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### **Citation**

Paradijs, J. van, Amerongen, S. van, Kool, M. de, Pakull, M., Deul, E. R., Lub, J., & Greve, A. (1984). Photometry of A0538 - 66 during an active and subsequent inactive state. *Monthly Notices Of The Royal Astronomical Society*, 210, 863-871. Retrieved from <https://hdl.handle.net/1887/6475>

Version: Not Applicable (or Unknown)

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## Photometry of A0538–66 during an active and subsequent inactive state<sup>★</sup>

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Accepted 1984 May 8. Received 1984 May 4; in original form 1984 March 12

**Summary.** We present the results of photometric observations of the optical counterpart of the recurrent X-ray transient A0538–66. Three outbursts were observed in 1982 April and May. During the period 1982 October–1983 February the source did not show outbursts. Combining our data with those of Densham *et al.* we find evidence for a secular decrease of the size of the outbursts throughout a period of activity. The interoutburst *UBV* properties of A0538–66 likewise show a progressive change. During the off-state A0538–66 shows small-amplitude variability, similar to that observed in some 'normal' Be stars. In the (*V*, *B–V*) and (*U–B*, *B–V*) diagrams both these variations and the secular variations of the previous interoutburst data lie along tracks which appear to be connected.

### 1 Introduction

A0538–66 is a periodically recurrent transient X-ray source which (when active) shows X-ray outbursts every 16.6 days (White & Carpenter 1978; Johnston *et al.* 1979; Johnston, Griffiths & Ward 1980; Skinner 1981). Together with the X-ray outbursts the optical counterpart (Johnston *et al.* 1980) shows a large increase in brightness (Skinner 1980). Spectroscopic observations of the optical counterpart have shown that it is located in the Large Magellanic Cloud (Johnston *et al.* 1980; Pakull & Parmar 1981; Charles *et al.* 1982). Consequently, the X-ray luminosity at maximum reaches values up to  $10^{39}$  erg s<sup>-1</sup>. A0538–66 is an X-ray pulsar, with a 69 ms pulse period (Skinner *et al.* 1982), and hence a neutron star.

<sup>★</sup>Based on observations made at the European Southern Observatory.

A0538–66 also shows extended periods of inactivity\*, during which no X-ray and optical outbursts are observed (Pakull & Parmar 1981; Pakull *et al.* 1982).

Photometry of a series of four consecutive optical outbursts has been reported by Densham *et al.* (1983). Their results show evidence for continued activity throughout the outburst cycle, and also suggest a progressive weakening of the outbursts.

Based on optical and UV observations Charles *et al.* (1982) and Densham *et al.* (1983) proposed a binary model for A0538–66, consisting of a  $\sim 1 M_{\odot}$  neutron star and a  $\sim 16 M_{\odot}$  primary star (spectral type B2III) in a 16.6 day (outburst period) eccentric ( $e \sim 0.7$ ) orbit.

During a period of activity forced tidal-lobe overflow of the primary occurs near periastron passage of the neutron star, which gives rise to the formation of an extended envelope around the primary. Accretion of matter from this envelope gives rise to the X-ray and optical outbursts. Through a series of subsequent periastron passages the envelope is thought to be both replenished by tidal-lobe overflow and to be dispersed (probably by radiation pressure). Within this model the long periods of activity and inactivity are the result of secular variations of the size of the primary.

To account for the long periods of inactivity Pakull & Parmar (1981) and Howarth *et al.* (1983) proposed that the formation of such an envelope around the primary is not due to forced tidal-lobe overflow, but to intrinsic activity of the primary star. They suggest that the primary star may undergo episodes of Be-type activity, during which a dense envelope is formed in the equatorial plane of the primary.

Information on the long-term outburst behaviour of A0538–66 may help in deciding what the mechanism is that governs the outburst activity in this system. Obvious aspects of these problems are: In which way does an episode of activity start and end? Is there a secular trend in the outburst behaviour? In an attempt to provide a data base for a possible answer to this sort of question we have started a long-term programme of photometric observations of A0538–66. In this paper we present the results of our observations, made in 1982 April/May, and between 1982 October and 1983 February. During the second period the source was inactive (*cf.* Pakull *et al.* 1982).

## 2 Observations

Observations were made between 1982 May and 1983 February (JD 2445100 to 2445400) with the Walraven five-colour photometer (see Lub & Pel 1977) on the Dutch 90-cm telescope at the European Southern Observatory. Usually, one or two observations were made per night, except during an outburst in 1982 May, when the source was observed continuously for  $\sim 3$  hr.

Each observation consisted of eight to 16 integrations of 32 s each, preceded and followed by four such integrations on the sky background. The observations were made using a 11 arcsec diaphragm. All measurements were taken relative to the nearby Walraven standard star HD 39844.

During 1982 November and December (JD 2445275 to 2445305) we made *UBV* (Johnson system) observations of A0538–66 with the Bochum 61-cm telescope at ESO. All observations were made through an 11 arcsec aperture. Each observation consisted of two to four integrations of  $\sim 2$  min in each of the *U*, *B* and *V* filters, alternated by similar integrations of the sky background. As a companion star we used star No. 2–6 from the list of Dachs (1972).

Observations were also made during 1982 April with the Walraven photometer on the 90-cm Dutch telescope. Two outbursts were detected during this period. However, a 16-arcsec diaphragm was then employed, and this has led to contamination of the signal with light from a

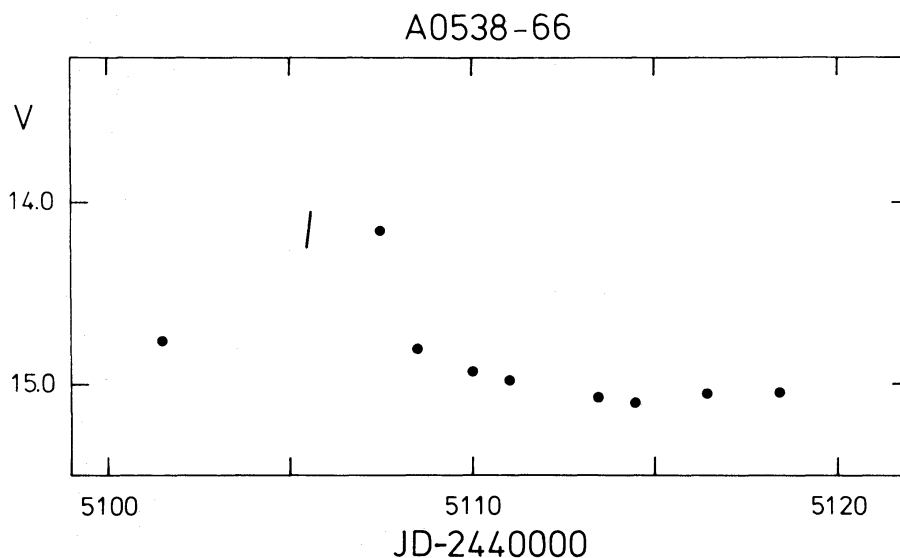
\*We use the terms 'off-state' and 'inactive' to indicate such a long-term state of A0538–66, during which no outbursts occur at all. We use the terms 'quiescent' and 'interoutburst' to indicate the state of A0538–66 between two consecutive outbursts during a single long period of outburst activity.

nearby 13.4 mag star located at  $\sim 16$  arcsec from A0538-66 (star R on the finding chart of Johnston *et al.* 1980). This contamination is clear from the level of quiescent brightness between outbursts Nos 99 and 100 (numbers according to the ephemeris\* of Skinner 1981), which lies at  $V=14.35\pm 0.05$ . This is substantially above the quiescent magnitude between the outbursts discussed by Densham *et al.* (1983) and that observed after the 1982 May outburst. Taking for the true quiescent level in 1982 April values between 14.6 and 15.0 (as indicated by the other observations at quiescence) the contamination corresponds to a star with a magnitude between 15.2 and 16.1. The quiescence data obtained in 1982 April have not been utilized in this paper. We have assumed that the same level of contamination was present during the observations made near outburst maxima. It turns out then, that the contamination does not seriously affect the result of these observations.

In order to combine all data we have transformed the Walraven data to the Johnson *UBV* system, using relations between the two photometric systems based on *UBV* data (Nicolet 1978) for the Walraven standard stars (Lub & Pel 1983, private communication). The transformations from  $V_W$  to  $V_J$ , and from  $(V-B)_W$  to  $(B-V)_J$  are well defined and single-valued. However, the significant difference in the *U* passbands of the two photometric systems shows up in a rather large scatter in the relation between  $(B-U)_W$  and  $(U-B)_J$  for early-type stars, increasing to a substantial divergence for late B-type stars of different luminosity class. We decided to use the average slope of the relation between  $(B-U)_W$  and  $(U-B)_J$  for early-type stars to derive  $(U-B)_J$  colours. For the comparison stars we used  $V=5.11$ ,  $B-V=-0.14$ ,  $U-B=-0.49$  (for HD 39844) and  $V=9.87$ ,  $B-V=0.24$ ,  $U-B=0.11$  (for Dachs No. 6). From observations of A0538-66 made during five nights in both photometric systems we find that no significant zero point error in  $U-B$  has been introduced in this way.

### 3 Results

The light and colour curves of A0538-66, obtained during 1982 May (JD 2445100-2445120), are shown in Figs 1 and 2. In spite of the incomplete coverage of the observations around maximum light it is clear that the 1982 May 17 outburst ( $N=101$ , according to Skinner's 1981 ephemeris)



**Figure 1.** Light curve (*V* band) of A0538-66 during 1982 May. The outburst near JD 2445105 has  $N=101$  according to the ephemeris of Skinner (1981).

\* Outbursts occur at  $JD=2443423.96+16.6515N$ .

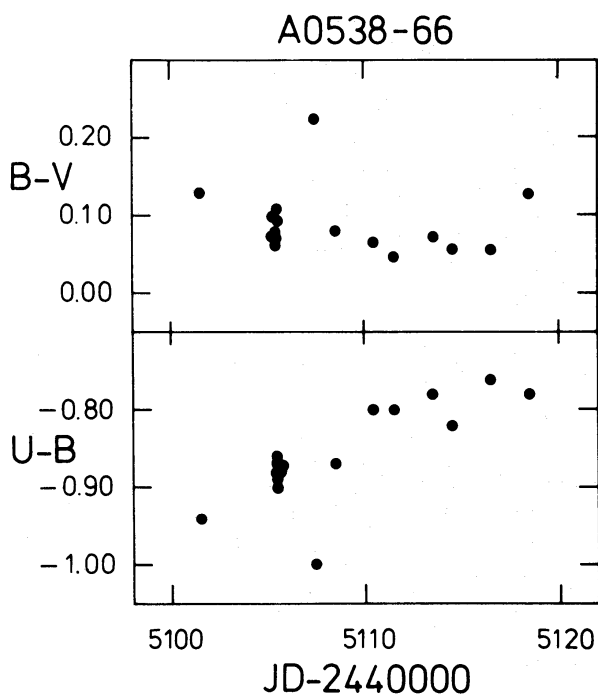


Figure 2. Variation of  $B-V$  and  $U-B$  during 1982 May.

reached a maximum brightness that was substantially smaller than those observed about five months earlier (Densham *et al.* 1983). We find that at maximum  $V \sim 13.3$ , with an estimated uncertainty of  $\sim 0.2$  mag.

If we apply the correction for contamination from the nearby star R to the 1982 April observations (see above), we find maximum magnitudes  $V \sim 13.1$  and  $\sim 12.8$  for outbursts Nos 99 and 100, respectively. The error due to the uncertainty in this correction is small ( $< 0.05$  mag), that due to incomplete coverage is estimated to be  $\sim 0.2$  mag.

Light and colour curves of A0538-66 during the period of inactivity (data covering the interval

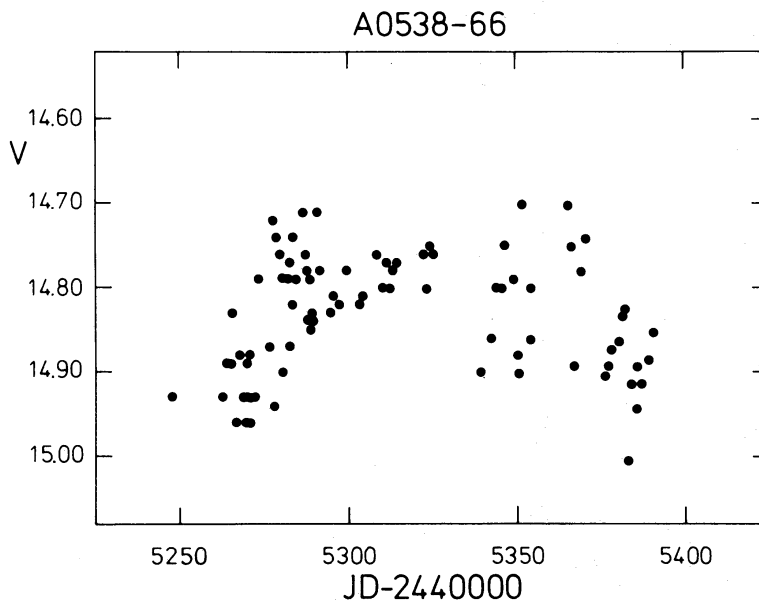


Figure 3. Variation of the  $V$  magnitude of A0538-66 during the period of inactivity between 1982 October and 1983 February (JD 2445240-2445400).

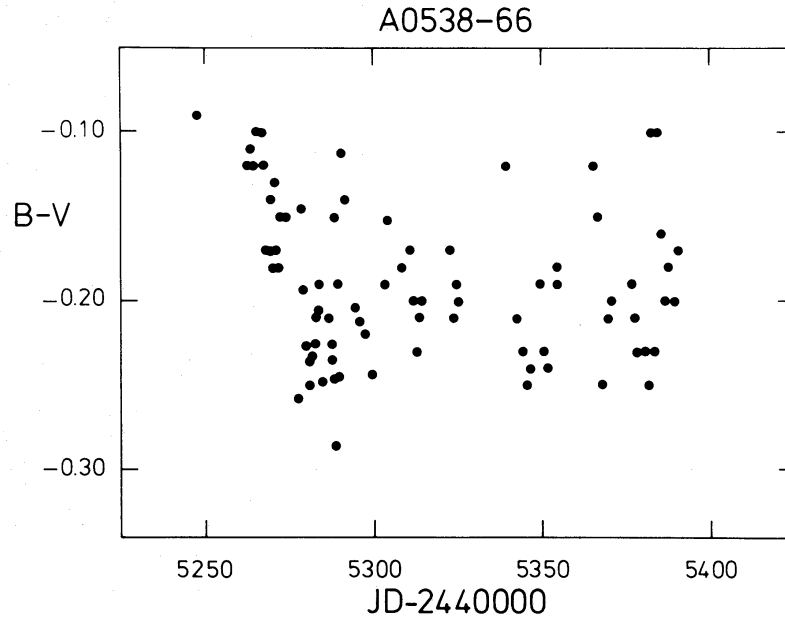


Figure 4.  $B-V$  variations of A0538-66 between 1982 October and 1983 February.

between 1982 October and 1983 February (JD 2445250–2445400)) are shown in Figs 3–5. The average visual magnitude and colour indices during this off-state were  $V=14.84\pm 0.05$ ,  $B-V=-0.19\pm 0.03$  and  $U-B=-0.91\pm 0.02$ . These values are in good agreement with off-state  $UBV$  data reported by Pakull & Parmar (1981). The standard deviations for a single data point are 0.06 mag in  $V$ , 0.04 mag in  $B-V$  and 0.03 mag in  $U-B$ .

#### 4 Discussion

From Figs 3 to 5 it appears that during the off-state the brightness and colours of A0538-66 show long-term changes, the source being slightly bluer by  $\sim 0.08$  mag in  $B-V$  and  $\sim 0.05$  mag in  $U-B$

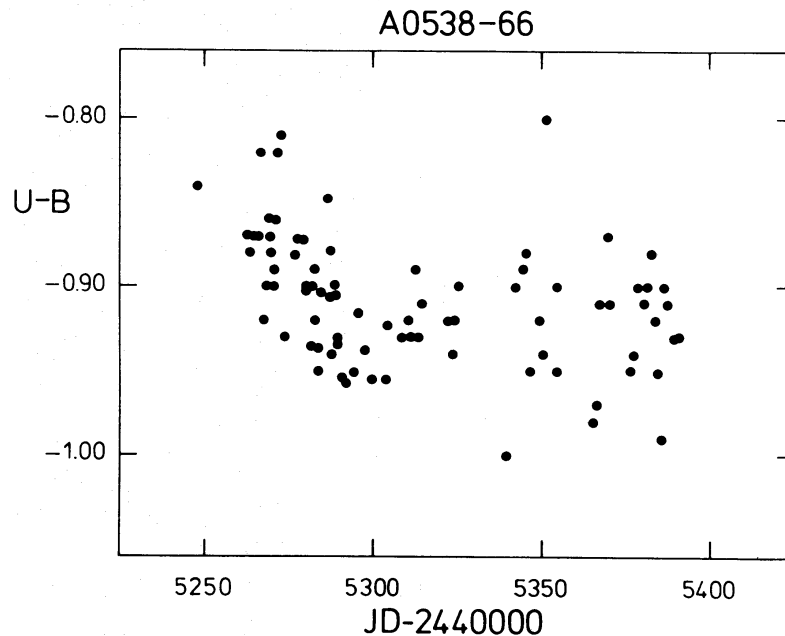
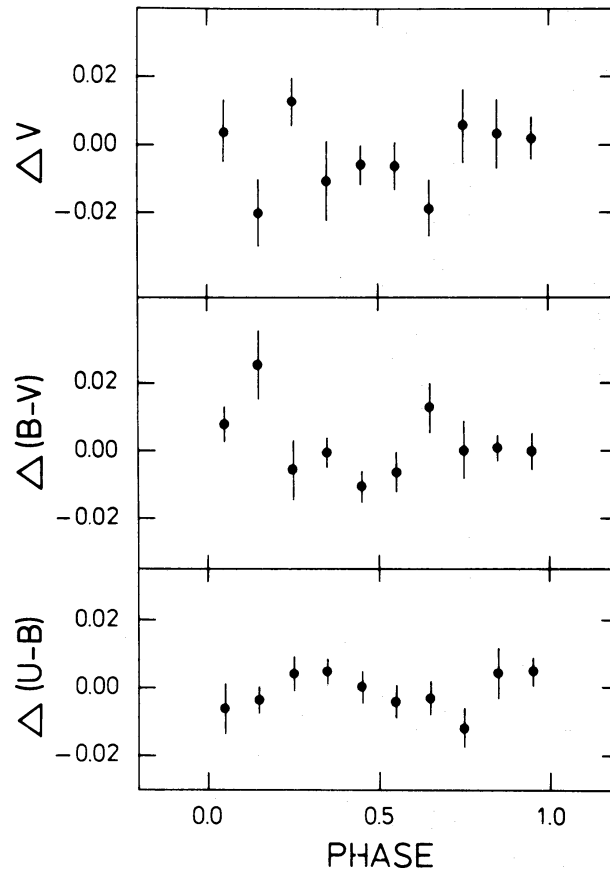


Figure 5.  $U-B$  variations of A0538-66 between 1982 October and 1983 February.



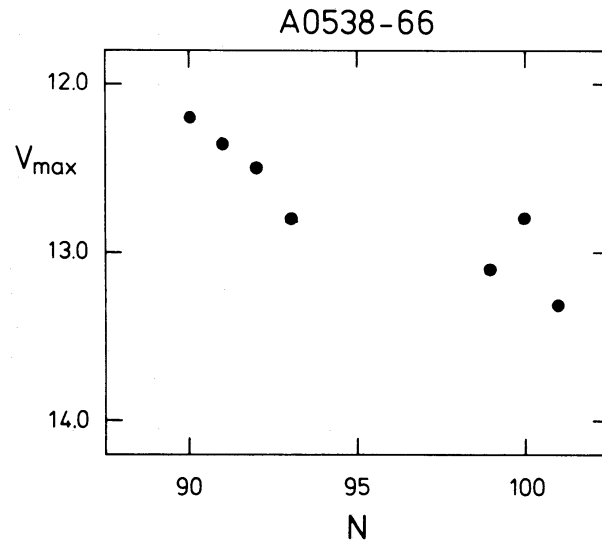
**Figure 6.** Orbital light and colour curves of A0538–66 during the off-state (JD 2445250–2445400). The phase has been determined using the ephemeris of Skinner (1981). The data have been averaged in phase bins of 0.1 cycle. The error bars indicate the mean error of the average value.

before JD 2445290 than after that date. The brightness in the  $V$  band increased by  $\sim 0.13$  mag between JD 2445260 and JD 2445280, then remained approximately constant for  $\sim 75$  day, and thereafter decreased by  $\sim 0.1$  mag. This indication for continued (low-level) variability during the off-state is supported by the presence of strong and variable  $H\alpha$  emission, found in spectra obtained in 1982 November and 1983 February by one of us (MP). (See also the paper of Smale *et al.* 1984.)

In order to detect a possible variation of the brightness and colours of A0538–66 during the off-state we have folded the residuals of  $V$ ,  $B-V$  and  $U-B$  (relative to the long-term average light and colour variations) using the ephemeris of Skinner (1981). The folded light and colour curves are shown in Fig. 6. No regular orbital modulation is visible, with amplitudes in excess of  $\sim 0.02$  mag in  $V$ , 0.02 mag in  $B-V$  and 0.01 mag in  $U-B$ . This confirms the result found by Smale *et al.* (1984).

The long-term behaviour of the outbursts between 1981 November and 1982 May (JD 2444920–2445120) is represented in Fig. 7, where we have plotted the visual magnitude at outburst maximum as a function of their sequence number  $N$  (Skinner's ephemeris, 1981). This figure suggests that the outburst behaviour of A0538–66 undergoes a secular change, with the outburst becoming progressively weaker through a period of activity.

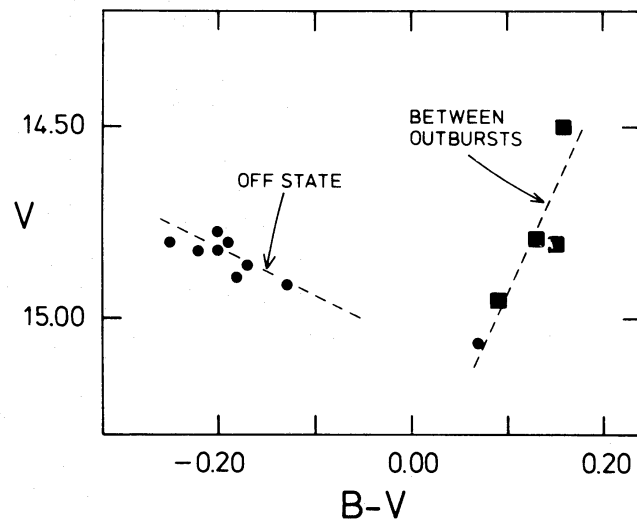
During an activity period the quiescent colours also show a secular trend. During the quiescent state following the 1982 May outburst ( $N=101$ ) we find for the average colour indices of A0538–66  $B-V=0.07\pm 0.02$  and  $U-B=-0.80\pm 0.03$ , substantially bluer than the quiescent colours reported by Densham *et al.* (1983). This confirms a trend already noticed by Densham *et al.* (1983).



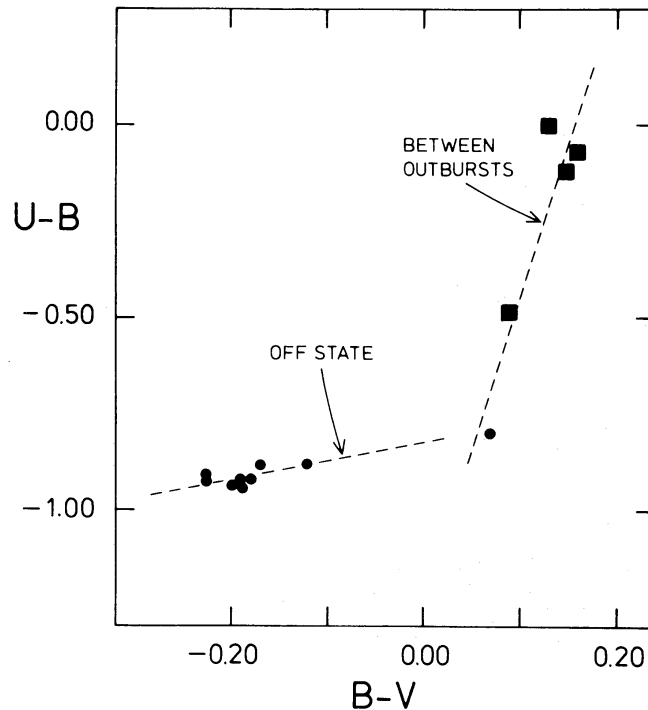
**Figure 7.** Long-term variation of the visual magnitude  $V_{\max}$  at outburst maximum. The numbering of the maxima is according to the ephemeris of Skinner (1981). The estimated accuracy of  $V_{\max}$  is  $\pm 0.2$  mag. The data for the outbursts near  $N=90$  were obtained from Densham *et al.* (1983).

The long-term trend in the average non-outburst  $UBV$  data is illustrated in Figs 8 and 9, where we have plotted the average  $V$  and  $U-B$  versus  $B-V$ , combining quiescence data obtained between the outbursts observed by Densham *et al.* (cycles 89-92) and that observed in 1982 May, (cycle 101) with the off-state data.

There is a gap of about five months in the observations between the period when the source was active and when it was inactive. However, linear extrapolations of the off-state data in these diagrams join the average relations for the interoutburst data reasonably well. This suggests that there is perhaps a more or less continuous long-term change in the quiescent  $UBV$  properties of



**Figure 8.** Relation between  $V$  and  $B-V$  for A0538-66, as observed between outbursts (1981 November-1982 May; JD 2444920-2445120) and during the subsequent off-state (1982 October-1983 February; JD 2445250-2445400). The interoutburst data combine those given by Densham *et al.* (1983), and those observed by us in 1982 May. The off-state data are average magnitudes taken over time intervals of order 10 day. Typical errors in the mean values of  $V$  and  $B-V$  are  $\sim 0.03$  mag and  $\sim 0.015$  mag, respectively. The interoutburst data and the off-state data lie along tracks which seem to join near  $V \sim 15.2$  and  $B-V \sim 0.0$ . The straight lines drawn in the figure are linear least-squares fits. Data taken from Densham *et al.* (1983) are indicated by squares; data presented in this paper by dots.



**Figure 9.** Relation between  $U-B$  and  $B-V$  for A0538–66, as observed between outbursts (1981 November–1982 May) and during the subsequent off-state (1982 October–1983 February). Typical errors in the mean value are  $\sim 0.03$  mag and  $\sim 0.015$  mag in  $U-B$  and  $B-V$ , respectively. The interoutburst data and the off-state data lie along tracks which seem to join near  $U-B \approx -0.80$  and  $B-V = 0.05$ . Data taken from Densham *et al.* (1983) are indicated by squares; dots indicate data presented in this paper.

A0538–66 throughout a period of activity into a subsequent off-state. (Such a relation is not apparent when interoutburst data, obtained during different periods of activity are combined; see table 1 in Densham *et al.* 1983.)

Densham *et al.* (1983) have suggested that such a systematic change of the  $UBV$  properties of A0538–66 is due to a secular change of the envelope around the primary. Correlated long-term variations in  $V$ ,  $B-V$  and  $U-B$  have been observed for many Be stars (Hirata 1982), and they are believed to be due to variations in the properties of the envelopes surrounding these objects (for models see e.g. Poekert & Marlborough 1978).

The variations of A0538–66 during the off-state can be described approximately by  $\alpha = \Delta V / \Delta(B-V) \sim +1$  and  $\beta = \Delta(U-B) / \Delta(B-V) \sim 0.5$ . These values fit nicely into the  $(\alpha, \beta)$  diagram covered by the Be stars (Hirata 1982). This suggests that the low-amplitude photometric variability of A0538–66 during the inactive state may be of a similar nature to that observed for normal Be stars.

On the other hand the interoutburst colour–magnitude relation is described by  $\alpha \sim -3$  and  $\beta \sim +8$ , which lie completely outside the range covered by the Be stars. With very few exceptions the latter have values of  $\alpha$  and  $\beta$  obeying the constraint  $\alpha/\beta \geq 0$ , i.e.  $\Delta V / \Delta(U-B) \geq 0$ . Thus, when Be stars become brighter, they also become bluer in  $U-B$ . Such a result is also obtained from the model calculations of Poekert & Marlborough (1978), and is independent of the inclination of the equatorial plane in their models. The  $U-B$  variations are mainly the result of changes in the bound–free (Balmer continuum) emission of the envelope, and Balmer continuum absorption by the envelope of the stellar light. Apparently, during its evolution through a series of outbursts the envelope of A0538–66 changes in such a way as to give rise to a fainter quiescent  $V$  brightness together with a bluer  $U-B$  colour index.

We do not pretend to have an obvious explanation for this unique behaviour. It could be the result of a decrease in the optical depth of the envelope towards the end of the period of outburst activity, related to a progressive dispersal of the envelope due to radiation pressure exerted during outbursts (Densham *et al.* 1983). This could give rise to a decrease of the bound-free absorption in the Balmer continuum, as measured by the  $U-B$  colour index. Another factor, which could be of importance, is the presence of some residual X-ray emission between outbursts, decreasing through an activity period. Some earlier X-ray outbursts have been observed to last for a significant fraction of the 16.6 day outburst cycle (Skinner *et al.* 1980). Finally, it is possible that throughout a period of activity major long-term changes occur in the geometry of the envelope which, perhaps, at the end of the activity settles into a state comparable to that of normal Be stars. After the system has been in an inactive state for an extended time interval this remnant Be type envelope can apparently disappear completely (see Pakull & Parmar 1981) and the primary of A0538-66 turns into a normal B2 III star. This is confirmed by the spectrum shown by Pakull & Parmar (1981) and by our most recent spectrum (1984 February), which shows that the  $H\alpha$  emission has disappeared completely.

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