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A digital technique for the separation of the eclipses of a white dwarf and an accretion disc

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Summary. A method of extracting the white-dwarf component of an eclipse from the light curve of an eclipsing cataclysmic variable is presented. The method also gives the times of ingress and egress of the white dwarf and the times of mid-eclipse.

1 Introduction

Dwarf novae are low-mass binary systems which consist of a cool quasi-main-sequence star transferring mass via a stream and an accretion disc on to a white-dwarf primary. A bright spot occurs where the mass-transfer stream strikes the edge of the disc. In a number of these systems the white dwarf and, if present, the bright spot are eclipsed by the red-dwarf secondary. Because the size of the white dwarf ($\sim 10^9$ cm) is much less than the binary separation ($\sim 5 \times 10^{10}$ cm) the white-dwarf eclipse at ingress and egress is seen as a sharp feature in the light curve. If the bright spot is sufficiently compact, its eclipse is also a sharp feature. In Fig. 1(a) we show a phase-folded light curve (11 cycles) for HT Cas in quiescence taken in the V band by K. D. Horne and R. Stiening at the 60-inch telescope at Mt Palomar using a four-channel high-speed photometer. HT Cas has an orbital period of 106 min and the white dwarf is totally eclipsed but no contribution from the hotspot can be seen (Patterson 1981). The white-dwarf ingress, lasting about 50 s, and egress some 300 s later are clearly visible.

In order to interpret the detailed shape of the light curve it is advantageous to be able to remove the eclipse of the white dwarf. If this can be done in an objective and repeatable manner then a deconvolution of the remaining light curve can be undertaken (e.g. using the eclipse mapping technique of Horne 1983, 1985) to discover the structure of the disc and the stream. (Strictly Horne's technique can be applied without the removal of the white-dwarf eclipse, but the presence of such a sharp feature in the light curve slows the computations involved and causes spurious features along the ingress and egress phase arcs.) In this paper we demonstrate how the white-dwarf eclipse can be removed. A by-product of the method is an objective measurement of the times of mid-ingress and egress of the white dwarf and of mid-eclipse, which is essential for the accurate measurement of the period and of period changes.

2 Method

The reduction technique is illustrated by describing its application to the phase-folded light curve of HT Cas [curve (a) in Fig. 1]. Individual sample points are spaced at 1 s intervals.

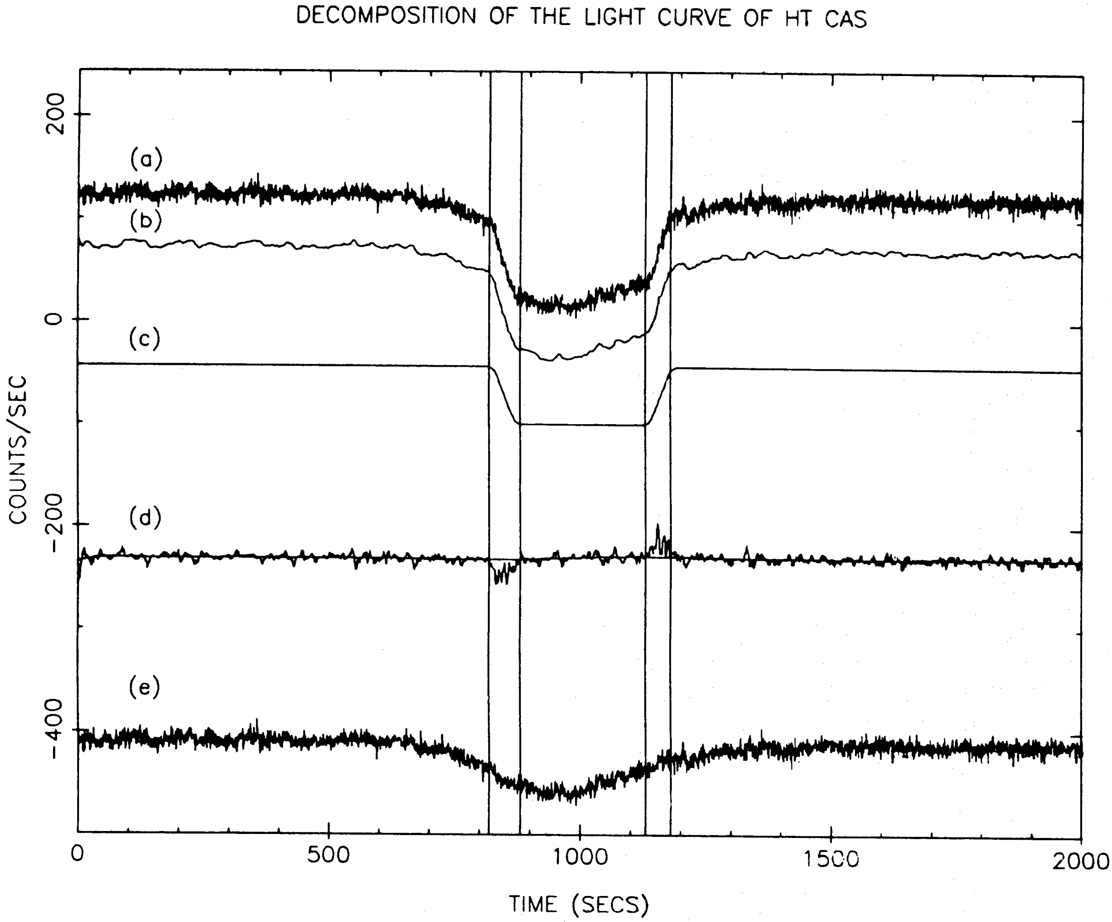

Figure 1. Stages in the processing of the light curve of HT Cas. The vertical lines show the measured positions of the contact points. (a) Folded light curve of HT Cas; (b) filtered light curve, shifted downwards by 50 counts s^{-1}; (c) reconstructed white-dwarf eclipse, shifted downwards by 100 counts s^{-1}; (d) the derivative and the final spline fit, scaled by a factor of 10 (s) and shifted downwards by 230 counts s^{-1}; (e) folded light curve without white-dwarf component, shifted downwards by 475 counts s^{-1}.

First the light curve is passed through a median filter (Tukey 1971). A median filter is used since, for a noise-free signal, this operation would preserve the shape of the light curve provided that the filter width was less than the width of any real detail in the signal. To illustrate this property and to contrast it with the effect of a linear filter, such as box car averaging (a running average), we show in Fig. 2 the response of a simple ramp function (approximately the basis element of an eclipse in a light curve) to both filters. When noise is present, the median filter rounds off the edges of ramp-like features, although to a smaller extent than does a linear filter. Fortunately in practice the edges of a real eclipse do not have discontinuities in the first derivative and the extra rounding effect is subsequently small. The major advantage of a median filter is that the underlying signal is preserved, which is a vital requirement for recovering the white-dwarf eclipse, whilst at the same time any random noise is reduced by a factor $\sqrt{2N/\pi}$, where N is the width of the filter.

In order to minimize any loss of definition at the edges of sharp features, the filter width used must be small compared to the duration of the feature. The width chosen is therefore a compromise between the previous requirement and the desirability of reducing the noise in the data to an acceptable level for further processing. A practical upper limit to use for the width of the median filter is of order one quarter the full width of the feature. For the light curve of HT Cas

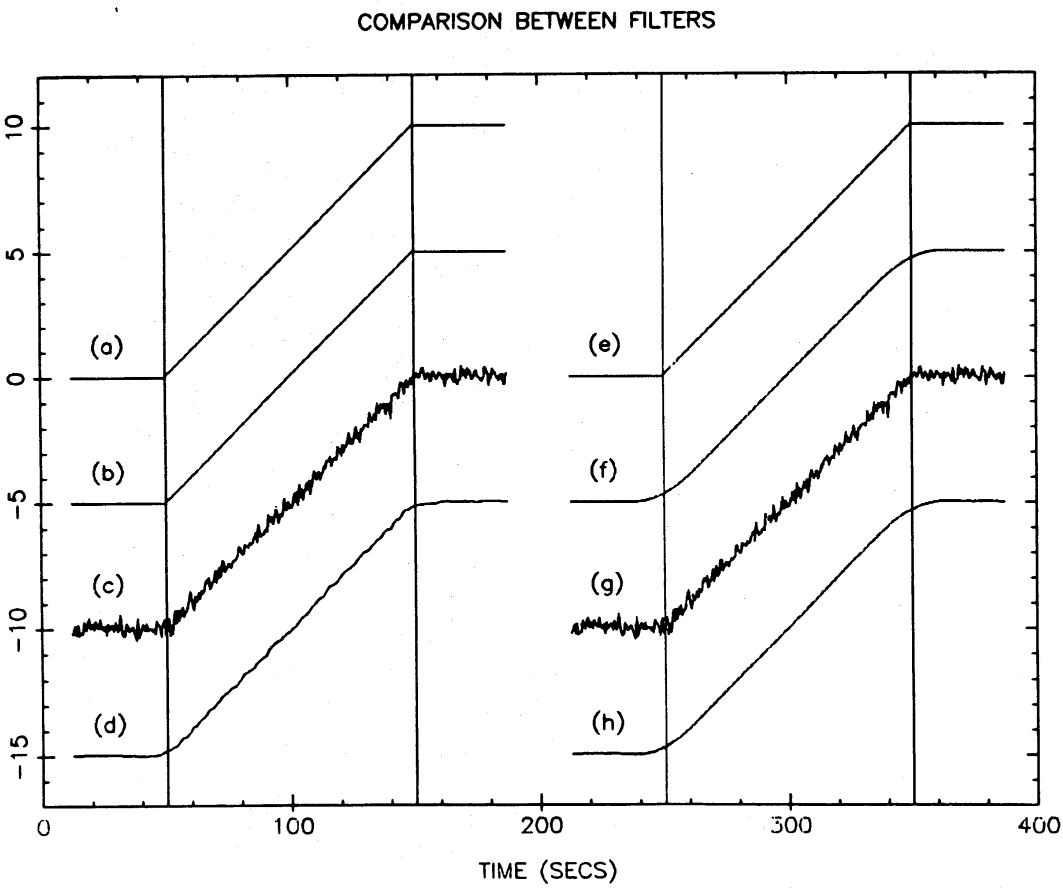

Figure 2. Comparison of the effects of median and box car filtering on a noisy and a noise-free ramp function, each curve has been displaced by 5. (a) Unfiltered noise-free ramp function; (b) curve (a) after passing through a median filter of width 51 s; (c) curve (a) with Gaussian noise added; (d) curve (c) after passing through a median filter of width 51 s; (e) unfiltered noise-free ramp function; (f) curve (e) after passing through a box car filter of width 51 s; (g) curve (e) with Gaussian noise added; (h) curve (g) after passing through a box car filter of width 51 s.

a median filter of length 11 s was used. The filtered light curve is shown in Fig. 1(b). Curve (b) has been shifted downwards by 50 counts s^{-1} for clarity.

The preceding filtering operation is necessary to produce a more readily interpretable derivative of the light curve. This can now be obtained simply by taking the difference between adjacent samples of the filtered light curve. The result is shown in Fig. 1(d) [scaled by a factor of 10 (s)]. Times of white-dwarf ingress and egress correspond to those intervals during which the derivative is significantly non-zero.

The next stage is to locate these regions accurately and automatically. It is well known that the optimum method for locating a signal in the presence of noise is to use a matched detection filter. In this case the expected signal is a roughly constant value of the derivative during the times of ingress (negative) and egress (positive), and zero elsewhere. This implies that the optimum detection filter is in fact a box car filter of width equal to the expected duration of ingress and egress. The largest negative and positive peaks after application of the detection filter indicate the location of the mid-points of ingress and egress respectively, whilst the half-power points of these peaks give rough limits to their duration.

The regions of the derivative lying within ingress and egress can then be flagged. A spline function is then fitted to the unflagged regions of the derivative. The purpose of this is to allow for the fact that the light-curve derivative is non-zero outside the times of ingress and egress. It is vitally important to obtain a good fit to the remaining derivative as any trends here are due to light variations other than those caused by the white-dwarf eclipse. It is possible to distinguish between the two sources of light because the white-dwarf eclipse is sharper than the eclipse of the remaining light. It is necessary to make allowance for the more gradual eclipse or we could misjudge the depth of the white-dwarf component. A cubic spline function with knots spaced at intervals of roughly three times the duration of the white-dwarf ingress/egress provides a reasonable compromise between temporal resolution and noise rejection. This fitted function is now subtracted from the derivative and the resultant signal is reprocessed to redetermine the contact points. Usually one iteration of this technique is sufficient. The final spline fit is shown as the slowly varying line superimposed on the derivative in Fig. 1(d). It is significantly non-zero in the neighbourhood of the eclipse.

Once the final spline fit has been determined and subtracted the times of the contact points are re-examined. This is necessary since the previous estimate although eminently suitable for locating the mid-points is not quite as reliable in locating the contact points because of the inherent convolution involved in the method. To locate the beginning and end points of ingress/egress we are in fact attempting to find the times at which the corrected derivative (after spline subtraction) becomes non-zero.

To do this reliably we need to filter the corrected derivative, disturbing the signal as little as possible and yet reducing the noise to a level where we are not misled in our choice. Again a median filter is the best operation to use. The filter width is set equal to the original median filter width used in the first part of the reduction. A further narrow box car filter (width 5 s) is also used to aid in the detection. A simple search is then made outward from the mid-points of ingress and egress to locate more precisely the limits of the non-zero region in the filtered corrected derivative. The vertical lines shown in Fig. 1 indicate these limits. We are now in a position to reconstruct the white-dwarf eclipse.

We assume that the light from the white dwarf is constant outside ingress and egress and that it is zero between the second and third contact points. The filtered corrected derivative is then integrated through ingress and egress and if necessary further smoothed to obtain a noise-free estimate of the white-dwarf eclipse.

As a final step the result can be symmetrized about the mid-point of the eclipse. The reconstructed white-dwarf eclipse is shown in Fig. 1(c). This eclipse can then be subtracted from the original light curve to obtain the eclipse of the remaining components, shown in Fig. 1(e). Curve (e) has been shifted downwards by 475 counts s^{-1}.

3 Discussion

We have shown how digital filtering techniques may be used to remove a sharp eclipse from an otherwise slowly varying light curve and have illustrated the method by applying it to an eclipse of HT Cas. This eclipse consists of the eclipse of a white dwarf (size $\sim 10^9$ cm) and the eclipse of an accretion disc (size $\sim 10^{10}$ cm). We have been able to separate the two components in a reasonably objective and repeatable manner.

In order to examine the limitations of the eclipse removal technique, the method was tested on a variety of simulated data. Naturally, any form of processing introduces systematic errors in determining the location of the contact points. The question to consider is whether or not the reduction in the random error for describing these points outweighs the systematic effects. It is convenient to think in terms of three parameters describing the extracted eclipse: the times of mid-ingress/egress, the duration of these events, and the depth of the feature. We expect heuristically that both the time of mid-ingress/egress and the depth of the eclipse will be accurately determined using this method with virtually no systematic errors introduced, and this is indeed borne out in tests on simulated data. The extent of the error in the duration of ingress and egress depends on the sharpness of the underlying eclipse and the filter lengths used in processing. Fortunately a real eclipse does not possess sharp discontinuities in gradient and the introduced systematic error is expected to be much smaller than statistical uncertainties such as those caused by the irregular flickering in these systems or that due to random noise in the data.

The scatter in measurements of the contact points using this technique is significantly smaller than those made on the same data by eye. Furthermore the method is both objective (and hence repeatable) and capable of a fully automatic implementation.

We feel that methods similar to this should be adopted in measuring the eclipse timings for this and other similar systems. We also note that, when the bright spot in such a system is sufficiently compact an extension of the method outlined here can be used to measure its times of ingress and egress and to remove its contribution from the light curve.

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