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Outbursts of EX Hydrae: mass transfer events or disc instabilities?

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ABSTRACT

We present the 45-yr record of EX Hya's lightcurve and discuss the characteristics of its 15 observed outbursts. We then concentrate on the 1998 outburst, reporting the first outburst X-ray observations. We discover an X-ray beat-cycle modulation, indicating that an enhanced accretion stream couples directly with the magnetosphere in outburst, confirming our previous prediction. Optical eclipse profiles late in outburst show that the visible light is dominated by an enhanced mass-transfer stream overflowing the accretion disc. We are uncertain whether the enhanced mass transfer is triggered by a disc instability, or by some other cause. While in outburst, EX Hya shows some of the characteristics of SW Sex stars.

Key words: accretion, accretion discs – novae, cataclysmic variables – stars: individual: EX Hydrae – binaries: close – X-rays: stars.

1 INTRODUCTION

If intermediate polars (IPs) are cataclysmic variables possessing partial accretion discs, with the centre disrupted by a magnetic field, then we expect that they can show disc instability outbursts, as dwarf novae do. Several IPs — XY Ari (Hellier, Mukai & Beardmore 1997), YY Dra (Patterson et al. 1992) and GK Per (e.g. Kim et al. 1992) — appear to show just that.

However, two other IPs — V1223 Sgr & TV Col — show short, low-amplitude outbursts that are unlike dwarf nova eruptions and probably result from another instability such as mass-transfer bursts (see Warner 1996 and Hellier et al. 1997 for reviews). The outbursts of TV Col last ∼ 8 h with 2-mag amplitudes (Szkody & Mateo 1984; Schwarz et al. 1988; Hellier & Buckley 1993); increased S-wave emission during this period points to enhanced mass transfer. V1223 Sgr has shown a very similar event (van Amerongen & van Paradijs 1989). Since these two stars have novalike discs (e.g. TV Col shows superhumps and V1223 Sgr shows VY Scl low states) the outbursts are unlikely to be thermal instabilities in the disc. Very similar short-lived flare events have been seen in AM Her stars (e.g. Warren et al. 1993), which cannot be disc instabilities since such stars don't have discs. [The possible IP RX J0757+6306 may be a similar system (Tovmassian et al. 1998; Kato 1999), but the data are currently too sparse for certainty.]

The remaining IP showing outbursts, EX Hya, is intermediate between the above two types, with outbursts lasting ∼ 2–3 d (cf. 0.5 d for TV Col & V1223 Sgr, and 5 d for XY Ari & YY Dra). Previous outbursts have been reported by Bond et al. (1987); Hellier et al. (1989; hereafter Paper 1); Reinsch & Beuermann (1990) and Buckley & Schwarzenberg-Czerny (1993).

A major finding from the 1987 outburst (Paper 1) was a high-velocity feature in the emission-line wings. This seemed to arise from an enhanced accretion stream overflowing the disc and connecting directly with the magnetosphere. We predicted that since the stream rotated with the orbital frequency (Ω) and the magnetosphere with the spin frequency (ω), the relative geometry (and thus the X-ray emission from stream-fed accretion) should vary at the $\omega - \Omega$ frequency. Such X-ray beat modulations have since been seen in many IPs (e.g. Hellier 1998) but not, so far, in EX Hya. Accordingly, we applied for Target of Opportunity time to observe the next outburst of EX Hya with the rapid-response RXTE X-ray satellite. This was successfully triggered during an outburst in 1998 August and we report the results here.

EX Hya is also well studied in quiescence, showing a prominent sinusoidal modulation at the 67-min spin period and a grazing eclipse recurring with the 98-min orbital period. See, e.g., Hellier (1987, hereafter Paper 2) for spectroscopy, Siegel et al. (1989) for optical photometry, and Rosen et al. (1991) for X-ray data.

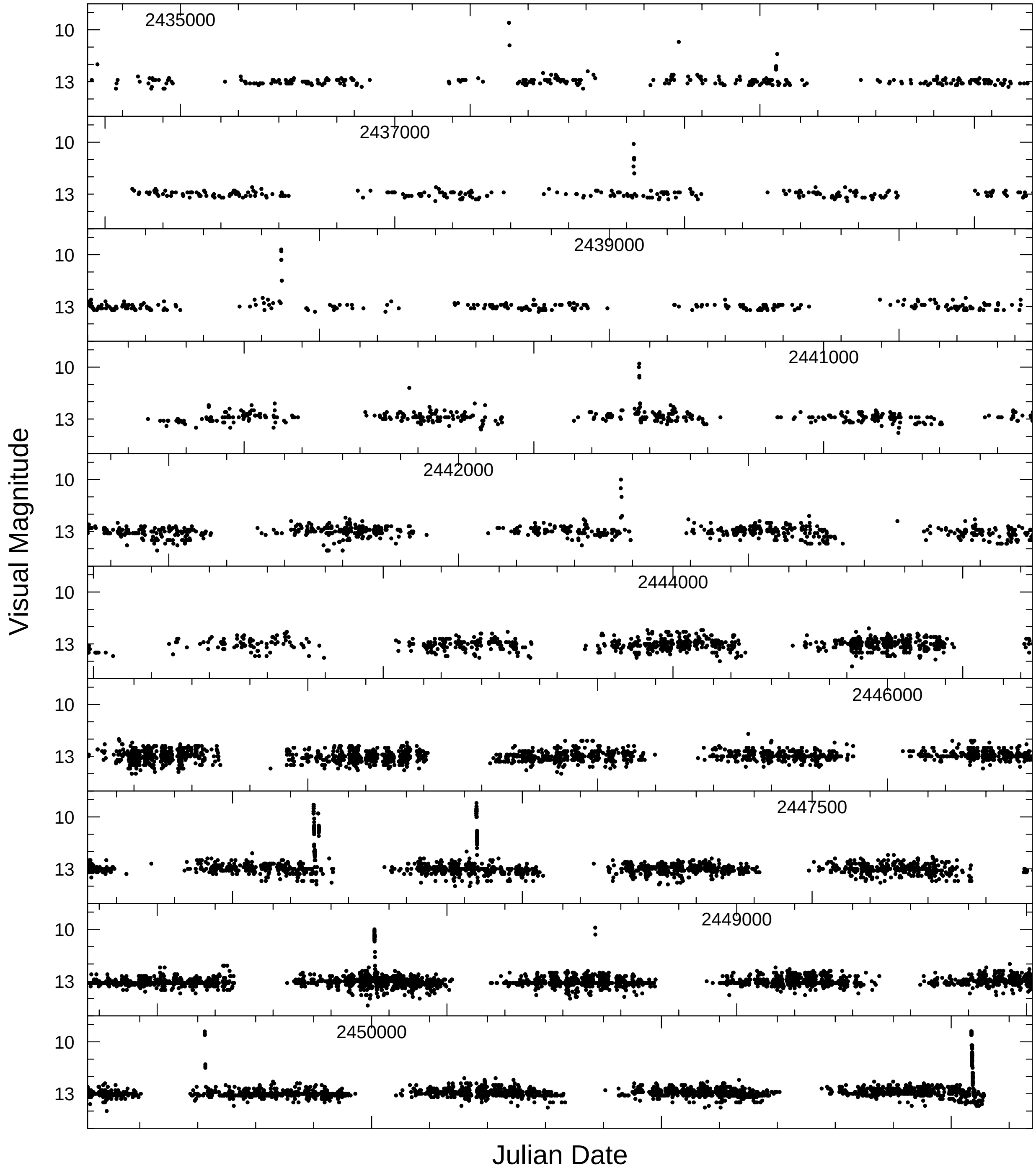

Figure 1. The record of EX Hya by the Variable Star Section of the Royal Astronomical Society of New Zealand.

2 THE LONG-TERM RECORD

Since EX Hya's behaviour is clearly different from that of normal dwarf novae it is worth presenting the complete record. Fig. 1 shows the visual estimates of EX Hya compiled by the Variable Star Section of the RASNZ. While EX Hya mostly sits at 13th mag, it rises to mag 9.5 in infrequent outbursts lasting 2–3 d. Note that much of the variability at quiescence is real, caused by the spin and orbital modulations. Fig. 2 contains details of the outbursts on an expanded scale. We note the following points:

(i) 15 outbursts have been seen in 44 years, for an average recurrence of $\sim$ 3 yrs. However, the yearly and monthly data gaps mean that many will have been missed. Coverage dense enough to catch 2-d outbursts is $\sim$ 2/3^{rds} complete in recent times, dropping to $\sim$ 1/3rd complete earlier, so we can estimate that only $\sim$ half the outbursts have been caught, reducing the recurrence to $\sim$ 1.5 yrs.

(ii) The outbursts occur irregularly: near JD 244 8370 a 'double' outburst occurred with an interval of only 8 d. In contrast, taking the sampling into consideration, there is a 95% probability that inter-outburst intervals > 2.7 yrs

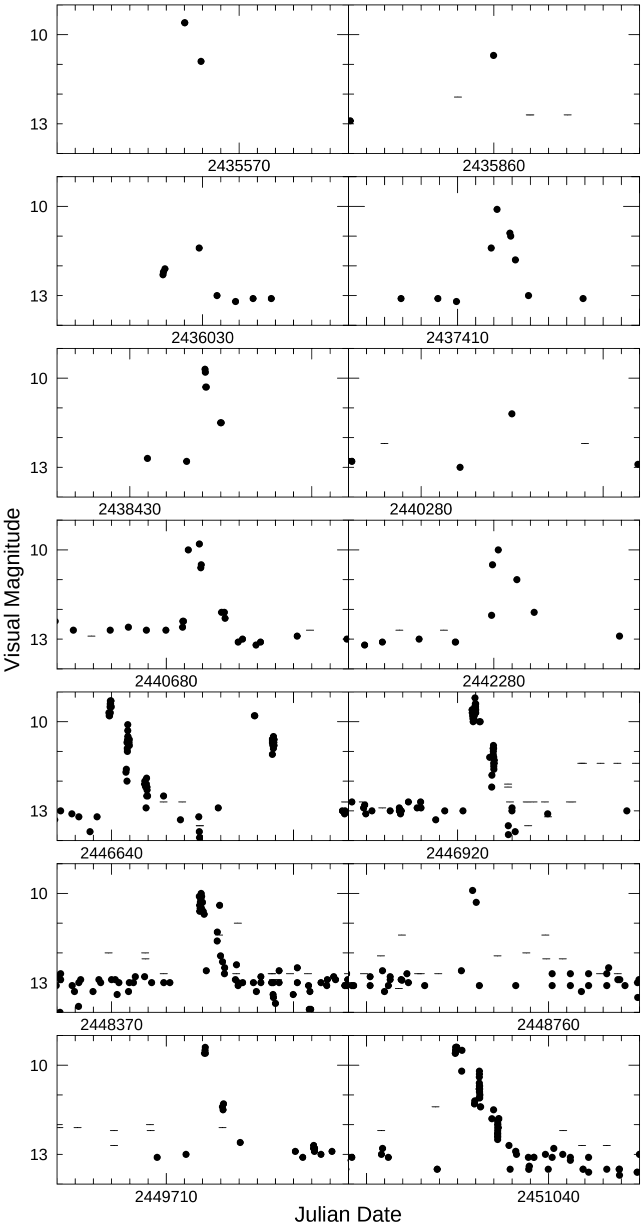

Figure 2. Expanded plots of the outburst from Fig. 1. The tick-marks are at 1-d intervals. Bars are upper-limits.

have occurred (most likely in the 12-yr period between JD 244 2300{244 6600 when no outburst was seen).

(iii) The outburst rises are unresolved in the RASNZ data, where rises of 3.4 mags in < 12 hrs are seen. Reinsch & Beuermann (1990) caught part of a rise, seeing the brightness increase by a factor 10 within 3 hrs.

(iv) The declines are slower than the rises and are variable: the outburst at JD 244 6920 declined by 3.5 mags in 1.8 d while that at JD 245 1040 took 3.0 d to decline by the same amount.

(v) The outburst at JD 244 8760 was peculiar. EX Hya rose from mag 13.1 to 9.9 in < 15 hrs and declined from 10.3 to 12.6 in only < 4.5 hrs, the whole event being over in < 1 d. [The two outburst points are by different observers; the observers involved (including the current authors AJ and DO) are highly experienced observers of EX Hya, and the data points have been confirmed from the original observing logs.]

(vi) If the accretion rate scales as the optical magnitude and if the quiescent accretion rate is 10^{16} g s$^{\{1}$ then the outbursts typically involve 10^{22} g of material.

3 THE 1998 OUTBURST DATA

The August 1998 outburst (Fig. 3) showed the usual unresolved rise but decayed to quiescence in 3 d, 1 d longer than the other well-studied outbursts.

3.1 RXTE X-ray observations

Following notification of the outburst we observed EX Hya with RXTE [see Bradt, Rothschild & Swank (1993) for a description of this satellite] gaining three sections of data on the outburst decline (Fig. 3). The first section, lasting 1 hr, recorded a 2{15 keV count rate varying between 70 and 330 c s^{1} (all 5 PCUs); during the second section, lasting 9 hr, the count rate was in the range 60{220; and by the third section, lasting 6 hr, the count rate had declined to 35{70, essentially a quiescent count rate.

We Fourier transformed the 2{15 keV X-ray dataset, first normalizing the three data sections to the same count rate. The result (Fig. 4) reveals power at the spin frequency (!) and at the beat frequency between the orbital and spin periods (!). An X-ray beat frequency has never been seen in EX Hya in quiescence, but its occurrence in outburst confirms the prediction in Paper 1. However, some scepticism is in order since the X-ray data cover only 4.5 cycles of the 3.5-hr beat period. One might also be concerned that since the spacecraft orbital period is near EX Hya's orbital period (96 vs 98 mins), beating with the spacecraft orbit might explain the peak seen. However, this would produce equal peaks at ! $_{\rm rxte}$ and ! + $_{\rm rxte}$ whereas there is no power at ! + $_{\rm rxte}$.

By fitting a sinusoid to the three sections of 2{15 keV X-ray data we find that the spin pulse had a modulation depth (semi-amplitude/mean) of 52% in the first section, declining to 25% in the second section and 5% in the third (the errors are dominated by flickering, and the first result is particularly unreliable since the data cover only 1 cycle). For comparison, Rosen et al. (1991) quote a 14% depth in quiescent Ginga data over a similar energy range; thus the pulse amplitude was markedly bigger during outburst. There was no apparent change in pulse phase during the RXTE observations.

The spectral changes over the spin cycle are consistent with the usual quiescent behaviour | greater modulation at lower energies | but the difficulty of disentangling (in a limited dataset) two periodicities, considerable flickering, and the outburst decline, made further investigation unreliable.

The X-ray data show the expected narrow, partial eclipse (not shown), with a profile similar to that of the quiescent eclipse. It is close to the time predicted by the ephemeris of Hellier & Sproats (1992; not including the sinusoidal term), being early by 40 10 s (0.007 in phase). Other than this, there was no orbital modulation.

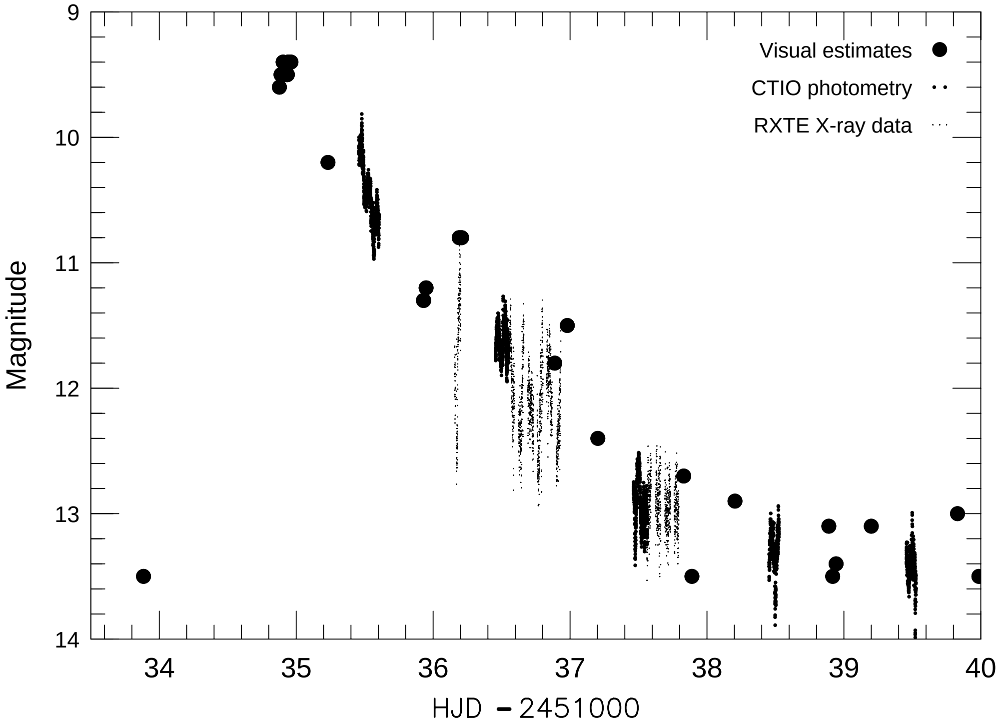

Figure 3. The 1998 outburst of EX Hya showing RASNZ visual estimates, CTIO optical photometry and RXTE X-ray data. The CTIO and RXTE datasets have had the zero-points adjusted to match the visual records.

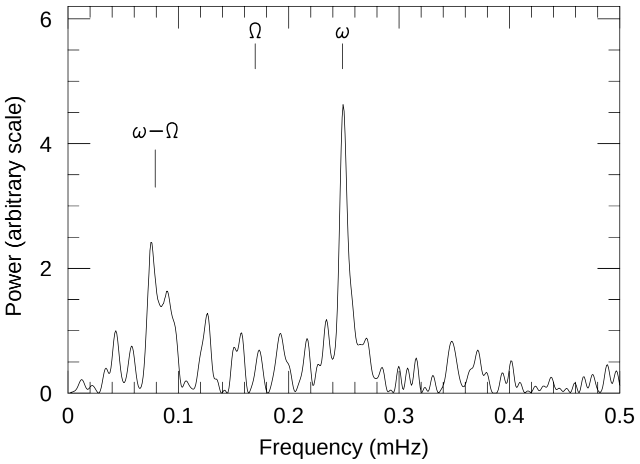

Figure 4. The Fourier transform of the RXTE data revealing modulations at the spin (ω) and beat (ω − Ω) periods.

3.2 CTIO photometry

We obtained R-band photometry with the Cerro Tololo Inter-American Observatory 0.9-m telescope over 5 nights of the decline and return to quiesence (Figs. 3 & 5).

The spin pulse is present throughout the dataset, but with different amplitudes (the semi-amplitudes/mean, as far as can be told given the flickering, are 12, 13, 24, 10 and 7 per cent on the five nights respectively). Reinsch & Beuermann (1990) also report the pulsation throughout their outburst dataset, with an amplitude comparable to that in quiescence.

It might appear from Fig. 5 that the pulse is late compared to the predicted times of maxima (which use the quadratic ephemeris of Hellier & Sproats 1992) but the situation is more complex: Fig. 6 shows that X-ray maximum occurs where predicted (to within 0.05 in phase) but that the optical pulse remains bright for ∼0.15 longer. This effect has not been reported previously, but this is the first simultaneous optical/X-ray dataset.

4 THE QUIESCENT ECLIPSE

Since interpreting the eclipse profiles during outburst will be crucial, we'll first take a detour into the quiescent lightcurve. Note, firstly, that the partial, flat-bottomed X-ray eclipse implies that the secondary limb grazes the white dwarf, eclipsing the lower accreting pole but leaving the upper pole uneclipsed (Beuermann & Osborne 1988; Rosen et al. 1991; Mukai et al. 1998).

To investigate the quiescent optical eclipse we have used the 45 h of B-band photometry reported by Sterken et al. (1983) and Sterken & Vogt (1995). We first folded the data on the 67-min spin period (using 50 phase bins) to obtain the mean pulse profile. We then removed the pulse by subtracting from each datapoint the value of the mean pulse profile at that phase. Then we folded the data on the orbital cycle, to obtain the curve displayed in Fig. 7. The ∼30 per cent optical eclipse lasts for 3 mins and is coincident with the X-ray eclipse. Detailed studies (e.g. Siegel et al. 1989) show that the eclipse centroid depends on spin phase and reveal that most of the eclipsed light arises from the accretion curtain of material falling onto the lower pole of the white dwarf.

Fig. 7 also shows an orbital hump extending between phases ∼0.6–0.15, and is presumably caused by the bright

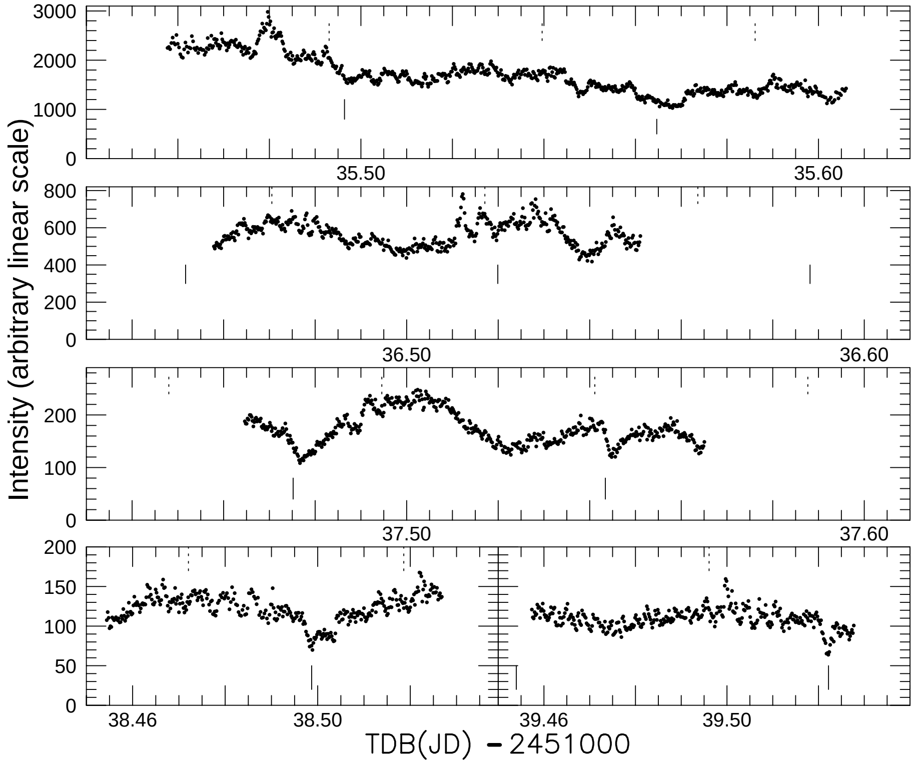

Figure 5. The CTIO R-band photometry of EX Hya on the decline from outburst (note the differing y-axes). The lower tick marks show predicted eclipse times and the dotted ticks show times of spin maxima using the ephemerides of Hellier & Sproats (1992).

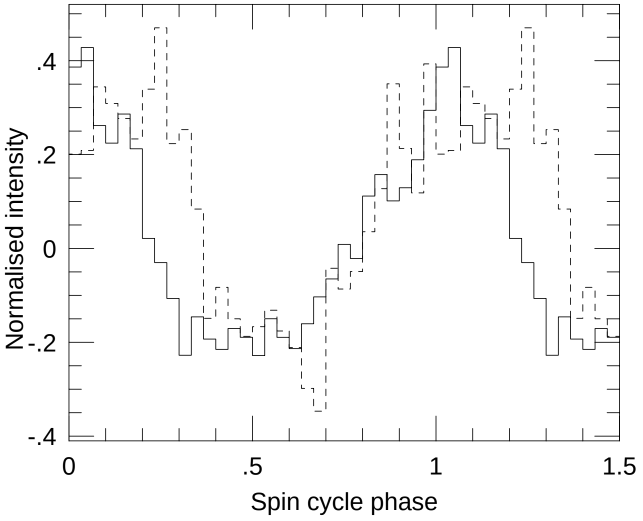

Figure 6. The $2^{\rm nd}$ section of X-ray data (solid line) and the optical data (dashed) folded on the spin cycle.

spot where the stream hits the accretion disc. Similar features are seen in dwarf novae such as Z Cha, where the hump extends between phases 0.62–0.13 (Wood et al. 1986).

By analogy with Z Cha, we would also expect to see a disc eclipse and a bright spot eclipse. However, the disc eclipse involves only 23 per cent of the light in Z Cha (Wood et al. 1986), and in the grazing eclipse of EX Hya the fraction might be lower. It is possible that the EX Hya light curve contains a disc eclipse of 10 per cent depth, which starts at phase 0.95 as a steepening of the hump decline, and finishes at phase 0.05. It is also possible that the 'shoulder' to the eclipse, ending at 0.07, involves the eclipse of the bright spot. However, both interpretations are near the margins of the data quality given the flickering.

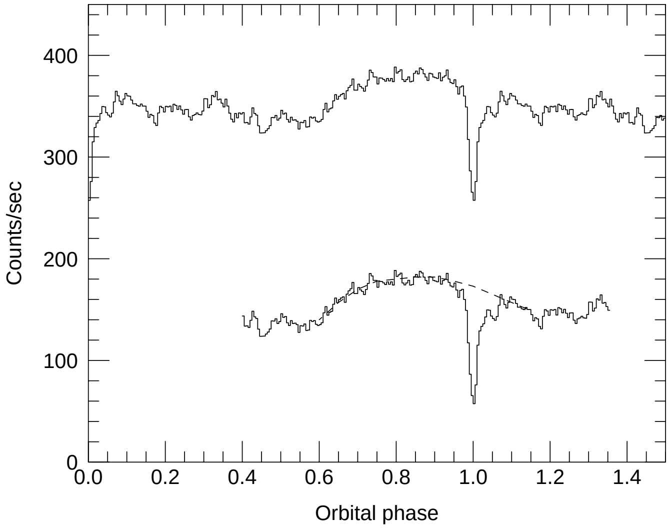

Figure 7. The average quiescent orbital modulation from 45 h of B-band photometry. The data are repeated, displaced downwards by 200 counts/sec, and with a smoothed orbital hump added to guide the eye.

Since the evidence for a disc eclipse is marginal we can ask whether EX Hya contains a disc at all, especially given the proposed models of discless accretion in IPs (Wynn & King 1995) and in EX Hya in particular (King & Wynn 1999). The other evidence for a disc can be summarised as (see Hellier 1991 for a fuller account): (1) the dominance of

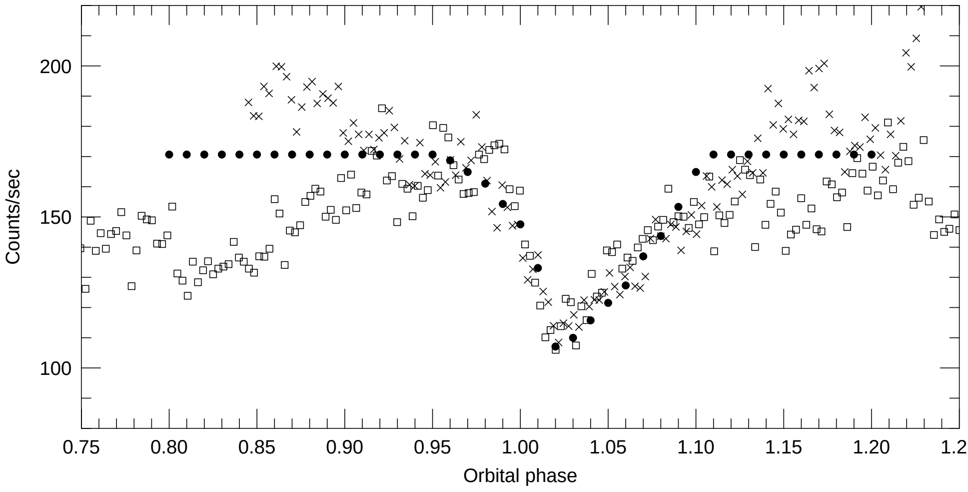

Figure 8. The eclipse profiles from the third night of CTIO photometry phased relative to the X-ray eclipse (crosses are from the first cycle, squares from the second). The solid dots are a model eclipse of a bright stream. Much of the out-of-eclipse variability is related to the spin cycle.

the spin period, rather than the beat period, in quiescent X-ray lightcurves, which implies that the accreting material circularizes and loses knowledge of orbital phase; (2) a weak 'rotational disturbance' seen in the emission lines (Paper 2); (3) an emission-line S-wave with the correct phase and velocity to arise from an impact at the edge of a disc (Paper 2); (4) the orbital hump and its being at the same phase as in Z Cha (above); (5) material above the plane consistent with a splash where the stream hits the disc edge, revealed by soft X-ray and EUV dips (Cordova, Mason & Kahn 1985; Mauche 1999), and (6) the double-peaked lines seen in quiescence (Paper 2);

Note, though, that none of these secure the velocity field of the disc, and so don't rule out a magnetically threaded structure (e.g. King & Wynn 1999) if it is able to mimic a disc in the above respects. We leave the issue of whether the outburst was a disc instability, thus implying the presence of a disc, to the discussion.

5 THE OUTBURST ECLIPSES

In the last night of photometry (when EX Hya was back in quiescence) the observed eclipse was narrow, V-shaped, coincident with the X-ray eclipse, and similar to previous quiescent eclipses (Section 4). On the penultimate night (JD 2451038) the eclipse egress had a 'shoulder' lasting until phase 0.07. The night before, both eclipses had asymmetrical V shapes with minima at phase 0.02 (relative to the X-ray mid-eclipse). Earlier still in the outburst the eclipse is difficult to discern: some shallow dips may be eclipses, but there is not enough repeatability in consecutive cycles to distinguish them from flickering. Similarly, near the peak of the 1987 outburst Reinsch & Beuermann (1990) saw broad, shallow dips that may be eclipses, but again there were not enough cycles to be sure.

The lateness of the eclipses on the third night (JD 2451037) implies that they are probably eclipses of an accretion stream rather than a disc. To test this we have computed the eclipse of a model stream, assuming it to have a constant brightness along the freefall trajectory between the initial impact with the disc and the point of its closest approach to the white dwarf. The model parameters (based on those of Paper 2) are: $P_{\rm orb}$ = 5895 s, M_1 = 0.7 $M_\odot$, M_2 = 0.13 $M_\odot$, i = 79° and $R_{\rm disc}$ = 0.76 R_{L1}.

Fig. 8 shows that the model stream eclipse exhibits the same features (V shape, minimum at phase 0.02, faster ingress, slower egress) as the two eclipses observed on that night. The only free parameter is the model normalization, where in order to match the data we have diluted the stream with uneclipsed light such that the stream is 43% of the total [for comparison, in AM Her stars the stream is commonly found to contribute 50–60% of the total light (Harrop-Allin et al. 1999)]. Fig. 9 illustrates the geometry of the above model, showing the system at phases 0.00 (white dwarf eclipse), 0.02 (stream-eclipse minimum) and 0.07 (see below).

On the fourth night (JD 2451038) the eclipse is of the white dwarf and its environs, with an additional shoulder lasting until phase 0.07 (unfortunately we only have one cycle that night so can't check the feature's repeatability). The constant intensity during the shoulder implies an eclipse of a pointlike source. If this source is located along the track of the accretion stream, the start and end phases of the shoulder and the depth would be reproduced if it emitted 22% of the system's light and was 0.29a from the white dwarf (where a is the stellar separation).

Is this distance (1.3 × 10^{10} cm) the radius of the magnetosphere? The (not particularly reliable) estimate of Paper 2 is different, at 6 × 10^9 cm. However, we can check the plausibility by estimating the field strength that would place the magnetosphere there. Using the standard theory for a disc (e.g. Frank, King & Raine 1992) we find that for an accretion rate of 10^{16} g s^{-1} the implied magnetic moment is 9 × 10^{32} G cm^3, an order of magnitude greater than other estimates (e.g. Paper 2; Warner 1996). One could argue that a stream would penetrate further in than a disc, increasing the derived magnetic moment further, although if the stream carried only a fraction of the accretion flow this would reduce the estimate again.

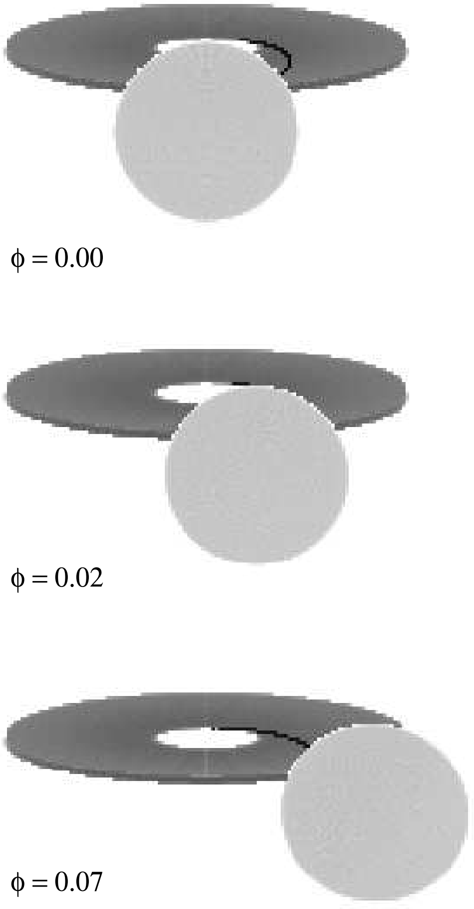

Figure 9. An illustration of EX Hya using the parameters discussed in the text, shown at three phases during eclipse.

Is the distance then the radius of the outer disc edge? Again, it is inconsistent with Paper 2, which found a value of 2.3×10^{10} cm from the extent in phase of the rotational disturbance during the eclipse, and also from the separation of the double peaks in the emission lines, assuming these to give the Keplerian velocity at the disc edge. However, the extent of the rotational disturbance is hard to estimate, and the assumption of Keplerian motion could well be wrong. Further uncertainties are that an enhanced stream might penetrate into the disc, and also that the disc size might change in outburst, enlarging due to the enhanced viscosity of a disc instability but shrinking due to the addition of low-angular-momentum material from an enhanced stream.

Note, though, that the egress at phase 0.07 is consistent with a possible bright-spot egress at that phase in the quiescent lightcurve; thus, overall the most likely conclusion is that the feature is at the disc edge, and that previous estimates of the disc radius were too large.

6 DISCUSSION

Several features of EX Hya's outbursts are unlike those expected from a disc instability (Section 2). The most striking is the rarity of the outbursts. Over time, only 4% of EX Hya's accretion occurs during outburst (assuming, simplisticly, that the accretion rate scales as the optical flux). In contrast, the figure for a typical dwarf nova such as SS Cyg is 90%. Another peculiarity is the range of interoutburst intervals, from 8 d to > 2 y, when there is no change in quiescent magnitude (and hence mass-transfer rate). Note also the decline times: the 2–3 d declines are typical of dwarf novae and are comparable with the viscous timescale of a disc, but the 5-hr decline is not (even if allowance is made for the lack of inner disc). Further, the emission line equivalent widths increase during outburst (Paper 1); in dwarf novae (with the exception of IP Peg) they decrease.

In contrast, the evidence for an enhanced mass-transfer stream is clear. High-velocity line wings from an overflowing stream hitting the magnetosphere have been observed in both the 1987 and 1991 outbursts (Paper 1; Buckley & Schwarzenberg-Czerny 1993). They were accompanied by greatly enhanced line emission from the stream impact at the edge of the disc. An X-ray beat period, caused by the stream connecting to the magnetic field and predicted in Paper 1, has now been seen (Section 3.1). Lastly, the eclipse profiles during late decline reveal a bright overflowing stream (Section 5).

The above suggests that EX Hya's outbursts are mass transfer events, rather than disc instabilities, but is not conclusive. The disc-instability enthusiast could argue that the instabilities are reduced in duration and frequency by the magnetic disruption of the inner disc (Angelini & Verbunt 1989). If they are reduced to minor perturbations on the disc, the irregularity of the outbursts could follow. The enhanced mass transfer might then be a consequence of a disc instability, triggered by enhanced irradiation of the secondary star. This is easier in a magnetic system than in a dwarf nova since radiation from the magnetic poles is less likely to be hidden by the disc, compared to radiation from a boundary layer. There is indeed increased line emission from the secondary in the 1987 outburst, in addition to the increased line emission from the stream/bright-spot (Paper 1).

In principle the optical eclipse profiles early in the outburst should tell us whether the disc has gone into a high state, however the difficulty of judging which features are real, given the flickering and limited data, precludes a firm conclusion. The first two nights of our optical dataset, and also the dataset early in an outburst by Reinsch & Beuermann (1990) are compatible with broad dips, ∼ 20 per cent deep, at the expected eclipse times. If a disc were the only light source, the grazing eclipse would produce dips of ∼ 30 per cent depth, so the observed depth is consistent with some dilution by light from the magnetosphere (which must be present given the spin pulse). The broad dips might also be centered slightly late, compared to the expected eclipse time (Reinsch & Beuermann 1990, and also upper panel of our Fig. 5), which would indicate a contribution from an enhanced stream.

The absence, early in the outburst, of the narrow eclipses seen in quiescence is puzzling. It indicates either that the white dwarf and its accretion curtains are relatively faint (but why then do we still see a spin pulse?) or that in outburst we see predominantly the upper (uneclipsed) accretion curtain (but why is this?).

In summary, there is clearly enhanced mass transfer, but we cannot be sure whether or not this is triggered by a disc-instability outburst.

7 CONCLUSIONS

(1) EX Hya's outbursts are unlike those of any other dwarf novae. However, it is possible that they are characteristic of disc instabilities in a magnetically truncated disc rather than the result of a different process.

(2) There is clearly enhanced mass transfer in outburst. The evidence includes an enhanced stream/disc impact, eclipse profiles resulting from a bright stream overflowing the disc, line emission from where the overflowing stream hits the magnetosphere, and an X-ray periodicity at the beat period, indicating coupling of the overflowing stream to the magnetosphere.

(3) It is unclear whether the enhanced mass transfer is triggered by a disc instability. The eclipse profiles early in outburst are consistent with a brightened disc, but there isn't enough repeatability over different cycles to distinguish them from flickering with certainty.

(4) After reviewing the evidence we conclude that EX Hya does possess an accretion disc, or a circulating structure with very similar characteristics. The optical orbital modulation in quiescence is similar to that of non-magnetic dwarf novae, including an orbital hump and marginal evidence for eclipses of the disc and bright spot.

(5) We find evidence that previous estimates for the disc size are too large, prefering instead a disc radius of 0.29 of the stellar separation.

(6) In possessing an overflowing stream giving rise to distorted emission line wings and distorted eclipse profiles, EX Hya in outburst shows some of the characteristics of SW Sex stars (e.g. Hellier 1999).

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