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Letter to the Editor

Further ROSAT measurements of the period of 4U 1820–30

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Abstract. We have made two new observations of 4U 1820−30 with the ROSAT PSPC. The measurements do not provide further evidence for a secular period decrease of this source. Instead, after inclusion of our new arrival time measurements the significance of the orbital period derivative drops (from 5.5 to 4.6σ), its best-fit value decreases (to $\dot{P}/P = (-5.3 \pm 1.1) \times 10^{-8}\,\mathrm{yr}^{-1}$) and the formal probability that statistical fluctuations have caused the observed $\dot{P}$ increases to 0.5% (from 0.003%). We detect light curve changes that are large enough to be the cause of some (or all) of the period changes seen in 4U 1820−30, but not large enough to explain the discrepancy of the observed period derivative with that theoretically predicted. We explore the possibility that the secular period change observed during 1976–1991 could have been dominated by random or systematic changes in the position and shape of an occulting bulge on the disk rim and conclude that phase shifts caused by this mechanism could in principle explain the discrepancy entirely.

Key words: stars: individual: 4U 1820−30; X-rays: stars; stars: binaries; stars: evolution

1. Introduction

The observed decrease of the 11-minute period of 4U 1820−30 over the years 1976–1991 (Sansom et al. 1989, Tan et al. 1991, van der Klis et al. 1993, hereafter Paper 1) has been hard to explain in terms of binary evolution models. The standard scenario, involving conservative mass transfer from a Roche lobe filling degenerate dwarf in an 11-minute orbit around a neutron star predicts a secular *increase* in the orbital period of $> 8.8 \times 10^{-8}\,\mathrm{yr}^{-1}$ (Verbunt 1987, Rappaport et al. 1987) rather than a decrease. Acceleration of the binary by the gravitational potential of NGC 6624 or by a third star, and the possibility of a companion star more massive than the turn-off mass of the globular cluster are among the scenarios that have been considered to resolve this discrepancy. As noted in Paper 1, another explanation of the observed decrease of the period of 4U 1820−30 might be that there are intrinsic changes in the light curve that mimic a period change. In particular, we noted that the structure at the disk rim that is most likely causing the 11-minute period (Stella et al. 1987) might move in azimuth and thus change the phase of the light curve minimum and thereby the observed period without any changes in the true orbital period.

In this paper, we present new ROSAT measurements of the period of 4U 1820−30 and find that these do not confirm a further period decrease. We detect light curve shape changes of sufficient magnitude that, if they would also have occurred (at the right times) in the historical record, could have caused the 1976–1991 period decrease if the true period were constant. The shape changes are not sufficient to explain the discrepancy with the theoretical prediction of a positive $\dot{P}$. We explore the possibility that changes in the disk rim structure as a function of accretion rate play a role in explaining this remaining discrepancy.

2. Results

We performed two ROSAT PSPC (Trümper 1983, Pfeffermann et al. 1986) pointed observations of 4U 1820−30 on March 10–11 and 24–25, 1993. Each observation lasted about 1 day. The duty cycle was ∼ 40%; interruptions in the data occurred every ∼ 90-min satellite orbit. We used the data in the 0.5–1.2 keV band (PSPC channels 50–120) at a time resolution of 10 s. The source was observed off-axis to minimize the effects of periodic obscuration by PSPC support structure wires. Source count rates corrected for a slightly variable telescope vignetting factor (near 60%) varied between 100 and 160 c/s; background

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Send offprint requests to: M. v.d. Klis and dead time were negligible. The 11-minute period was detected during both observations, as is evident from the epoch folding analysis shown in Fig. 1.

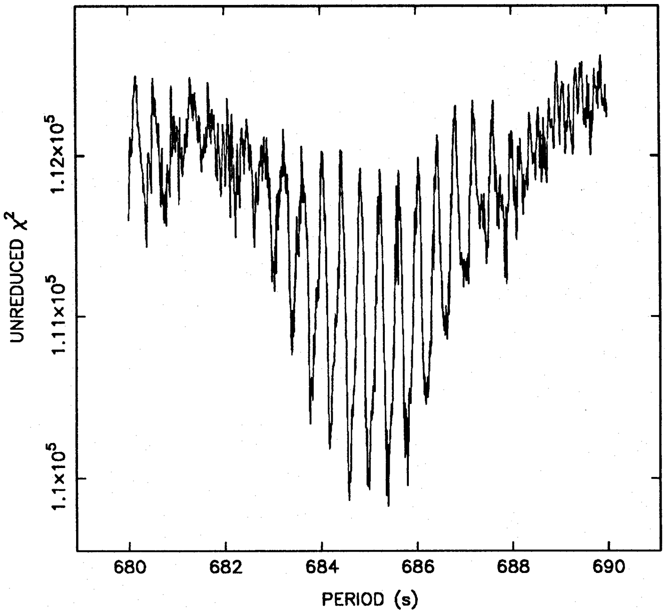

Fig. 1. Phase dispersion periodogram of our two observations together. Data were folded into 20 phase bins at trial periods around 685 s. Plotted is the χ^2 of the data around the average folded light curve. The pattern due to the 13-day interval between the two observations is obvious.

We analyzed the data in the same way as described in Paper 1. Sinusoidal fits to the light curves gave arrival times of the best-fit-sinusoid maximum of HJD 2449057.60196±0.00044 and 2449071.39731±0.00017, respectively. Combining these two new arrival times with the previous ones (Fig. 2), we find that they are inconsistent by 1.8 and 4.7 σ, respectively, with the parabolic ephemeris of Paper 1 (dashed parabola in Fig. 2). The new measurements favour instead a lower and less significant period derivative of $\dot{P}/P = (-5.3 \pm 1.1) \times 10^{-8}\,\mathrm{yr}^{-1}$ (drawn). An F-test for the additional parabolic term shows that it is still required at the 99.5% confidence level (however, this is down from 99.997% prior to our measurements).

In order to check whether light curve shape variations might be affecting the arrival times, we compared the folded light curves of our three ROSAT PSPC observations (Fig. 3). There is clear evidence for light curve shape variations. We compared the relative phases of these three light curves determined with sinusoidal fits to those determined by cross correlating the light curves. We find differences between these two phase determination methods of typically ~ 0.0003 d. As the light curve shape changes appear arbitrary, we have no way to determine which of the two methods is the "better" one, or whether another method of phase determination is preferable.

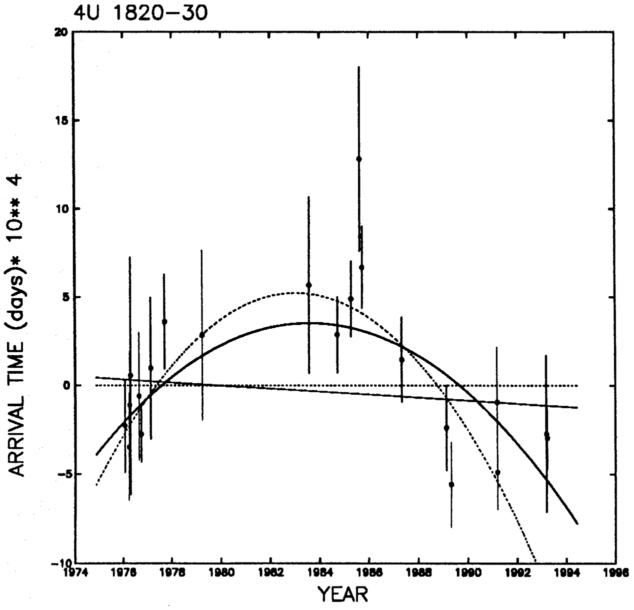

Fig. 2. Arrival time residuals with respect to the linear ephemeris of Paper 1 (dashed line). The parabolic ephemeris of Paper 1 (dashed), and the present best fit linear and parabolic ephemerides are also indicated.

It seems likely that if light curve shape changes similar to those shown in Fig. 3 are common, arrival time shifts of about 0.0003 d which are not related to true period changes are present in the historical arrival time record. The observed scatter of the arrival times around the best-fit linear ephemeris (drawn line in Fig. 2) is 0.0004 d (rms). This scatter is similar to that expected from light curve shape changes. This in itself is not sufficient to conclude that the secular period decrease in 1976–1991 has been caused by light curve shape changes, as we do not know how the shape changes depended on time. In Section 3 we mention the possibility of a systematic trend in the shape changes. Here we consider the effect of shape changes that occur randomly. These would effectively increase the uncertainties of the individual arrival time measurements by ~ 0.0003 d. If we quadratically add this number to the errors in the arrival times in the historical record, we find that a linear ephemeris provides a good fit. A period derivative is then no longer required. A parabolic ephemeris with a **positive** period derivative of $8.8 \times 10^{-8}\,\mathrm{yr}^{-1}$ as required by the standard scenario is still excluded with high confidence (χ^2= 70 for 19 dof).

3. Discussion

Our conclusion is that phase shifts due to light curve shape variations could have caused the observed negative $\dot{P}$ in

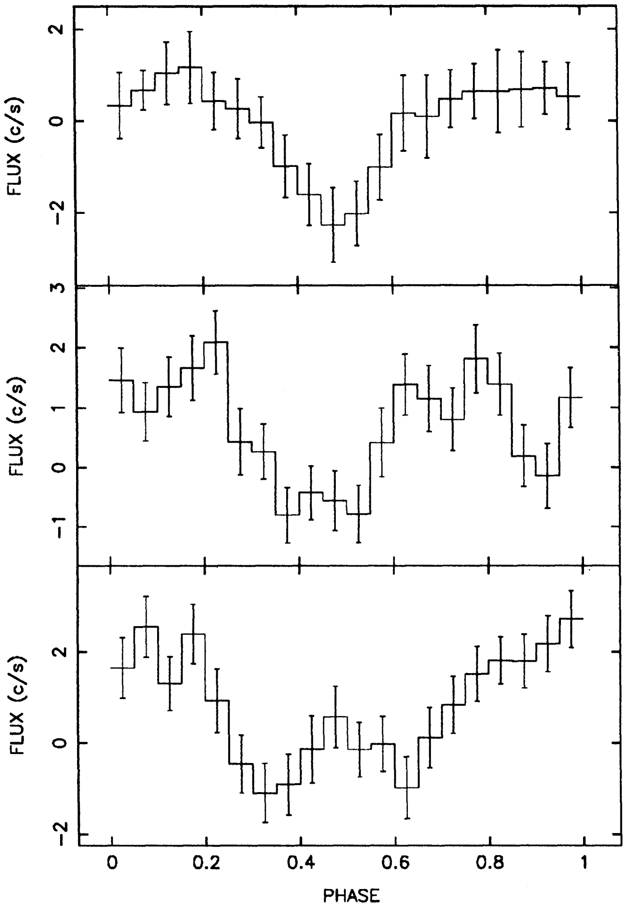

Fig. 3. The folded light curves of our three ROSAT PSPC observations. The data were folded on the linear ephemeris of Paper 1 after correction for telescope vignetting and subtraction of the mean flux in each satellite orbit. Top: 1991 March 12-13; middle: 1993 March 10-11; bottom: 1993 March 24-25.

a constant-period source, but are not enough to explain the discrepancy with the positive $\dot{P}$ predicted by the standard scenario. If in the historical record phase shifts would have occurred *larger* than the ones we derived here on the basis of the observed light curve shape changes, then this remaining discrepancy might be resolved. In this light, we now explore the possibility of phase shifts which are accompanied by only minor changes in the shape of the light curve.

The orbital variation of the X-ray intensity of 4U 1820−30 is presumably due to variable thickness of the outer disk rim causing variable absorption and/or reflection of X-rays in different azimuthal directions (Stella et al. 1987, see Mason 1986 for a review). A dozen other LMXBs are known that show periodic dips due to this mechanism (Parmar & White 1988). The azimuthal variation in the disk thickness is probably related to the impact on the outer disk of the mass flowing from the secondary. The azimuth of the point of impact depends on the direction of the gas flow from the inner Lagrangean point and on the size of the disk, as illustrated in Fig. 4. The azimuth of the impact point varies as the disk expands or shrinks. Variations in the disk radius are expected as the rate of mass transfer to the accretion disk varies (e.g. Livio & Verbunt 1988). The total range in azimuth over which the bulge on the disk rim might move by this mechanism is ~ 120 deg, well in excess of the observed phase shifts (~ 45 deg). The velocity with which the matter impacts on the accretion disk also varies with disk radius, both because the velocity of the gas stream increases along its trajectory, and because the angle of impact varies. Thus, in addition to the phase, also the shape of the orbital light curve could change as a function of disk radius and hence, mass transfer rate.

An alternative process that would cause the azimuth of the impact point to vary is precession of an elliptical disk. Such precession is expected in binaries with an extreme mass ratio (in excess of ~ 4; Whitehurst 1988) and could therefore occur in 4U 1820−30.

So, there are at least two ways in which orbital phase shifts larger than expected from the observable light curve shape changes could occur without changes in the true orbital period. This might explain the discrepancy between observed and predicted period derivative even without recourse to systemic acceleration or other proposed mechanisms (see Paper 1). This proposal can in principle be tested by looking for a dependence of orbital phase on $\dot{M}$. In 4U 1820−30 there is a 176-d variation of the X-ray flux (Priedhorsky & Terrell 1984) known to be caused by variations in the mass accretion rate as the burst activity is related to the low-intensity state (Lewin et al. 1993). It would be interesting to see whether there is a correlation between the phase of the X-ray maximum and/or the shape of the X-ray orbital light curve with the 176-day phase. However, the sparseness of the data and the uncertainties in the 176-day ephemeris at present make this difficult.

We note that orbital period measurements in other X-ray binaries based on X-ray dips could in principle be subject to similar effects. Period changes have been obtained for Cyg X-3 (van der Klis & Bonnet-Bidaud 1981; van der Klis & Bonnet-Bidaud 1989), 4U 1822-37 (Hellier et al. 1990) and EXO 0748-676 (Parmar et al. 1991). In the latter two systems, an eclipse by the secondary of, respectively, the accretion disk corona and the neutron star marks the orbital phase and thus the phase does not depend on the shape of the outer disk rim. In Cyg X-3 the light curve is probably formed through scattering in a stellar wind (van Kerkwijk et al. 1992), not through disk rim effects. If the disk rim model does apply to Cyg X-3 as earlier proposed by White & Holt (1982), then similar effects as in 4U 1820−30 might, in principle, apply there. Light curve changes in Cyg X-3 as a possible cause of orbital

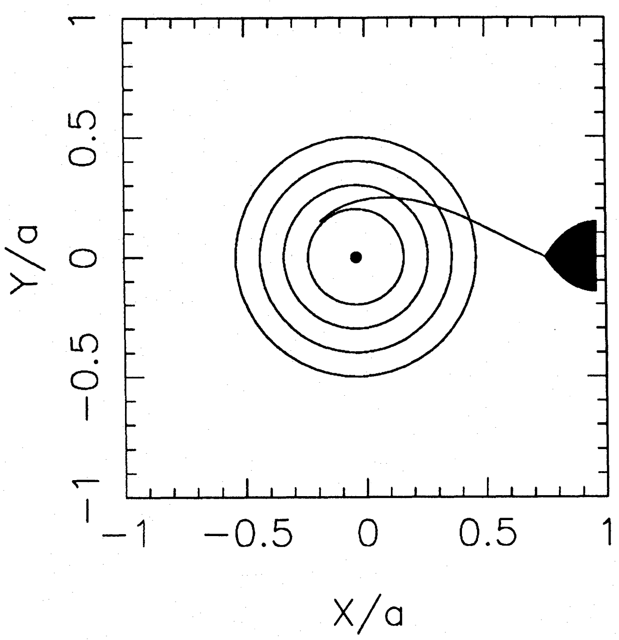

Fig. 4. Trajectory of the gas stream in a binary in which the accreting star is 25 times more massive than the donor star. The trajectory has been calculated according to the prescription of Lubow and Shu 1975. Coordinates are given in units of the semi-major axis a of the binary orbit. The azimuth of the point where the gas stream hits the accretion disk varies with disk size. A precessing elliptical accretion disk will also show variation in the azimuth of the impact point.

phase changes were previously discussed by van der Klis & Bonnet-Bidaud (1981); van der Klis & Bonnet-Bidaud (1989).

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