in a state of "absence of emission in the Balmer lines", and stated that by no later than November 1977 (approx. JD 2443450) the Balmer emission had reappeared, along with a redder colour for the star. However, all the evidence now suggests that the 1974–1977 event was almost identical to the current phase, with X Per showing the colours of a "normal" O9.5III star without the near infrared excess (Norton et al. 1991; Fabregat et al. 1992).

By 1981, the Hz emission was seen as a narrow, single-peaked line, with a highly asymmetric profile, with the violet side being very sharp (Andrillat 1983). Observations by Ballereau et al. (1987) found a strong double-peaked line, with detectable short timescale variability of around 20% over 8 d (see Table 1). Ballereau et al. (1987) noted that the blueward peak appeared to be the most active feature, as noted in the Hβ line by Hutchings & Walker (1976). Norton et al. (1991) reported the spectral changes seen in X Per between March 1988 and November 1990, where the Hz emission line was seen to revert to absorption. However, the gap in coverage (980 d) was too large for any conclusions to be drawn about the nature and speed of the disk-loss event that this spectral change indicated. We have now uncovered further unpublished high resolution Hz spectra that show that X Per was still in emission as late as February 2nd 1990 (JD 2447925) and was in absorption by September 2nd 1990 (JD 2448137), narrowing the gap for the disk loss to a period of less than 212 d (Fig. 3).

Table 1 lists the equivalent widths of the Hz emission/absorption lines found from our measurements of the previously unpublished spectra. Comparison with the values in Norton et al. (1991), and similar high resolution spectra by other observers (de Loore et al. 1979; Andrillat 1983; Ballereau et al. 1987) shows a marked change in the equivalent width of the emission line around JD 2447230, where the optical lightcurve is at a maximum. This may represent the effects of an extended circumstellar shell, which would contribute both to the optical brightness of the star and to the emission in the Balmer series. This extended shell phase seems to have been followed by the gradual dispersal of the shell material to leave X Per in the "disk-less" phase. It would thus appear that the shell was first inflated then gradually dispersed, presumably by the same mechanism.

Figure 4 shows the variations of Hz equivalent width with time (showing the rapid rise just prior to the long optical/infrared fade, at around JD 2447230) and also with
Fig. 3. High resolution Hα spectra taken at the INT on February 2nd 1990 and September 2nd 1990, showing the last known emission line and first absorption line observed. The period of disk loss is thus reduced to 212 d (from the previous 980 d, Norton et al. 1991)

$V$ mag. The latter shows a clear correlation between the equivalent width and the optical brightness, consistent with the theory that the circumstellar shell is responsible for a significant fraction of the optical luminosity and for the variability of X Per.

4. Infrared behaviour

The infrared excess seen in Be-type stars is associated with free-free emission in the circumstellar shell, and as the shell disappears, so the excess disappears. Archive data from Larionov & Larionova (1989) combined with our own measurements (Norton et al. 1991) now shows that the infrared fade exactly follows the optical, and that the excess had completely disappeared by JD 2447620. The optical lightcurve reached a minimum around JD 2447520. Figure 5 shows the infrared lightcurve of X Per, and Fig. 6 shows the associated $(J-K)$ colour of the star. Although there is only one point in the 1974–1977 low, it is evident that here again the near infrared excess vanished. This is further evidence that this earlier low state saw either a partial or complete loss of the disk, as has been observed in the current episode.

From the spectral information now available, we can see that the $(J-K)$ infrared excess had vanished before the emission line disappeared [i.e. the infrared $(J-K)$ colour is zero by JD 2447620, but the emission line is still present on JD 2447925]. This suggests that the disk material, whilst still present, was not contributing to the measured infrared emission of the star at this time. However, it is very likely that at longer wavelengths an infrared excess is still present.

5. X-ray observations

The discovery of 835 s X-ray pulsations by White et al. (1976) from X Per confirmed the presence of a magnetised neutron star in the system. The identification of the X-ray source with the Be star was confirmed by Weisskopf et al. (1984) using the Einstein High Resolution Imager. The X-ray characteristics of X Per are notably different to those of other Be/X-ray systems in several ways. It has been noted as an unusually weak source ($L_x \lesssim 10^{34}$ erg s$^{-1}$) in the
2–11 keV range; $L_x/L_{opt} = 10^{-2} - 10^{-3}$; Nagase 1989); it is the least variable of the high-mass X-ray binaries in the X-ray region [$L_x$(max)/$L_x$(min) = 5], and has one of the longest pulsation periods (second only to 4U0114+65 with a period of 850 s). The X-ray spectrum of X Per is also significantly different from those of other HMXBs. These features are discussed below.

5.1. Long-term X-ray behaviour

The earliest X-ray monitoring of X Per was discussed by White et al. (1976), who reported observations obtained by the Copernicus and Ariel 5 (experiment C) detectors over the period 1972–1975. They found that the mean source strength dropped by around 30% between February 1974 and January 1975–prior to 1974, observations had shown only a small ($\approx 15\%$) variation from a mean of 22 Uhuru flux units ($\approx 8 \times 10^{34}$ erg s$^{-1}$ in the 2–6 keV range assuming a distance of 1300 pc), a value consistent with the initial Uhuru observation (Giacconi et al. 1974).

During 1974–1979 the Ariel 5 satellite observed X Per on 36 occasions (i.e. covering the 1974–77 extended low state). The Sky Survey Instrument (SSI) results are presented here for the first time (Fig. 7), and show an almost linearly decreasing trend in the 2–10 keV flux. The count rates correspond to a maximum observed luminosity of $3 \times 10^{35}$ erg s$^{-1}$ and a minimum of around $7 \times 10^{34}$ erg s$^{-1}$ (assuming a distance of 1300 pc). The factor of around 4–5 variability is as reported in White et al. (1982) and Nagase (1989), but the maximum luminosity is significantly higher [Nagase reports $L_x$(max) of $10^{34}$ erg s$^{-1}$], due to the revised distance to the source (earlier calculations assume a distance of 350 pc).

Figure 8 shows the long-term (2–10 keV) X-ray lightcurve of X Per, along with an optical lightcurve covering the same period. The Copernicus 2–8 keV observations (taken from White et al. 1982) have been corrected to 2–10 keV (assuming a power-law spectrum as seen by Tenma and EXOSAT) to extend the lightcurve to cover 1972–1974, and show the rise in luminosity associated with
the change in pulse period (Fig. 9) and the beginning of the 1974–1977 extended optical low. The Copernicus data and our Ariel 5 results both show X Per fading almost linearly from a high in 1975 (Figs. 7 and 8). The Einstein observations (10th Feb., 1979) were reported to be at a comparable level to the Copernicus observations in late 1978/early 1979 (Weisskopf et al. 1984), and the EXOSAT and Tenma observations suggest that this fade continued until at least February 1984. The later EXOSAT observation in February 1986 showed a slightly higher count rate than was seen in 1984, suggesting that the X-ray flux may have been rising again (see Fig. 8). However, the Ginga observations in Jan. 1990 (Robba et al. 1991) suggest that X Per has not returned to the extremely bright X-ray state of 1975 as the current disk loss event progresses.

It thus appears that the X-ray luminosity is not directly related to the behaviour of the optical lightcurve, as there is no change in the linear fade of the X-ray luminosity during the optical brightening/fading events of 1978 or 1980. However, it is interesting to note that the decrease in the X-ray luminosity after 1974 is preceded by the dramatic optical fade, the time delay between the two fades being of the order of 1000 d. Other than this, it would appear that the stellar wind accretion is largely unaffected by the disk formation.

5.2. X-ray flares from X Per

White et al. (1976) reported the observation of a “flare” event in X Per seen by the Copernicus detectors on
February 7th, 1974 (JD 2442086), where the power-law spectral index changed from $-2$ to $-1.5$ (i.e. significant hardening of the 2.5–7.5 keV spectrum over a period of about 6 h). It may also be significant that an X-ray flare was also reported from the Perseus region on 6th July 1974 (JD 2442235), as seen by a balloon flight (Fuligni et al. 1976). This flare lasted only 12 min, and could be fitted by a thermal bremsstrahlung ($T_e = 5 \times 10^7$ K) or by a very soft power-law spectrum. However, the error circle for the flare was large enough to include several other sources, any of which could have been responsible for the event. It is interesting to note that these flare events seem to coincide with the beginning of the optical low state and with a high X-ray flux. We would therefore suggest, based on the coincidence between the detection of this flare and the significant changes that are seen in X Per at the same time, that the Be/X-ray system was in fact the source of the observed X-ray flare.

Most X-ray observations show variability from X Per on timescales of months/years, but short timescale variability has been reported by Frontera et al. (1979), where an increase by a factor of 2.6 was seen on successive days (JD 2442990–1) during a balloon flight. This “flare” event occurred near the end of the 1974–1977 extended low period, immediately after the minor optical brightening in 1975. This may have been due to the reformation of a small, “temporary” disk, which quickly dispersed, resulting in increased accretion onto the neutron star.

As has previously been noted for the $U$ band dips seen in optical lightcurves during minima, there are no reports of such X-ray flaring activity being observed at other times. If such behaviour were “normal” to X Per, it would be expected that the extended observations by Tenma, Ginga or EXOSAT (all made whilst the disk was present) would have detected flaring. The X-ray flares (2 definite and 1 potential) from X Per were all observed during the 1974–1977 extended low phase, and were not reported by any subsequent satellite observations. As with the optical dips, there may be a link between the occurrence of these flares and the unusual state of X Per at the time. Examination of the optical lightcurve (Fig. 1) indicates that the flares all occur immediately after a period of optical fading (the first one, or possibly two, after the long linear fade that preceeded the 1974–1977 low, the last after the small optical brightening seen during the low phase). If these fades represent a thinning or dispersal of the disk material, then the flaring may represent episodes of enhanced accretion onto the neutron star caused by an increase in the
density of the stellar wind due to the additional presence of the dispersing material.

If a lag exists between the optical fade and the X-ray flares, it may be attributable to the time required for material leaving the stellar disk to reach the neutron star, form an accretion disk, and accrete onto the compact object. A similar scenario was used to explain the lag between optical and X-ray flares seen in the Be/X-ray system 4U0115 + 63 (Kriss et al. 1983). However, for X Per, both X-ray flares occurred once the star had reached its low state ($V = 6.7$), following a long (approx. 1000 d) fade, rather than after a dramatic brightening as is often the case during periastron passage in the 4U0115 + 63 system.

5.3. Pulse period history

The X-ray pulse period history of X Per is shown in Fig. 9. A comparison with the optical lightcurve shows no obvious relation between spin-up/spin-down episodes and optical brightenings/fadings. However, during the 1974–1977 low state, and possibly following the flare events, the neutron star appears to have begun spinning-up, and to have reversed this trend directly after the low state ended.

The EXOSAT data (Robba & Warwick 1989) suggest that the subsequent spin-down continued until 1986 at least. Ginga observations following this period have shed more light on the recent spin period history of X Per, and in particular over the crucial period prior to the disk-loss event. Robba et al. (1991) presented the preliminary results from the January 1990 Ginga observations of X Per, showing that the spin-down episode seems to have continued until at least early 1990 (i.e. just prior to the disk loss event).

Similarly, comparison of the pulse period history with the X-ray lightcurve (Fig. 8) shows no correlation after the 1974–1977 period. The onset of the spin-up event ($\approx$ MJD 2442000) and the peak X-ray luminosity ($\approx$ MJD 2442400) are separated by around 400–500 d. However, as the pulsar changes to a state of spin-down, the X-ray luminosity of the source continues to decline.

5.4. X-ray spectral changes

The early spectra were best modelled by a thermal bremsstrahlung model at low energies (White et al. 1976, 1982; Becker et al. 1979) but with a hard power-law tail at higher
Fig. 8. The long-term 2–10 keV lightcurve of X Per. The rise is luminosity in 1973–1974 coincides with the onset of the extended optical low phase and the detection of at least one (possibly two) X-ray flares from X Per. This is consistent with the loss of material from the circumstellar shell to form an accretion disk around the neutron star. The linear fade seen in the Ariel 5 data (Fig. 7) is seen to extend to 1980–1981, with the source continuing in a low state until at least the beginning of 1990 (data from White et al. 1976, 1982; Robba & Warwick 1989; Robba et al. 1991).

energies (Mushotzky et al. 1977; Frontera et al. 1979, 1985; Worrall et al. 1981; White et al. 1982). White et al. (1982) reported no evidence for the iron Kα line often found in high-mass X-ray binary systems (Nagase 1989), with an upper limit on the equivalent width of 130 eV. Tenma observations (Murakami et al. 1987) showed a power-law spectrum with a high-energy cutoff, and also no evidence for an iron line. The high-energy cutoff was noted to occur at an unusually low energy (approx. 5 keV as opposed to the usual 10–20 keV for similar sources), and this was attributed to the low X-ray luminosity of X Per (and therefore presumably with a weak magnetic field for the neutron star). The EXOSAT observations (Robba & Warwick 1989) during 1984 and 1986 confirmed the Tenma results, and again showed the lack of an iron line at 6.4–6.7 keV, with an upper limit to the equivalent width of 60 eV. X Per is thus considered unusual among the Be/X-ray class.

The Copernicus and Ariel 5 X-ray data reported by White et al. (1976) suggest that the spectrum of X Per softened significantly between December 1972 and February 1974 (power-law photon index −1.0 in 1972, −2.0 in 1974). In January 1975, the spectrum was soft (power-law index −2.0) and the X-ray flux was around 30% lower than the 1974 observations. The Ginga results (Robba et al. 1991) suggest that in January 1990 the spectrum was again soft (power-law index −1.84). It may be seen from Fig. 8 that the harder spectral state of X Per occurred prior to the increase in X-ray luminosity from 1972–1974, and thereafter the source has been observed in a softer state.

6. Discussion

6.1. Optical and infrared behaviour

We have presented the most comprehensive optical light-curve of X Persei over the past 27 yr, and compared it with the spectroscopic, infrared and X-ray behaviour of the star over a similar period. It is evident that the star has undergone two extreme low states, covering 1974–1977...
Fig. 9. Pulse Period History of X Per from 1972–1990. Note the abrupt change to a spin-up coinciding with the X-ray flares seen by White et al. (1976) and Fuligni et al. (1976), and the onset of the low, non-variable phase in the optical lightcurve (Fig. 3). This spin-up event is then followed by a spin-down episode that appears to have continued until at least 1990. Data from Nagase (1989) and Robba et al. (1991)

and mid-1990 to the present day, the latter event having been shown to be due to the loss of the Be stars circumstellar shell. It seems reasonable to suppose that the earlier extreme low state was caused by a similar or identical event, although no reports of the Hα line being seen in absorption have been found. The new spectral data limit the final changeover from a Hα emission line to an absorption line in 1990 to a period of less than 212 d. However, from the optical and infrared lightcurves and the equivalent widths measurements, it can be seen that the line had been gradually weakening whilst the lightcurves faded almost linearly. The appearance of the absorption line occurred at least 400 d after the star had reached its minimum optical brightness. It would thus appear that the disk material had been gradually dispersing over a period probably in excess of 700 d (from the optical maximum to the last observed emission line).

The spectral observations of 1987–1988 (Table 1) also suggest that the circumstellar shell of X Per expanded prior to being dispersed. The Hα equivalent width reaches values of around 12–14 Å immediately prior to the long fade episode, compared to the “normal” value of around 9–10 Å. The simplest explanation for this increase and subsequent decrease in the shell is large scale variability in the stellar wind. Clearly the material in the equatorial regions (the disk or shell) was ejected from the primary star, and can be considered part of the wind, even though it may have very different kinematical properties to the wind observed in the UV region (which appears to be a high velocity, low density wind) (Waters, private communication). The persistent X-ray emission of X Per is evidence for stellar wind accretion onto the compact companion, presumably from the slow, high density wind in the equatorial plane. Such a model is also used to explain the persistent emission levels seen in 4U0053 + 604/Gamma Cassiopeiae (assuming it has a neutron star companion). Variations in this slow moving, dense equatorial wind would result in significant changes in the circumstellar shell material, and hence the Balmer emission and near infrared excess, as observed, but should also influence the accretion onto the neutron star. The lack of correlation between the optical and X-ray lightcurves is thus difficult to explain,
but may be related to the unknown orbit of the neutron star (which may be highly eccentric and inclined to the equatorial plane). However, an increase in the velocity/density structure of the equatorial wind (leading to an expanded disk and unusually bright optical state) followed by a dramatic decrease in the same (with a long optical fade and an increased accretion rate onto the neutron star), seems the best explanation for the observed expansion and disk-loss behaviour.

Figure 10 shows colour–magnitude plots of X Per. The optical high and low states are clearly associated with very differing colours, showing the effects of the presence or absence of a disk. The current colours of X Per have been shown to be consistent with an O9.5III star at a distance of 1300±400 pc (Fabregat et al. 1992). No infrared data are available for the deep optical lows reported by Mook et al. (1974) or Gottlieb et al. (1975), but the $B-V$ colours inferred from combining their results (0.0–0.1 for the 1897 low, ∼0.2 for the 1902 low) suggest that these were also disk-loss or near disk-loss events.

The lack of optical variability during the current diskless phase and the similar behaviour observed in 1974–1977 point to the circumstellar disk as being the source of these variations. We also note an apparent link between the detection of optical dips seen in the $U$ band lightcurves, the only reported detection of the X-ray pulse period in an optical photometric run and the low state of the star. Photometric observations taken outside optical minima show no evidence for either the dips or optical or spectroscopic periodicity. If these minima are due to a thinning or shrinking of the circumstellar shell, the optical phenomena seen only in these low phases must be associated with either the underlying star or with the “new” disk state. No evidence for such transient $U$ band dips has yet been found for the current optical low phase, although their occurrence cannot be ruled out. The model put forward by Murdin et al. (1976) of an obscuring body passing across the Balmer emitting region, causing a substantial decrease in the Hα and $U$ band fluxes, could represent large (of the order of 1$R_{\odot}$) clouds of cool outer disk material passing in front of an inner remnant disk. The initial model assumed the Hα emitting region was around the neutron star, possibly as some form of accretion disk—this would again seem to fit the observational evidence (assuming such a disk formed as a result of the expulsion of material from the Be stars shell) but would
require the accretion disk to be the site of the Hz emission from the system. The usual strong Hz emission seen from X Per in its "normal" state (i.e. circumstellar disk present) is taken to indicate that it is the primary which is the source of most of the Balmer emission. Our data shows no evidence for an alternative site of the Balmer emission.

No evidence has been found for the suspected 580 d orbital period in our V band lightcurve. An upper limit of 0.02 mag can be placed on any variation in the V band at this period. In addition, X Per enters a state of unusually low photometric variability (\(AV \leq 0.01\) mag for 1990–present) during the extended low phases.

Observations of the system in its disk-less (i.e. optical low, \(V = 6.8\)) and full disk (optical high, \(V = 6.25\)) states allows us to estimate the relative contributions of the components (disk and star) in the various wavebands:

- \(V\) band: \(F_{\text{disk}}/F_{\text{star}} = 0.66\) (normal, \(V_{\text{max}} = 6.25\))
- \(V\) band: \(F_{\text{disk}}/F_{\text{star}} = 1.09\) (1971–1972 extreme high, \(V_{\text{max}} = 6.0\))
- \(J\) band: \(F_{\text{disk}}/F_{\text{star}} = 1.29\)
- \(H\) band: \(F_{\text{disk}}/F_{\text{star}} = 1.51\)
- \(K\) band: \(F_{\text{disk}}/F_{\text{star}} = 1.88\)

The larger value quoted for the \(V\) band ratios (\(F_{\text{disk}}/F_{\text{star}} = 1.09\)) is taken from the extremely bright state that X Per is found in in 1971–1972, immediately before the first of the extended optical low periods (1974–1977). It would appear that the disk was in an extremely inflated state at this point, as the optical luminosity is around 65% higher than the "normal" star plus disk value (i.e. \(V = 6.0\) instead of 6.25).

### 6.2. X-ray behaviour

The Ariel 5 results reported here, when taking into account the revised distance for X Per of 1300 pc, give an X-ray luminosity (2–10 keV) of \(\approx 3 \times 10^{35}\) erg s\(^{-1}\) in the "high" state (1975), falling to \(\approx 7 \times 10^{34}\) erg s\(^{-1}\) as the source faded towards its low state (1979–1980 onwards). The later EXOSAT, Tenma and Ginga observations yield revised luminosities of 3–6 \(10^{34}\) erg s\(^{-1}\) in the 1979–1990 period. However, the low X-ray variability range of X Per \([L_\alpha(\text{max})/L_\alpha(\text{min}) = 5]\) and the revised luminosity are still more comparable with those observed in the Supergiant class of high-mass X-ray binaries [i.e. 4U1538-52, \(L_\alpha(\text{max})/L_\alpha(\text{min}) = 10\), \(F_\alpha(\text{max}) = 4 \times 10^{36}\) erg s\(^{-1}\); 4U1907+09, \(L_\alpha(\text{max})/L_\alpha(\text{min}) = 20\), \(F_\alpha(\text{max}) = 4 \times 10^{36}\) erg s\(^{-1}\)] rather than the Be/X-ray class [i.e. A0535 +26, \(L_\alpha(\text{max})/L_\alpha(\text{min}) = 700\), \(F_\alpha(\text{max}) = 2 \times 10^{37}\) erg s\(^{-1}\)]. This is attributable to the absence of transient flaring activity, as seen in most Be/X-ray systems (thought to be due to periastron passage of the neutron star through the circumstellar disk), so that accretion in X Per is via stellar wind processes only in the wide binary orbit.

White et al. (1982) noted that \(\ldots\) the lack of rapid response from the X-ray source indicates that the mass loss rate in the orbital plane is insensitive to the stellar luminosity." Our X-ray lightcurve (Fig. 8) shows no correlation with the optical or infrared lightcurves, except where the X-ray luminosity rises in the period 1972(?)–1975—this seems to correspond to the end of the fade from the unusually bright optical state (\(V = 6.0\)) seen in 1971–1972, and the onset of the low, non-variable optical phase of 1974–1977. This also supports the theory that accretion is due to stellar wind only. Changes in the X-ray luminosity should therefore be related to variations in the stellar wind, and hence only indirectly with the status of the Be star circumstellar disk. However, if the wind is responsible for maintaining the disk, then variations in the wind would be expected to result in variations in the disk content and structure in the long-term. As there appears to be no link between the optical lightcurve (Fig. 1) and the X-ray lightcurve (Fig. 8) (except in the period noted above), it may suggest that processes other than stellar wind variability are responsible for the observed disk changes. A future paper will investigate possible variations in the stellar wind (from archival IUE data), in the light of the long-term optical and infrared lightcurves presented here, to determine whether wind variability alone could be responsible for the observed optical variability.

Figure 8 suggests that in the period 1970–1971, the circumstellar disk of X Per may have reached an unusually large size. The \(V\) mag of the star and disk reached 6.0, compared to the usual maximum of around 6.25, suggesting much more disk material is present. If the disk becomes "hyper-extended", and contains substantially more material than usual, then as it dissipates we would expect to see a rise in the accretion rate onto the neutron star. This may explain why we see a connection between the optical and X-ray luminosities and the pulse period — as the optical luminosity fades from a maximum in 1971–1972 ("hyper-expanded" disk dissipating) the X-ray luminosity steadily increases (increased accretion rate onto the neutron star due to the presence of the dissipating disk material) and the increased accretion rate spins-up the pulsar (see Fig. 9). Once the additional material from the dissipating disk has been accreted, the X-ray luminosity of the system fades and the pulsar reverses to its usual state of spin-down.

Based on the Ariel 5 and Copernicus observations in the 1974–1977 low, we might expect a steadily decreasing X-ray flux from X Per at present. However, based on the most recent observations (by Ginga in Jan. 1990, and BBXRT in Nov. 1990; Eric Schlegel, private communication), the source does not appear to have attained the unusually high X-ray luminosity seen in 1972–1975. As noted previously, this may be attributable to the unknown orbital characteristics of the neutron star, as the shell expansion/loss may have occurred at very different phases of the orbit. We might expect the pulsar to currently be in a
state of spin-up, but again the lack of any obvious increase in the X-ray luminosity suggests that the dissipating circumstellar material did not substantially alter the accretion rate onto the neutron star.

Acknowledgements. We are indebted to the referee, Rens Waters, for his extremely useful comments and suggestions. PR acknowledges receipt of an SERC studentship, SJU acknowledges financial support from Meiko. Data reduction was carried out on the Southampton node of STARLINK, funded by the UK SERC. The archive search would not have been possible without the aid of the SIMBAD database in Strasbourg. We thank Harry Lehto for his help with the CLEAN package, and Bob Warwick for communicating and discussing his Ginga results. The Telescopio Carlos Sanchez is run by the Spanish CAT panel, to whom we are grateful for continued support. Special thanks to Mark Kidger at the TCS, and all the members and coordinators of the BAA and AAVSO for their help and dedication, especially the Southampton Local Astronomy Project (High Energy Astrophysics Division).

Appendix 1: sources of data

Reference list for the previously published data used in the optical lightcurves (Figs. 1 and 2)


Reference list for the previously published data used in the infrared lightcurves (Figs. 5 and 6)


Reference list for the previously published X-ray data used (Figs. 8 and 9)


Additional data has been obtained from the American Association of Variable Star Observers (AAVSO) and the British Astronomical Association (BAA).

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Note added in proof: A recent paper by Babalyan et al. (Sov. Astr. Lett. 1992, V. 18, p. 303) has revealed an almost identical spin-up phase occurring during the current disk-loss event, as seen in Art-P observations of X Per in Feb. and Aug. 1990.