

Optical photometry of the eclipsing Large Magellanic Cloud supersoft source CAL 87

C. Alcock,^{1,2} R. A. Allsman,³ D. R. Alves,^{1,4} T. S. Axelrod,^{1,5} D. P. Bennett,^{1,2} P. A. Charles,⁶ K. H. Cook,^{1,2} D. O'Donoghue,⁷ K. C. Freeman,⁵ K. Griest,^{2,8} J. Guern,^{2,8} M. J. Lehner,^{2,8} M. Livio,⁹ S. L. Marshall,^{2,10} D. Minniti,¹ B. A. Peterson,⁵ M. R. Pratt,^{2,10} P. J. Quinn,⁵ A. W. Rodgers,⁵ K. A. Southwell,⁶ C. W. Stubbs,^{2,10,11} W. Sutherland⁶ and D. L. Welch¹²

¹Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

²Center for Particle Astrophysics, University of California, Berkeley, CA 94720, USA

³Supercomputing Facility, Australian National University, Canberra, ACT 0200, Australia

⁴Department of Physics, University of California, Davis, CA 95616, USA

⁵Mt Stromlo and Siding Spring Observatories, Australian National University, Weston, ACT 2611, Australia

⁶University of Oxford, Department of Astrophysics, Nuclear and Astrophysics Laboratory, Keble Road, Oxford OX1 3RH

⁷Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa

⁸Department of Physics, University of California, San Diego, CA 92093, USA

⁹Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

¹⁰Department of Physics, University of California, Santa Barbara, CA 93106, USA

¹¹Departments of Astronomy and Physics, University of Washington, Seattle, WA 98195, USA

¹²Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1

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ABSTRACT

We present optical photometry of the eclipsing supersoft source CAL 87. These observations comprise long-term data accumulated as a by-product of the MACHO Project, and high-speed, white-light photometry of a single eclipse. We (i) derive an improved ephemeris of $T_0 = \text{HJD } 245\,0111.5144(3) + 0.442\,677\,14(6)E$ for the time of minimum light, (ii) find the eclipse structure to be stable over a period of ~ 4 yr, and (iii) investigate the colour variation as a function of orbital phase. The resolution afforded by the high-speed nature of the white-light observations enables us to see new structure in the light-curve morphology.

Key words: accretion, accretion discs – binaries: close – binaries: spectroscopic – stars: individual: CAL 87 – Magellanic Clouds – X-rays: stars.

1 INTRODUCTION

CAL 87 is one of the prototypical members of the new class of low-mass X-ray binaries (LMXBs) which exhibit luminous ‘supersoft’ emission. The supersoft sources (SSSs) are characterized by their essential absence of emission above 0.5 keV, and extremely high luminosities ($L_{\text{bol}} \sim 10^{38}$ erg s⁻¹), of the order of the Eddington limit for a 1- $M_{\odot}$ accretor.

The original SSSs, CAL 83 and 87, were first detected in the Large Magellanic Cloud (LMC) in 1979–1980 with the *Einstein* X-ray Observatory (Long, Helfand & Grabelsky 1981). These systems exhibit the characteristic hallmarks of LMXBs, namely blue continua with strong emission lines of

He II 4686 and H α (e.g. Crampton et al. 1987; Pakull et al. 1988).

ROSAT observations have shown the SSSs to comprise a range of objects, including a planetary nebula nucleus (Wang 1991) and symbiotic systems (e.g. Hasinger 1994), although the CAL 83 type binaries are distinguished by the highest (near-Eddington-limited) luminosities. Although theories of black hole (Cowley et al. 1990) and neutron star accretors (Greiner, Hasinger & Kahabka 1991; Kylafis & Xilouris 1993) have been invoked for the latter systems, the most popular model involves a white dwarf undergoing stable nuclear surface burning (van den Heuvel et al. 1992). This has received observational confirmation in at least one system, RX J0513.9–6951, which exhibits a collimated

bipolar outflow (Crampton et al. 1996; Southwell et al. 1996). The observed jet velocities are of the order of 3800 km s^{-1} , which corresponds to the escape velocity of a white dwarf. Hence the nature of the accretor is established in at least one SSS (see, e.g., Livio 1997). The required accretion rates are high ($\gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$), and thus require a donor star more massive than the white dwarf in order to sustain thermally unstable mass transfer.

CAL 87 has been optically identified with a $V \sim 19$ mag blue star in the LMC (Pakull et al. 1988). Optical photometry revealed the system to be eclipsing, with an orbital period of 10.6 h (Callanan et al. 1989; Schmidtke et al. 1993). Although Cowley et al. (1990) proposed the accretory to be a black hole from an analysis of the $\text{He II } 4686$ velocities, this identification is highly questionable, particularly since accretion disc winds may bias the measurements (van den Heuvel et al. 1992). Recently, Schandl, Meyer-Hofmeister & Meyer (1997) were able to model successfully the gross features of the optical light curve, assuming the model of van den Heuvel et al. (1992).

We present here the results of ~ 4 years of optical monitoring of the source, the most extended coverage of this system to date. These observations were acquired as a by-product of the MACHO project (Alcock et al. 1995a), owing to the serendipitous location of CAL 87 in a surveyed field (see also Alcock et al. 1996). Furthermore, we have acquired high-speed, white-light photometry of a single eclipse, enabling us to investigate the detailed structure.

2 OBSERVATIONS AND REDUCTION

The MACHO observations were made using the 1.27-m telescope at Mount Stromlo Observatory, Australia. A dichroic beamsplitter and filters provide simultaneous CCD

photometry in two passbands, a ‘red’ band ($\sim 6300\text{--}7600 \text{ \AA}$) and a ‘blue’ band ($\sim 4500\text{--}6300 \text{ \AA}$). The latter filter is approximately equivalent to the Johnson V passband (see Alcock et al. 1995a for further details). The images were reduced with the standard MACHO photometry code SODOPHOT, based on point-spread function fitting and differential photometry relative to bright neighbouring stars. Further details of the instrumental set-up and data processing may be found in Stubbs et al. (1993), Marshall et al. (1994) and Alcock et al. (1995b).

The high-speed, white-light observations were made on 1996 January 28 using the SAAO 1.9-m telescope at Sutherland, South Africa. The detector was the UCT CCD, operating in frame-transfer mode. In this configuration only half of the chip is exposed, and at the end of the integration the signal is read out through the masked half. In this way we are able to obtain consecutive integrations with virtually no CCD dead-time. The effective wavelength of the instrument, in the absence of a filter, is approximately that of the Johnson V passband, but with a bandwidth of $\sim 4000 \text{ \AA}$ (FWHM). We initially used 10-s integrations, but later increased the exposure time to 20 s to obtain better signal-to-noise ratios. The images were reduced using the profile-fitting technique implemented in DAOPHOT (Stetson 1987).

3 MACHO PROJECT PHOTOMETRY

3.1 Overall morphology

We show in Fig. 1 the folded blue and red light curves. Each passband comprises 495 observations acquired from 1992 August to 1996 May, averaged into 50 phase bins. We use the ephemeris $T_0 = \text{HJD } 245\,0111.5144(3)$ for the time of

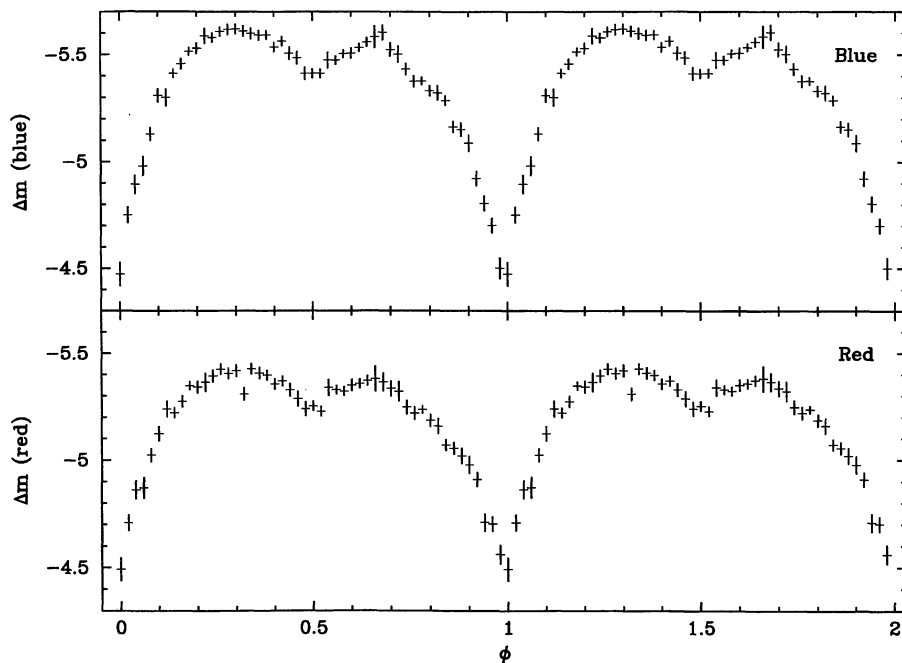


Figure 1. The blue (upper) and red (lower) optical light curves of CAL 87, blended with the contaminant stars (see Section 3.1), acquired from MACHO Project observations during 1992–1996. The data are folded on $T_0 = \text{HJD } 245\,0111.5144(3) + 0.442\,677\,14(6)E$ and averaged into 50 phase bins. Two cycles are plotted for clarity. The primary eclipse depth is affected by the dominating light of the field stars.

minimum light (see Section 4) and an orbital period of $P=0.442\,677\,14$ d (see Section 3.2 below). 1σ error bars are shown, and we plot two cycles for clarity. The absolute calibration of the MACHO fields and transformation to standard passbands are not yet complete; thus only the relative magnitudes are plotted.

We note that the light from CAL 87 is contaminated by two field stars which lie within 1 arcsec, and have recently been classified through *HST* observations as early-G- and late-A-type stars (Deutsch et al. 1996). The seeing at Mount Stromlo Observatory did not allow us to resolve these contaminants; thus the MACHO light curves include the contributions from these stars.

The principal features of the light curves are the deep, extended primary eclipse and shallower secondary dip at $\phi \sim 0.5$ (phase zero is defined as inferior conjunction of the donor star). During the primary eclipse the contaminant stars contribute $\lesssim 60$ per cent of the total light in *V* and *R* (Deutsch et al. 1996). Thus we do not see the full eclipse depth of CAL 87 since, at primary minimum, the light is dominated by the contribution of the contaminant stars. For example, in the blue light curve of Fig. 1, we see a primary eclipse depth of ~ 1.2 mag, compared with an expected intrinsic amplitude of 1.57 mag (Deutsch et al. 1996). The optical observations of Cowley et al. (1991) included a deblended *V* light curve with a primary eclipse depth of ~ 1.4 mag; this is consistent with the fact that one of the contaminant stars is not resolvable on their ground-based images, and was thus still contributing to the measured light.

Despite these contaminants, the light-curve *structure* is unaffected. The extended ingress of the primary eclipse is probably due to obscuration by an accretion disc bulge (e.g. Callanan et al. 1989), since the secondary itself could not occult the hot, inner-disc regions at phases $\phi \sim 0.7$. Follow-

ing the initial decline, which begins at $\phi \sim 0.7$, there is a ‘shoulder’ in the ingress throughout phases $\phi \sim 0.8$ – 0.9 . Furthermore, during the primary eclipse egress we see marginal evidence for a step at $\phi \sim 0.1$. However, these features are far more obvious in our high-speed light curve (Fig. 5); thus we reserve a discussion for Section 4.

A secondary dip is observed in both blue and red light curves at $\phi \sim 0.5$. In both cases, the amplitude of the dip is around 0.2 mag (we see the full intrinsic effect since, at this phase, the light from CAL 87 dominates the contaminants). A likely cause of the secondary dips is obscuration of the irradiated face of the donor star (van den Heuvel et al. 1992), although Callanan et al. (1989) favour an explanation in terms of a second accretion disc bulge, which occults the hot, inner-disc regions.

3.2 Light-curve stability and period analysis

In order to investigate the stability of the eclipse structure, we divided the data into four sections, each representing approximately one year’s worth of data. These blue and red light curves are shown in Figs 2 and 3. We see no significant changes in the overall morphology in either set of light curves during the ~ 4 -yr period from 1992 to 1996; furthermore, if we consider the data of Callanan et al. (1989) and Schmidtke et al. (1993), the stability may be extended back to ~ 1987 . However, we do note that the step in the egress at $\phi \sim 0.1$ sometimes seems more pronounced, particularly in the blue data of 1993–1994 (see Section 4 for an explanation).

We performed a power spectrum analysis on the red and blue datasets. A Lomb–Scargle (Lomb 1976; Scargle 1982) analysis indicated an orbital period of $P=0.442\,676 \pm 0.000\,007$ d, consistent with previous measurements (Schmidtke et al. 1993). However, combining our

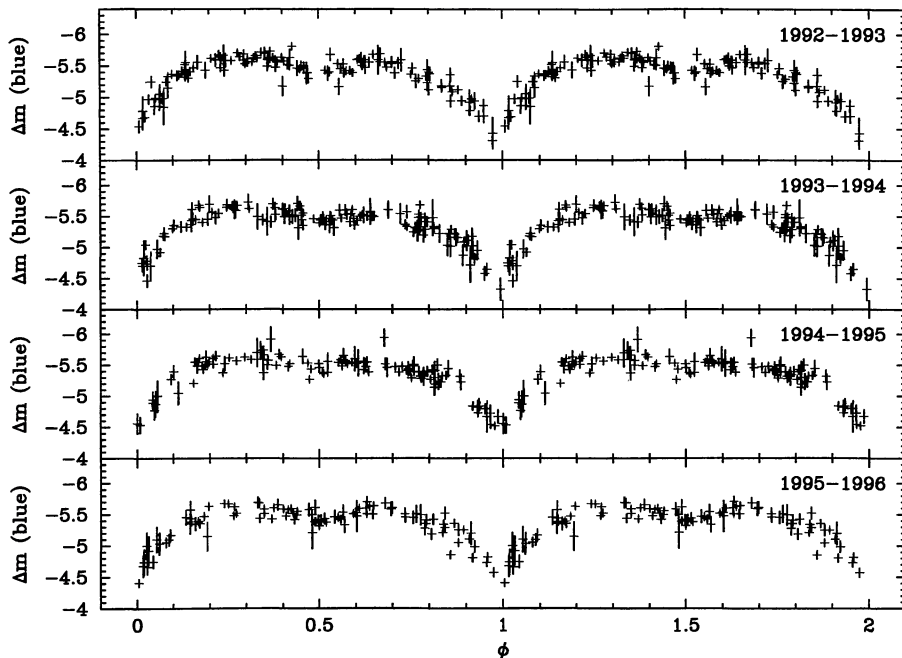


Figure 2. Blue light curves of CAL 87 + contaminants, split into ~ 1 -yr intervals. Two cycles of the unbinned folded data are plotted. The light-curve morphology is essentially stable during the 4 yr of observations.

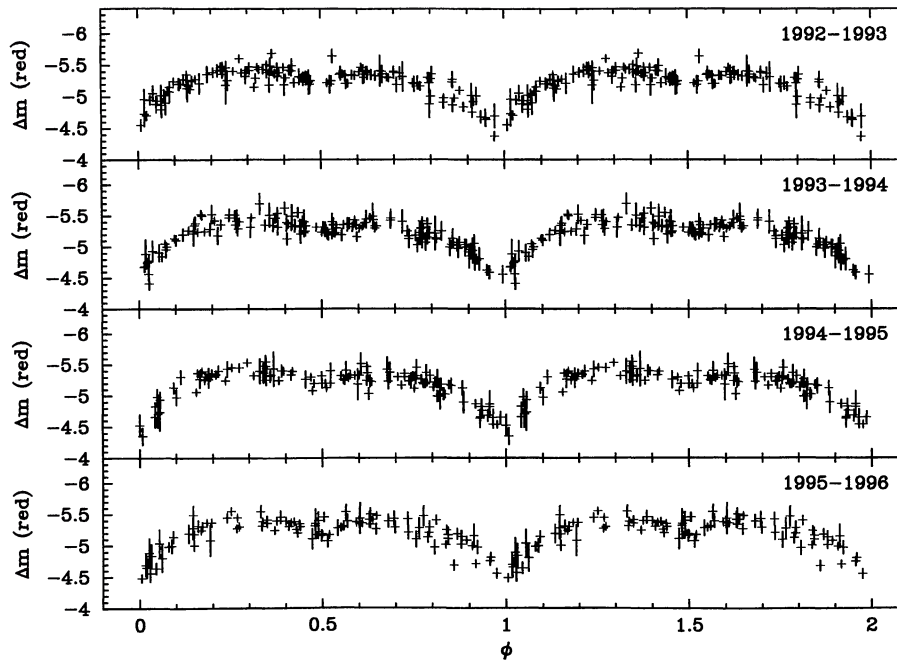


Figure 3. Red light curves of CAL 87 + contaminants, split into ~ 1 -yr intervals. Two cycles of the unbinned folded data are plotted. The light-curve morphology is essentially stable during the 4 yr of observations.

ephemeris (see Section 4) with that of Schmidtke et al. (1993) allows us to derive an improved orbital period of $P = 0.442\,677\,14 \pm 0.000\,000\,06$ d. A period analysis of each dataset failed to reveal any significant change in the orbital period over the 4 years of monitoring. From a consideration of the accuracy with which we are able to determine the period from 4 years of data, we derive an upper limit for the magnitude of any orbital period changes of $\dot{P} \lesssim 7 \times 10^{-8}$. This may be used to obtain an approximate upper limit on the mass-transfer rate (e.g. Robinson, Shetrone & Africano 1991), by assuming the main-sequence mass–radius relation for the secondary (e.g. Echevarría 1983), an equivalent volume Roche lobe radius relation (Paczynski 1971) and Kepler’s law. However, we find that the constraint on $\dot{P}$ is not stringent enough to yield a particularly useful result. We find an approximate upper limit on $\dot{M}$ of $\sim 7 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, which merely indicates that the accretion rate is sub-Eddington.

3.3 Orbital colour variation

As discussed in Section 3.1, the MACHO light curves represent the blended light of CAL 87 and the contaminant stars. However, the spectral types of these stars are sufficiently early that they have a virtually negligible effect on the orbital $V-R$ colour variation of CAL 87.

To demonstrate this, we plot the relative $V-R$ colour, folded on the orbital period, as a function of orbital phase in Fig. 4. We see a pronounced reddening of ~ 0.16 mag during the primary eclipse. However, we can be confident that this is not simply due to the changing contribution of the contaminant stars, since Deutsch et al. (1996) have quantified the effect. They observed the colour change during primary eclipse for both intrinsic and blended light

curves, finding that the amplitude differed by only ~ 0.03 mag between the two cases. Therefore, since we see a much larger effect, we conclude that this is an intrinsic variation which is consistent with the occultation of a hot, blue inner disc. Our value may be compared with the change of 0.21 mag found by Deutsch et al. (1996) in the blended $V-R$ colour.

There is also marginal evidence for a slight reddening centred on $\phi \sim 0.55$. This may be caused by the partial obscuration of the inner disc or the heated face of the donor star, although it is not clear whether the phase delay of 0.05, compared with the time of secondary minima in Fig. 1, is significant. We note that previous optical V -band observations (Callanan et al. 1989; Cowley et al. 1990; Schmidtke et al. 1993) indicate that the phase of the secondary minima in the optical light curves may be slightly variable ($\phi \sim 0.45$ – 0.55). The reddening throughout the primary eclipse is $\gtrsim 5$ times greater than in the dip at $\phi \sim 0.55$, although we stress that the latter may not be significant. Indeed, we find no explanation for the apparently anomalous data points at $\phi \sim 0.32$ and ~ 0.12 .

4 HIGH-SPEED PHOTOMETRY

We show in Fig. 5 the ‘real time’ white-light curve obtained from the SAAO observations. We plot the white-light counts relative to a local standard, although the absence of a filter prevents us from making an absolute calibration (the light is also blended with the contaminant stars). The errors on the data points are ~ 0.005 count, but rise for $\phi \gtrsim 0.15$ (these observations were made during morning twilight). We note a decrease in the scatter of the light curve for $\phi \gtrsim 0.85$, when we switched from 10- to 20-s integrations. However, it is also possible that we are seeing

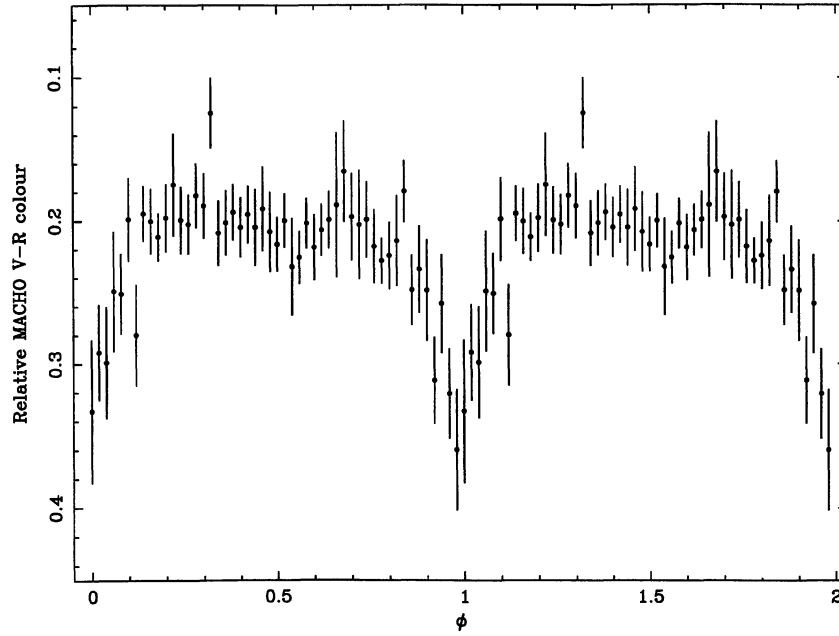


Figure 4. Relative $V-R$ colour of CAL 87 (and contaminant stars) plotted as a function of orbital phase. Note the pronounced reddening during the primary eclipse, and possible smaller dip at $\phi \sim 0.55$.

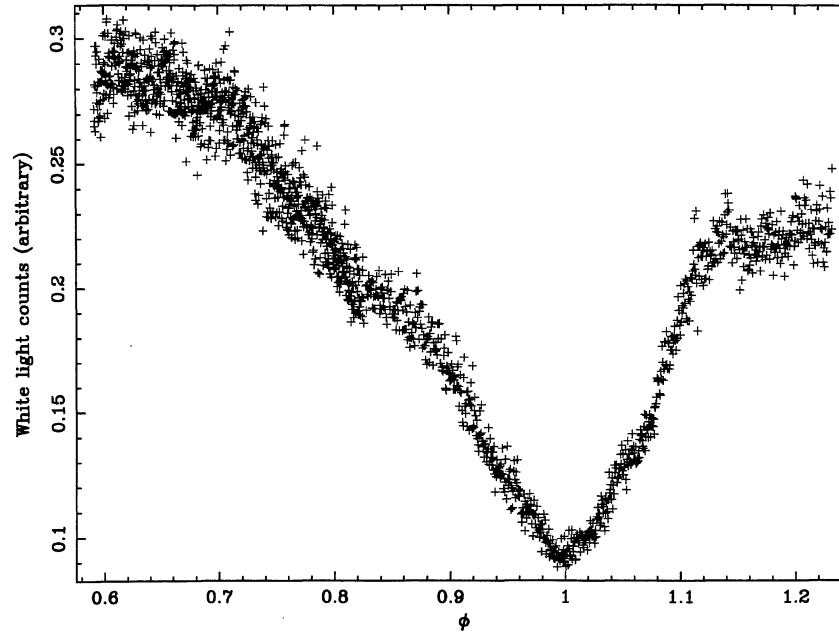


Figure 5. SAAO high-speed, white-light curve of CAL 87 + contaminants. The data are not folded and consist of 10- and 20-s integrations. Typical errors are ~ 0.005 count. Note the obvious structure at $\phi \sim 0.85$ and ~ 0.1 (see Section 4).

a visible contribution from the diminished effects of flickering as the disc is eclipsed, a phenomenon commonly observed in cataclysmic variables (see, e.g., Warner 1995). The time of minimum light was derived by fitting a parabola to the most symmetrical part of the eclipse centre ($\phi \sim 0.95-0.05$), and is found to be $T_0 = \text{HJD } 245\,0111.5144(3) + 0.442\,677\,14(6)E$.

The detailed morphology of the eclipse structure reveals several interesting features. In Fig. 5, we see an obvious shoulder in the ingress at $\phi \sim 0.82-0.87$, which is also apparent in the MACHO light curves of Fig. 1 (see also Callanan et al. 1989 and Cowley et al. 1990). The origin of this feature may probably be understood in terms of the variable obscuration by the thickened accretion disc rim.

Recently, Armitage & Livio (1996) have performed three-dimensional smooth particle hydrodynamic (SPH) simulations of accretion discs in LMXBs. In particular, they compute the column density profile towards the primary for a system inclination of 78° , which is probably appropriate for CAL 87 (Schandl, Meyer-Hofmeister & Meyer 1997). They find a strong peak centred on $\phi \sim 0.8$, which has declined by ~ 40 per cent at $\phi \sim 0.9$. Thus the gradient of our light-curve ingress appears to be qualitatively consistent with these model calculations, being steepest at the phase of maximum obscuration ($\phi \sim 0.8$), but levelling off as the column density declines towards $\phi \sim 0.9$. The rapid decline in the luminosity for $\phi > 0.9$ presumably occurs as the donor star itself begins to obscure our line of sight.

Within the deepest part of the primary eclipse ($\phi \sim 0.9-0.1$), we see suggestions of further structure at $\phi \sim 0.92, 0.96, 0.02$ and 0.06 . However, it is not clear that we can attach any physical significance to these points, given the accuracy of the data, and further observations are scheduled in order to investigate the repeatability of these features. Nevertheless, a very clear variation is observed in the egress for $\phi \gtrsim 0.1$. In this respect, the light curve of CAL 87 is reminiscent of certain eclipsing cataclysmic variables (e.g., Z Cha; Cook & Warner 1984). In the latter system, a marked turn-over is observed in the eclipse egress after the emergence of the primary star; then, following a short delay, the light curve rises again. This behaviour is attributed to the emergence of a ‘hotspot’, a highly luminous region on the disc rim caused by the accretion stream/disc interaction. In CAL 87, an analogous component may be the strongly irradiated inner surface of the accretion disc bulge. Indeed, Schandl et al. (1997) note that the existence of such a component is consistent with the fact that the luminosity is greater following an eclipse. The MACHO light curves in Figs 2 and 3 suggest that this feature is at some times more pronounced than others (see Section 3.2). This is probably not surprising, if indeed we are seeing the emergence of a variably irradiated region.

5 CONCLUSIONS

We find the light curve of CAL 87 to be essentially stable over a 4-yr period from 1992 to 1996, with an overall morphology consistent with earlier observations. We resolve structure in the primary eclipse at $\phi \sim 0.8-0.9$ and ~ 0.1 . These features are consistent with the presence of an accretion disc bulge, with a bright, irradiated inner surface. The orbital $V-R$ colour shows a pronounced reddening at primary eclipse and a probable smaller effect at $\phi \sim 0.55$, due to the obscuration of the primary/inner disc regions and the irradiated donor star respectively. We derive an improved orbital period of $P = 0.442\,677\,14(6)$ d, finding no evidence for a significant change in $\gtrsim 4$ yr.

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