Polarimetric analysis of mass transfer in the X-ray transient A0538 – 66

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Summary. New observations are reported of the optical polarimetric variations of the recurrent X-ray transient A0538 – 66 during outburst 99 (1982 April). These are utilized, together with data from outburst 75, to study the redistribution of gas in the system during periastron passage.

The observations exhibit a rapid ≈ 90° change in polarimetric position angle \( \phi \) and a large increase in the degree of polarization \( p \) very close to periastron, both changes persisting much longer than the photometric decay time. A number of interpretations are excluded by these data. In particular the slow decay of \( \Delta p \) and \( \Delta \phi \) are incompatible with the predominance of scattering of light from one star off material around the other, due to the rapid geometric changes in the highly eccentric orbit and regardless of the orbital elements.

It is shown that the data are broadly compatible with the polarization arising from light predominantly from the primary (Be-star) neighbourhood which is scattered off a Be-star type disc and a large gas cloud created near periastron by the neutron star passage. This cloud, which has a mass comparable to that accreted by the neutron star to produce the X-ray burst, has to persist near the periastron direction for longer than the Keplerian rotation time of the inner Be-star disc. An orbit inclined to the Be-star disc plane, suggested by several authors, is not demanded by the available data, but is not excluded either.

1 Introduction

The X-ray transient A0538 – 66, more properly known as 0535-668 (Hutchings et al. 1985) in the Large Magellanic Cloud has been observed extensively since its discovery in 1977 (White & Carpenter 1978; Johnston et al. 1979), largely due to its well established optical counterpart.

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Physically these observations are interpreted in terms of a neutron star in a highly eccentric orbit about a B-star primary, the outbursts occurring near periastron as the neutron star skims the outer layers of the B-star (Charles et al. 1983; Skinner et al. 1982). However, the system sometimes turns into an ‘off’ state showing no outbursts for several years. This may be interpreted in terms of small readjustments in the primary radius corresponding (for small values of the primary atmospheric scale height as a fraction of radius) to large changes in the primary atmospheric density at the periastron point (Brown & Boyle 1984). Analysis of the optical and near-UV data (Charles et al. 1983; Densham et al. 1983) suggest that the primary increases considerably in effective size during outburst and remains large well after periastron passage. Analysis of the X-ray light curve, and in particular its asymmetry about periastron, has led Apparao (1985) to propose a model in which the neutron star orbits a B-star with a characteristic equatorial disc but with the orbit highly inclined to the disc plane (cf. Johnston et al. 1979). However, it is not clear that an inclined orbit is necessary to produce asymmetry in the X-ray light curve when account is taken of the differing radial velocities pre- and post-periastron and of the fact that accreted matter must have a finite residence time in the accretion disc so that \( L_x \propto \dot{M} \) is not proportional to \(-\dot{M}_{\text{primary}}\) at each instant (Brown & Boyle 1984), as assumed by Apparao (1985). Such conclusions about the system (Densham et al. 1983; Apparao 1985) rest to some extent on ad hoc assumptions about the geometric interpretation of the spectrophotometric data. In principle, however, more direct information about the geometry of the system is obtainable by means of polarimetric observations (Brown et al. 1982; Boyle 1984).

Clayton & Thompson (1982; hereafter CT) reported variable linear polarization coincident with the optical outburst. They found that the broad-band optical polarization rose from near zero to almost 2 per cent around phase 0.0 of the outburst of 1981 March 10 [outburst no. 75 according to the ephemeris of Skinner (1981)]. The polarization subsequently decayed but more gradually than the optical brightness, being still over 1 per cent when the system had returned to near its pre-outburst brightness. CT also noted that the position angle of the polarization varied during the outburst. They suggested an electron scattering model for their polarization data in which most of the excess light occurs near periastron, when the compact companion in a highly inclined orbit intersects a gaseous disc surrounding the primary B-star, accounting for the sudden onset of the polarization increase. An enhanced mass loss to the disc from the B-star was proposed to account qualitatively for the sustained polarization enhancement. Changing scattering geometry, due to orbital motion of the secondary and shifting of the main centre of the light emission from the primary to the secondary and back, were suggested as sources of variation in the polarization direction.

Simmons & Boyle (1984; hereafter referred to as SB) gave an alternative interpretation of the CT data in which the variable degree of polarization was shown to be interpretable entirely in terms of the variable scattering geometry of the system, as the companion swung rapidly through periastron, without any change in the physical amount or distribution of scattering matter. The SB analysis ignored changes in polarimetric position angle and required a periastron longitude \( \lambda_p \) satisfying \( 270^\circ \leq \lambda_p \leq 360^\circ \) or \( 90^\circ \leq \lambda_p \leq 180^\circ \), and the occurrence of an optical light maximum substantially before periastron (phase \( \approx 0.86 \)).

Since the CT data and SB analysis, we have obtained polarimetric data during a further outburst of A0538 – 66 and there have been two further attempts at determining the spectrophotometric orbital elements (Corbet et al. 1984; Hutchings et al. 1985). It is the purpose of
Table 1. Observations.

<table>
<thead>
<tr>
<th>JD</th>
<th>Cycle</th>
<th>Phase</th>
<th>$p \pm \sigma_p$</th>
<th>$\phi \pm \sigma_\phi$</th>
<th>$p' \pm \sigma_{p'}$</th>
<th>$\phi' \pm \sigma_{\phi'}$</th>
<th>$Q'$</th>
<th>$U'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4668.58</td>
<td>74</td>
<td>0.745</td>
<td>0.17 ± 0.21</td>
<td>116.0 ± 52.0</td>
<td>0.39 ± 0.21</td>
<td>104.9 ± 15.6</td>
<td>-0.34</td>
<td>-0.19</td>
</tr>
<tr>
<td>4670.57</td>
<td>74</td>
<td>0.864</td>
<td>0.25 ± 0.22</td>
<td>41.9 ± 24.7</td>
<td>0.28 ± 0.22</td>
<td>68.4 ± 22.4</td>
<td>-0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>4671.62</td>
<td>74</td>
<td>0.927</td>
<td>0.08 ± 0.16</td>
<td>36.5 ± 52.0</td>
<td>0.21 ± 0.17</td>
<td>88.0 ± 23.0</td>
<td>-0.21</td>
<td>0.02</td>
</tr>
<tr>
<td>4672.62</td>
<td>74</td>
<td>0.987</td>
<td>0.51 ± 0.08</td>
<td>62.9 ± 4.4</td>
<td>0.64 ± 0.09</td>
<td>73.1 ± 3.9</td>
<td>-0.53</td>
<td>0.35</td>
</tr>
<tr>
<td>4673.52</td>
<td>75</td>
<td>0.041</td>
<td>1.66 ± 0.10</td>
<td>74.2 ± 1.7</td>
<td>1.84 ± 0.10</td>
<td>76.9 ± 1.6</td>
<td>-1.65</td>
<td>0.81</td>
</tr>
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<td>4673.76</td>
<td>75</td>
<td>0.056</td>
<td>1.24 ± 0.11</td>
<td>73.9 ± 2.5</td>
<td>1.41 ± 0.12</td>
<td>77.4 ± 2.3</td>
<td>-1.28</td>
<td>0.60</td>
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<tr>
<td>4674.52</td>
<td>75</td>
<td>0.101</td>
<td>1.44 ± 0.11</td>
<td>90.9 ± 2.2</td>
<td>1.68 ± 0.12</td>
<td>91.8 ± 2.0</td>
<td>-1.68</td>
<td>-0.10</td>
</tr>
<tr>
<td>4674.72</td>
<td>75</td>
<td>0.114</td>
<td>1.59 ± 0.21</td>
<td>90.6 ± 3.7</td>
<td>1.83 ± 0.21</td>
<td>91.4 ± 3.3</td>
<td>-1.83</td>
<td>-0.09</td>
</tr>
<tr>
<td>4675.69</td>
<td>75</td>
<td>0.172</td>
<td>1.22 ± 0.14</td>
<td>96.1 ± 3.4</td>
<td>1.46 ± 0.15</td>
<td>96.2 ± 2.9</td>
<td>-1.43</td>
<td>-0.32</td>
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<tr>
<td>4676.68</td>
<td>75</td>
<td>0.232</td>
<td>0.94 ± 0.20</td>
<td>91.3 ± 6.0</td>
<td>1.18 ± 0.20</td>
<td>92.5 ± 4.9</td>
<td>-1.17</td>
<td>-0.10</td>
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<tr>
<td>4677.59</td>
<td>75</td>
<td>0.286</td>
<td>0.90 ± 0.19</td>
<td>92.0 ± 5.9</td>
<td>1.14 ± 0.19</td>
<td>93.1 ± 4.8</td>
<td>-1.13</td>
<td>-0.12</td>
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<tr>
<td>5062.50</td>
<td>98</td>
<td>0.402</td>
<td>0.50 ± 0.08</td>
<td>167.7 ± 4.6</td>
<td>0.34 ± 0.09</td>
<td>154.9 ± 7.3</td>
<td>0.22</td>
<td>-0.26</td>
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<tr>
<td>5063.49</td>
<td>98</td>
<td>0.462</td>
<td>0.50 ± 0.08</td>
<td>150.5 ± 4.7</td>
<td>0.48 ± 0.09</td>
<td>136.4 ± 5.3</td>
<td>0.02</td>
<td>-0.49</td>
</tr>
<tr>
<td>5070.48</td>
<td>98</td>
<td>0.882</td>
<td>0.45 ± 0.11</td>
<td>141.3 ± 6.8</td>
<td>0.52 ± 0.11</td>
<td>127.6 ± 6.3</td>
<td>-0.13</td>
<td>-0.50</td>
</tr>
<tr>
<td>5071.50</td>
<td>98</td>
<td>0.943</td>
<td>0.59 ± 0.09</td>
<td>158.5 ± 4.5</td>
<td>0.50 ± 0.10</td>
<td>146.8 ± 5.7</td>
<td>0.20</td>
<td>-0.46</td>
</tr>
<tr>
<td>5072.48</td>
<td>99</td>
<td>0.001</td>
<td>0.70 ± 0.06</td>
<td>170.8 ± 2.7</td>
<td>0.51 ± 0.07</td>
<td>163.5 ± 4.2</td>
<td>0.43</td>
<td>-0.28</td>
</tr>
<tr>
<td>5072.50</td>
<td>99</td>
<td>0.002</td>
<td>0.52 ± 0.06</td>
<td>178.6 ± 3.1</td>
<td>0.30 ± 0.07</td>
<td>172.0 ± 6.3</td>
<td>0.29</td>
<td>-0.08</td>
</tr>
<tr>
<td>5073.50</td>
<td>99</td>
<td>0.062</td>
<td>0.30 ± 0.05</td>
<td>62.1 ± 4.7</td>
<td>0.44 ± 0.06</td>
<td>77.3 ± 4.0</td>
<td>-0.40</td>
<td>0.19</td>
</tr>
<tr>
<td>5073.52</td>
<td>99</td>
<td>0.063</td>
<td>0.32 ± 0.06</td>
<td>77.7 ± 5.4</td>
<td>0.53 ± 0.07</td>
<td>85.9 ± 3.9</td>
<td>-0.52</td>
<td>0.08</td>
</tr>
<tr>
<td>5074.50</td>
<td>99</td>
<td>0.122</td>
<td>1.14 ± 0.08</td>
<td>76.9 ± 2.1</td>
<td>1.33 ± 0.09</td>
<td>80.2 ± 2.0</td>
<td>-1.25</td>
<td>0.44</td>
</tr>
<tr>
<td>5074.52</td>
<td>99</td>
<td>0.124</td>
<td>1.10 ± 0.08</td>
<td>74.8 ± 2.2</td>
<td>1.28 ± 0.09</td>
<td>78.5 ± 2.0</td>
<td>-1.18</td>
<td>0.50</td>
</tr>
</tbody>
</table>
this paper to reconsider the CT and SB interpretations of the polarimetry of this system in the light of these new data and orbital elements.

2 New observations

Further polarimetric observations were obtained in 1982 April on the 2.5-m Dupont telescope at Las Campanas Observatory. The University of Western Ontario’s two-channel photoelectric Pockels cell polarimeter (Angel & Landstreet 1970) was used to measure linear polarization. The observations were unfiltered so the bandpass (3200–8600 Å) was determined by the atmospheric transmission and the response of the GaAs photomultipliers (RCA 31034A). The observations were corrected for instrumental efficiency and sky polarization. Observations of interstellar polarization and null standards (Serkowski 1973; Serkowski, Mathewson & Ford 1975) were used to reduce the position angle to the standard equatorial system and to check for instrumental polarization, respectively. The errors reported below are linear error estimates for photon-counting statistics only. Uncertainties in sky correction, interstellar polarization, and rapid stochastic variations in the source itself (cf. Simmons & Stewart 1985) will increase these errors substantially at times of low polarized flux prior to the outbursts. Galactic foreground polarization was determined through observations of Dachs No. 20, a star lying only 2 arcmin from the A0538 – 66 line-of-sight. An average of four observations of this star gives $p = 0.24 \pm 0.04$ per cent, $\phi = 7\dgr 1 \pm 4\dgr 4$. This is very close to the foreground value used by CT.

The observations corrected for foreground are given in Table 1. Observations made while the moon was up, which are considered somewhat uncertain, are marked with a colon in Table 1. In addition, the observations used in CT have been adjusted to the new estimate of the galactic foreground and are also listed in Table 1. Figs 1 and 2 show, respectively, the values of

![Figure 1](image-url)  

**Figure 1.** A plot of the magnitude and position angle of polarization for both outbursts, plotted against phase using the ephemeris of Skinner (1981). The filled squares represent observations from outburst 75 (CT) and the open squares represent the new data reported here from outburst 99. The error bars plotted here represent 1 $\sigma$. The plotted observations are corrected for foreground interstellar polarization (see text).
$p$, $\phi$, $Q$, and $U$ (in the equatorial system) plotted against binary phase (using the Skinner ephemeris), in which the CT observations (filled squares) are from outburst 75, while the new data (open squares) are from outburst 99. In Fig. 3, we show the corresponding photometric variations during outbursts 75 and 99. The relative 'photometry' from CT has been re-plotted. These observations have now been scaled using some coincident B-band photometry (Tuohy 1981, private communication). Differential photometry between A0538−66 and Dachs No. 20 was obtained coincident with the new observations using a 10.4 arcsec aperture and the polarimeter count rates. The peak magnitude agrees well with the $V = 13.1 \pm 0.2$ reported by van Paradijs et al. (1984). To assist in the interpretation, we show in Fig. 4 a plot of the data for the two outbursts in terms of the locus described in the $Q-U$ plane.

Reference to Fig. 1(a) shows that in both outbursts the main feature is a rapid rise in the degree of polarization in the phase range 0.00–0.05 followed (after phase 0.1) by a comparatively slow decline on a time-scale considerably longer than that for the brightness of the system to decline (see Fig. 3). There is some indication that the polarization rise in outburst 99 occurs at a later phase and has a more prolonged light maximum than outburst 75, but the phase sampling of the data remains too sparse to quantify these differences. Note that the quiescent brightness of the A0538−66 system differs by more than 1 mag between outbursts 75 and 99.

Fig. 1 suggests an apparently discrepant behaviour in the position angle between the two outbursts. However, the pre-outburst position angles in outburst 75 are rather poorly determined (noted by CT and SB) as can be seen from the (underestimated) formal errors in Fig. 1 at those phases. Therefore, we will henceforth discount these data for position-angle interpretation.* Then the main feature in the behaviour of $\phi$ with phase is a possible slight increase just before phase 0.0, followed by a rapid rotation through about $-90^\circ$ at phase 0.00–0.05, and then by a slow recovery. In terms of the $Q-U$ plane in Fig. 4, this can be seen in the form of a rapid near-linear transformation, mainly in the $-Q$ direction, changing $Q$ from positive to negative values ($180^\circ$ rotation in the $Q-U$ plane $\equiv 90^\circ$ in $\phi$) followed by a trend at about right angles to this line (i.e. roughly in the $-U$ direction), with $Q$ moving back to less-negative values. Again the data are too undersampled to see detailed behaviour near phase zero or to see detailed differences between outbursts. In Fig. 4, we also show a set of axes ($Q_0$, $U_0$), used later, which are rotated by $12^\circ$ from ($Q_0$, $U$) on the sky ($24^\circ$ in the $Q-U$ plane) so that the rapid change in $p$ lies along the $Q_0$ axis.

3 Qualitative interpretation

As is the case with spectrophotometry, the polarimetric light-curve modelling of an eccentric binary is a multi-parameter problem, demanding intensive observational coverage for an unambiguous solution. Thus, even with the improved spectrophotometric data and analysis of recent years (Hutchings et al. 1985; Corbet et al. 1984) there remains considerable doubt about the values of the orbital elements, some of the elements calculated by the two groups not agreeing at all, though a large eccentricity seems to be unanimously required. Because of the active nature of the A0538−66 system, the presence of small amounts of emission may affect the radial velocity measurements. In particular, Hutchings et al. (1985) comment that the mean spectrum of Corbet et al. (1984) contains blueshifted emission at H$\beta$, indicating that the star

*If the pre-outburst $\phi$ values were truly different the implications would be fascinating but problematic. They would imply a 90° rotation on the sky of the principal scattering plane in the non-outburst system, which would be normally taken as the plane of a Be-star disc. Such a rotation might be attributed to major disruption of the disc in a preceding outburst by the action of a companion in an orbit highly inclined to the preceding disc plane. It is hard, however, to see why repetition of such disturbances would not have quickly led to alignment of the disc and orbital axes.
Figure 2. A plot of $Q$ and $U$ against phase for the same observations specified in Fig. 1. The symbols are the same as in Fig. 1.

Figure 3. Photometry of A0538–66 taken during outbursts 75 and 99. The filled squares are magnitudes derived from polarimetric count rates from the observations of outburst 75 (see text). The triangles are $B$-band photometry taken during the same outburst (Tuohy 1981, private communication). The open squares are differential photometry taken along with the polarimetry of outburst 99.

still had significant emission when their observations were made. Smale et al. (1984) report similar problems with spectroscopic data they obtained around the same time. The Hutchings et al. data may be less affected, as the data were taken later when the system may have been more deeply in the ‘off’ state. The Hutchings et al. and Corbet et al. orbital elements are summarized in Table 2.
Figure 4. A $Q-U$ diagram showing the same observations as those plotted in Fig. 2. The symbols are the same. To follow the polarization evolution with time of the two outbursts, the points are connected by short dashes (outburst 75) and long dashes (outburst 99). Also plotted, are the $Q_o$ and $U_o$ axes, representing the natural axes of the A0538-66 system. They are rotated 12° on the sky and 24° in the $Q-U$ plane.

Table 2. Orbital elements.

<table>
<thead>
<tr>
<th></th>
<th>Corbet et al.</th>
<th>Hutchings et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentricity ($e$)</td>
<td>0.96 $^{+0.04}_{-0.03}$</td>
<td>0.82 ±0.04</td>
</tr>
<tr>
<td>Longitude of periastron ($\omega$)</td>
<td>330° $^{+60}_{-60}$</td>
<td>222°±21°</td>
</tr>
<tr>
<td>Mass function [$f(m)$]</td>
<td>$4.7 \times 10^{-7}$ $M_\odot$</td>
<td>0.027 $M_\odot$</td>
</tr>
</tbody>
</table>

Orbital elements of A0538-66 calculated with assumed period of 16.6515 days.

In the case of the polarimetry, the problem will involve not only the geometrical effects related to the orbital elements (cf. Brown et al. 1982) but also the variable relative contributions of the two light sources (cf. CT, SB) and the variable amount and spatial distribution of the scattering material, which has not been considered quantitatively in any of the previous analyses. Given, therefore, the limited polarimetric coverage of A0538-66 even with our new data, a variety of possible interpretations is to be expected.

Our aim here, however, is to show that the available data are adequate to rule out certain interpretations, regardless of the orbital elements adopted, and to put some limits on the parameters of one possible interpretation. Specifically, we will restrict ourselves to an interpretation in which the system comprises a Be-star primary surrounded by a disc accompanied by a neutron star, in a coplanar orbit, which disturbs and captures gas from the disc during close passage at periastron. While other interpretations would undoubtedly be possible, we will show that no more elaborate model is demanded by currently available data. Scattering of Be-star light from the disc is taken to be responsible for the polarization outburst, the direction of this polarization defining the projection of the system axis on the sky. Variations in the extent of the quiescent disc, which appear to be a common Be-star phenomenon (Coyne 1976; Hayes & Guinan 1984), will cause variations in the quiescent polarization (such as are seen in Fig. 1). Disc variations will also cause considerable variation in the size and properties of different outbursts, since the mass transfer and loss at periastron passage is very sensitive to the size of the primary envelope (Brown & Boyle 1984; Boyle & Walker 1986). Indeed such variations may be responsible for the ‘on-off’ states in A0538-66 outburst behaviour (Brown...
& Boyle 1984). Major enhancement of the disc by the disruptive effect of the periastron passage may contribute to the apparent enlargement of the optical primary at outburst (Charles et al. 1983; Densham et al. 1983) and to the amount of mass captured by the neutron star leading to the X-ray outburst.

One specific elaboration of the above model, proposed by CT and Apparao (1985) is that the orbit is highly inclined to the disc plane. CT proposed this as an explanation for the sudden onset of the polarization as the neutron star enters the plane of the disc while Apparao claims the inclined orbit is necessary to explain the asymmetry of the X-ray and optical light curves near periastron. However, the steep radial density gradient in the disc and the rapidity of secondary approach alone will guarantee a steep rise in the light curves and polarization, even for a coplanar orbit. Secondly, Apparao’s argument rests on the assumption that the X-ray luminosity is a function only of secondary location, which is symmetric about periastron in the coplanar case. In reality, the mass-accretion rate on to the neutron star (and hence the X-ray luminosity) is asymmetric about periastron because it is also affected by the sign of the radial velocity and by the storage time of the captured matter in the transient accretion disc (Brown & Boyle 1984).

Quantitatively, the possible contributions to the polarization are scattering of light from:

(i) the primary, $X_1$;
(ii) the secondary, $X_2$;
(iii) a disc, $S_1$, around $X_1$;

![Diagram of the orbit of A0538-66](image)

**Figure 5.** Two schematic views of the A0538-66 orbit. The positions of the primary, the secondary and periastron are given by $X_1$, $X_2$ and $P$, respectively. The large double arrow shows the polarization of the ‘equivalent scattering volumes’ $S$ containing $N$ electrons and located in the orbital plane at a distance $R$ from $X_1$ and at an angle (longitude) $\lambda$ from the plane $X_1EZ$ containing the Earth $E$ and the orbital axis $Z$. The line $X_1AX$ is the projection of $X_1E$ in the orbital plane. The scattering angle is given by $\chi$. The position of the secondary is $r, u$ in orbital polar coordinates. The longitude of periastron is $\omega$ and the true anomaly is $\lambda$. 

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(iv) accreting gas, \(S_2\), around \(X_2\), and
(v) any additional gas, \(S_3\), torn from \(X_1\) and \(S_1\) during periastron passage.

For reasons of symmetry, light from \(X_1\) scattered around \(X_2\), and light from \(X_2\) scattered around \(X_1\) show identical polarization variations when the number of scatterers does not change with time. However, the net observed polarization depends on the relative contributions, as a function of time, of the two sources of diluting unpolarized starlight (SB). Using only the earlier data (CT), SB argued that the observed variation in the degree of polarization could be explained purely geometrically in terms of scattering in a fixed mass around \(X_1\) of light, \(L_1\) and \(L_2\), from both \(X_1\) and \(X_2\). Both \(L_2\) and the position of \(X_2\) vary rapidly through periastron, with \(L_1\) fixed. This model is unrealistic in that it disregards the envelope redistribution which is bound to accompany the outburst. Furthermore, due to the high eccentricity, the light sources recede very rapidly from the scatterers around the other object so that the polarization can only be sustained for very specific scattering-angle geometries soon after periastron, i.e. for very specific \(\omega\) values for which SB also predict the position-angle variation expected in their model. We show below that the more complete observational material now available do not agree with these SB predictions; see Fig. 6.

We have therefore considered a wide variety of light-source/scatterer geometries, including variation in the amount of scattering material to see what kind of coplanar situations can fit the

Figure 6. A plot similar to Fig. 1, rotated into the natural system of A0538–66 shown in Fig. 4. In this frame of reference, \(p\) is unchanged and the position angle, \(\phi_0 = \phi + 12^\circ\). Only the points from both outbursts occurring near phase 0.0 are plotted. The predictions of the Simmons & Boyle (1984) model for the orbital elements of Hutchings et al. (1985) (solid line) and Corbet et al. (1984) (dashed line) are also shown.
observations. In doing so, we have assumed that the scattering polarization can be adequately described by the single scattering treatment of Brown, McLean & Emslie (1978), corrected by the depolarization factor required because of the large size of the primary (Cassinelli, Murison & Nordsieck 1987). Daniel (1981) and Dolan (1984) have shown that even multiple-scattering situations are quite accurately described by this simpler treatment. (We have neglected, however, any effects of variable occultation or eclipsing by the large primary. If these were important they should also have shown up in the X-ray and optical light curves.) In discussing the predictions of various models, we will refer the polarization to the natural axis of the system, i.e. the projection of the orbital/disc normal on to the sky. This is of course unknown a priori and in trying to fit the various models we have taken the system orientation on the sky to be a free parameter. We have done likewise with the system inclination, i, but found model predictions to be insensitive over a wide range of i. Quantitative results are therefore given only for i = 60°. In the following, all of the conclusions hold for any orbit with large eccentricity, regardless of the other elements.

The simplest situation we considered was one in which all of the light variation was attributed to changes in the luminosity $L_1$ in the neighbourhood of $X_1$ and all of the polarimetric variation due to changes in the total number $N_1$ of scatterers in the disc $S_1$. Such a description could, for a suitable $N_1(t)$, reasonably describe the rise and fall of the degree of polarization. However, the position angle of the polarization should never change from that of the pre-outburst Be-star/disc system in contradiction to the observations (Fig. 1).

Secondly, we tried attributing the light enhancement entirely to the changing luminosity $L_2$ of $X_2$ and the polarimetric changes to scattering of $L_2$ on $N_2$ electrons in $S_2$ around $X_2$. This does give rise to changes in position angle (though more rapid than those observed). However, the extra light $L_2$ must decline on the short decay time-scale of the optical light curve so that $L_1$ will again predominate and will dilute the polarization of $L_2$ scattered on $N_2$ faster than the degree of polarization is observed to decay (cf. Figs 1 and 3). Similarly, the position angle does not return to its pre-outburst value on this time-scale (Fig. 1).

Therefore, we conclude that the polarization cannot be described in terms of the predominance of scattering of $L_1$ on $S_1$ nor of $L_2$ on $S_2$. Next, we consider the contribution of $L_1$ scattered on $N_2$ and of $L_2$ on $N_1$. One can at once conclude that the latter cannot be predominant for the same reason as above, i.e. the decline of $L_2$ demanded by the light curve would cause the polarization to decline and the position angle to revert to its pre-outburst value much faster than is observed. The scattering of $L_1$ on $S_2$ does not suffer from the same objection since the decline of the light curve does not change the polarization as the polarized flux and the depolarizing flux (both $\propto L_1$) decline together. The problem with this option is that the distance and angle between $X_1$ and $S_2$ around $X_2$ change so quickly in a highly eccentric orbit. The consequences of this are best seen in the quantitative treatment below where we take $L_1$ to predominate throughout.

4 Quantitative interpretation with primary light source dominant

In view of the problems posed by alternative interpretations, we consider here the possibility of explaining the polarimetric data when the primary luminosity $L_1(t)$ is predominant throughout. In this model, the polarization arises from scattering in the neighbouring disc material $S_1$ (which may be enlarged during outburst), and from some additional scattering material $S_3$. This material $S_3$ may, but need not, be identical with $S_2$ accreting on to $X_2$ so that the last scenario described in Section 4 is included in this analysis.

The analysis of Brown et al. (1978) in fact shows that the Stokes parameters of any electron distribution near the orbital plane may be described by those of an equivalent idealized
scatterer at an appropriate site. Our procedure will be to consider the polarization expected from an ‘equivalent scattering volume’ \( S \) containing \( N \) electrons and located at a distance \( R \) from \( X \), at an angle (longitude) \( \Lambda \) in the orbital plane from the plane \( X,E,Z \) containing the Earth \( E \) and the orbital axis \( Z \) (see Fig. 5). The parameters \( N, R \) and \( \Lambda \) will be allowed to vary with time and, will identify the ‘scattering centroid’ properties when matched to the observations. These properties will therefore represent the sum of the contributions from \( S_1, S_2, \) and \( S_3 \).

A cloud of \( N \) electrons \((R, \Lambda)\) in the orbital plane illuminated dominantly by \( X \), with luminosity \( L_1 \), will result in Stokes parameters \( Q_0 \), and \( U_0 \), with \( Q_0 \) measured along the projection of \( X,Z \) on the sky, given by,

\[
Q_0 = p \cos 2 \phi_0 = \frac{\sigma_0 N}{R^2} \left( 1 - \frac{R_*^2}{R^2} \right)^{1/2} \left( \sin^2 \Lambda - \cos^2 i \cos^2 \Lambda \right) \quad (1)
\]

\[
U_0 = p \sin 2 \phi_0 = \frac{\sigma_0 N}{R^2} \left( 1 - \frac{R_*^2}{R^2} \right)^{1/2} \cos i \sin 2 \Lambda, \quad (2)
\]

where \( \phi_0 \) is the position angle in this system, \( \sigma_0 = (3/16 \pi) \sigma_T \) with \( \sigma_T \) the Thomson cross-section, and \( R_* \) is the stellar radius which arises in the depolarization factor, \( D = (1 - R_*^2/R^2)^{1/2} \) (Cassinelli, Murison & Nordsieck 1987).

Equations (1) and (2) can be used either to predict the \( Q_0 \) and \( U_0 \) from a model where \( N, R, \) and \( \Lambda \) are given (or from a sum of such contributions) for comparison with data, or to deduce the combination of \( N, R \) and \( \Lambda \) needed from the data. We have used the equations both ways and we present here the results where the observed \( Q \) and \( U \) of Figs 2 and 4 have been rotated through \( \Delta \phi = 12^\circ \) on the assumption that the pre-outburst position angle indeed indicates the direction of the natural system \( Q_0 \) axis, i.e. that pre-outburst polarization is the result of \( L_1 \) scattering from \( S_1 \) which can be considered a Be-star disc in the orbital plane. In fact we have experimented with \( \Delta \phi \) as a free parameter and found that none of the conclusions stated below are modified, i.e. the \( \Delta \phi \) value adopted gives the most self-consistent interpretation.

First we use (1) and (2) to examine the physically plausible hypothesis that the variable polarization arises from scattering of \( L_1 \) on both \( S_1 \) and \( S_2 \), containing \( N_1 \) and \( N_2 \) electrons, respectively. Both the disc and cloud scattering mass were allowed to vary with time. The disc is not itself a point scatterer but can be replaced by an equivalent uniform ring of \( N_1 \) electrons at radius \( R_1 \) and by averaging (1) and (2) over \( \Lambda_1 \). The scattering accretion cloud of \( N_2 \) electrons must have \( R_2 = r, \Lambda_2 = v + \omega \) where \( r \) and \( v \) are the orbital polar coordinates of the secondary at a time \( t \) (see Fig. 5). The total predicted polarization is then given by,

\[
Q_0(t) = \frac{\sigma_0 N_1}{2 R_1} \left[ 1 - \frac{R_*^2}{R_1^2} \right]^{1/2} \sin^2 i + \frac{\sigma_0 N_2}{r^2} \left[ 1 - \frac{R_*^2}{r^2} \right]^{1/2} \left[ \sin^2 (v + \omega) - \cos^2 i \cos^2 (v + \omega) \right] \quad (3)
\]

\[
U_0(t) = \frac{\sigma_0 N_2}{r^2} \left[ 1 - \frac{R_*^2}{r^2} \right]^{1/2} \cos i \sin[2(v + \omega)], \quad (4)
\]

where \( r = a(1 - e^2)/(1 + e \cos v) \). If we express \( a, R_1, \) and \( R_2 \) in units of the primary star radius \( R_* \), then for any given set of orbital elements the only unknown functions of time on the right sides of (3) and (4) are \( v_1 = \sigma_0 N_1/R_*^2 \) and \( v_2 = \sigma_0 N_2/R_*^2 \). With fixed \( v_1 \) and \( v_2 \) this is essentially
the model discussed by SB. Thus for a given set of data, $Q_0(t)$, $U_0(t)$, and an assumed orbit, the equations (3) and (4) can be solved for $N_1(t)$ and $N_2(t)$ for a given orbit, and given values of $R_\ast/a$ and $R_1/R_\ast$. In principle, this solution could yield valuable information on the redistribution of gas during the accretion outburst.

We have carried out this solution of the data in Table 1 for a variety of values of $\Delta \phi$, $i$, $R_\ast/a$ and $R_1/R_\ast$ using both the Corbet et al. (1984) and Hutchings et al. (1985) orbital elements. We use these for illustration of the procedure only. They are so different that neither can yet be taken seriously. On the other hand, the fact that conclusions below are the same in both cases shows them to be very insensitive to the orbital elements apart from high eccentricity. We found it impossible to obtain a physically acceptable solution, i.e. one with $N_1(t)$ and $N_2(t)$ both positive at all times. In those solutions with $N_1$, $N_2 \geq 0$ for as many data points as possible (namely with $\Delta \phi = 12^\circ$), we found that following periastron $N_2(t)$ became much larger (by 2 orders) than $N_1$ and continued to increase with phase. Such behaviour seems unphysical since $N_2$ presumably is drawn from $N_1$ and the transfer should decline rapidly as $r/a$ increases. The negative $N$ values in fact arise because of the incompatibility of predictions (3) and (4) with the observed position-angle changes. This is most clearly seen by considering the contributions of $Q_2$, and $U_2$ in (3) and (4) which would arise from $N_2$ alone if this were fixed in time, as follows. (These conclusions are unchanged for other $\omega$ values.) In Fig. 6 we show plotted against phase the observed polarization, $p$, and the rotated position angle $\phi$. Superposed are the (arbitrarily scaled) $p$ and $\phi$ predicted for an accretion cloud of fixed $N_2$ around X$_2$ (SB), for the orbital elements of both Corbet et al. (1984) and Hutchings et al. (1985). In both of the predicted curves, we have used the largest value of $R_\ast/a(1-e^2)$ (namely 0.5) compatible with the absence of eclipses for $i=60^\circ$ (cf. Hutchings et al. 1985). This has the effect of maximizing the reduction of the sharp peak in $p(t)$ due to finite source depolarization. Despite the error bars and undersampling of the data, it is clear that a fixed $N_2$ in orbit with X$_2$ cannot possibly explain the observations for either orbit, or indeed for any high-eccentricity orbit. The reason, as can be seen in (3) and (4), is simply that high eccentricity implies a much more rapid variation in $\phi_0$ than observed because of the $(\nu + \omega)$ factors and a much more rapid decline in $p$ than is observed because of the $1/r^2$ factor. To offset the $1/r^2$ variation in $p(t)$ would demand a correspondingly large rise in $N_2$ as found above.

We conclude therefore that $N_1$ and $N_2$ alone cannot explain our observations for any orbit. The only remaining way to interpret the sustained $p(t)$ well beyond periastron and the near constancy of $\phi$ at that time is to invoke a third scattering region $S_3$, the location of which changes only gradually. It should be noted that this conclusion does not conflict with the accumulation of a massive accretion cloud $S_2$ around X$_2$, as found in simulations (e.g. Boyle & Walker 1986) and needed to explain the X-ray light curve. Rather it just means that this $S_2$ recedes from X$_2$ so quickly that it soon makes a negligible contribution to $p$ compared to a persistent (possibly less massive) cloud that is located much nearer the light source.

To estimate the location and mass of $S_3$, we return to equations (1) and (2) and invert them to give,

$$\tan \Lambda = \cos i \left( \frac{\cos 2\phi_0 \pm 1}{\sin 2\phi_0} \right)$$

$$p_0 = \frac{\sigma_0 N}{R^2} \left( 1 - \frac{R_2^2}{R_1^2} \right)^{1/2},$$

where $p_0$ is given by either (1) or (2) once $\Lambda$ is obtained from (5).
We have used equations (5) and (6) to infer the longitude $\Lambda$ and the quantity $N$ of the 'effective scattering centroid' needed to fit the (rotated) data of Table 1 with well-defined $\phi_0$. The results for $i = 60^\circ$ are shown in Table 3. The number of scatterers, $N$, has been shown in the scaled form,

$$fN = \frac{10^{24}}{\sigma_0} p_0 = 1.5 \times 10^{46} p_0 \text{ (per cent) (electrons)}$$  \hspace{1cm} (7)

where the factor,

$$f = \left(\frac{10^{12}}{R_*}\right)^2 \left(1 - \frac{R_*^2}{R^2}\right)^{1/2} \left(\frac{R_*}{R}\right)^2$$  \hspace{1cm} (8)

which reflects the fact that an $N$ value at one $R$ value, is polarimetrically equivalent to a different $N$ at a different $R$. The maximum possible value of $f$ is $0.33 \left(10^{12}/R_*\right)^2$ attained when $R = 1.5 R_*$ so that $N$ must take a value greater than those shown in Table 3 by a factor $= 3(R_*/10^{12})^2$. The absolute values of $N$ cannot be determined by the polarimetry since $R$ is unknown (and may vary with time) but the numbers in Table 3 imply a value of $N$, near the polarization peak, exceeding $3 \times 10^{47}$ electrons. For ionized hydrogen this corresponds to a scattering mass of $5 \times 10^{23}$ g. If a comparable mass is accreted by a neutron star ($X_2$) of $2 M_\odot$ the resulting

| JD 4668.58 | Cycle 74 | Phase 0.745 | $p'$ 0.39 | $\phi_0$ 116.9 | $fN (x10^{-46})$ 2.05 | $\Lambda$ 345.8 | $\Lambda + 180^\circ$ 165.8 |
| JD 4670.57 | Cycle 74 | Phase 0.865 | $p'$ 0.28 | $\phi_0$ 80.4 | $fN (x10^{-46})$ 1.67 | $\Lambda$ 4.6 | $\Lambda + 180^\circ$ 184.6 |
| JD 4671.62 | Cycle 74 | Phase 0.928 | $p'$ 0.21 | $\phi_0$ 100.0 | $fN (x10^{-46})$ 1.30 | $\Lambda$ 355.3 | $\Lambda + 180^\circ$ 175.3 |
| JD 4672.62 | Cycle 74 | Phase 0.988 | $p'$ 0.64 | $\phi_0$ 85.1 | $fN (x10^{-46})$ 3.79 | $\Lambda$ 2.4 | $\Lambda + 180^\circ$ 182.4 |
| JD 4673.52 | Cycle 75 | Phase 0.042 | $p'$ 1.84 | $\phi_0$ 88.9 | $fN (x10^{-46})$ 11.03 | $\Lambda$ 0.5 | $\Lambda + 180^\circ$ 180.5 |
| JD 4673.76 | Cycle 75 | Phase 0.056 | $p'$ 1.41 | $\phi_0$ 89.4 | $fN (x10^{-46})$ 8.54 | $\Lambda$ 0.2 | $\Lambda + 180^\circ$ 180.2 |
| JD 4674.52 | Cycle 75 | Phase 0.102 | $p'$ 1.68 | $\phi_0$ 103.8 | $fN (x10^{-46})$ 9.73 | $\Lambda$ 353.1 | $\Lambda + 180^\circ$ 173.1 |
| JD 4674.72 | Cycle 75 | Phase 0.114 | $p'$ 1.83 | $\phi_0$ 103.4 | $fN (x10^{-46})$ 10.61 | $\Lambda$ 353.2 | $\Lambda + 180^\circ$ 173.2 |
| JD 4675.69 | Cycle 75 | Phase 0.172 | $p'$ 1.46 | $\phi_0$ 108.3 | $fN (x10^{-46})$ 8.20 | $\Lambda$ 350.6 | $\Lambda + 180^\circ$ 170.6 |
| JD 4676.68 | Cycle 75 | Phase 0.232 | $p'$ 1.18 | $\phi_0$ 104.5 | $fN (x10^{-46})$ 6.83 | $\Lambda$ 352.7 | $\Lambda + 180^\circ$ 172.7 |
| JD 4677.59 | Cycle 75 | Phase 0.286 | $p'$ 1.14 | $\phi_0$ 105.1 | $fN (x10^{-46})$ 6.47 | $\Lambda$ 352.4 | $\Lambda + 180^\circ$ 172.4 |
| JD 5062.5 | Cycle 98 | Phase 0.402 | $p'$ 0.35 | $\phi_0$ 166.9 | $fN (x10^{-46})$ 0.60 | $\Lambda$ 295.0 | $\Lambda + 180^\circ$ 115.0 |
| JD 5063.49 | Cycle 98 | Phase 0.462 | $p'$ 0.49 | $\phi_0$ 148.4 | $fN (x10^{-46})$ 1.33 | $\Lambda$ 320.9 | $\Lambda + 180^\circ$ 140.9 |
| JD 5070.48 | Cycle 98 | Phase 0.881 | $p'$ 0.52 | $\phi_0$ 139.6 | $fN (x10^{-46})$ 1.76 | $\Lambda$ 329.6 | $\Lambda + 180^\circ$ 149.6 |
| JD 5071.5 | Cycle 98 | Phase 0.943 | $p'$ 0.50 | $\phi_0$ 158.8 | $fN (x10^{-46})$ 1.05 | $\Lambda$ 307.8 | $\Lambda + 180^\circ$ 127.8 |
| JD 5072.48 | Cycle 99 | Phase 0.001 | $p'$ 0.51 | $\phi_0$ 175.5 | $fN (x10^{-46})$ 0.78 | $\Lambda$ 278.9 | $\Lambda + 180^\circ$ 98.9 |
| JD 5072.5 | Cycle 99 | Phase 0.002 | $p'$ 0.30 | $\phi_0$ 184.0 | $fN (x10^{-46})$ 0.46 | $\Lambda$ 82.0 | $\Lambda + 180^\circ$ 262.0 |
| JD 5073.5 | Cycle 99 | Phase 0.062 | $p'$ 0.44 | $\phi_0$ 89.3 | $fN (x10^{-46})$ 2.66 | $\Lambda$ 0.3 | $\Lambda + 180^\circ$ 180.3 |
| JD 5073.52 | Cycle 99 | Phase 0.063 | $p'$ 0.53 | $\phi_0$ 97.9 | $fN (x10^{-46})$ 3.13 | $\Lambda$ 356.0 | $\Lambda + 180^\circ$ 176.0 |
| JD 5074.5 | Cycle 99 | Phase 0.123 | $p'$ 1.33 | $\phi_0$ 92.2 | $fN (x10^{-46})$ 7.96 | $\Lambda$ 358.9 | $\Lambda + 180^\circ$ 178.9 |
| JD 5074.52 | Cycle 99 | Phase 0.124 | $p'$ 1.28 | $\phi_0$ 90.5 | $fN (x10^{-46})$ 7.70 | $\Lambda$ 359.7 | $\Lambda + 180^\circ$ 179.7 |
X-ray outburst should contain about $10^{44}$ erg or a peak luminosity of about $10^{39}$ erg s$^{-1}$ over an X-ray burst peak of one day, closely comparable to that observed (Skinner 1980). Our data imply that comparable fractions of the material drawn from the Be-star and its disc are accreted by $X_2$ and remain in the vicinity of $X_1$, though the relative proportions may vary greatly from one periastron passage to the next. Careful polarimetric monitoring with simultaneous X-ray coverage could thus reveal the variability of this episodic mass-loss fraction.

As far as the angular location of the scattering material centroid is concerned, this is most readily seen from Fig 7(a) and (b) which portray in polar coordinates the polar angle $\Lambda$ of the scatterers, and a radial coordinate measuring the amount of scattering material (in terms of $10^{-46} fN$) for those points in Table 3 where it is adequately determined. Of course every point can take the value $\Lambda$ or $\Lambda + \pi$, but in plotting them we have adopted solutions in the same quadrant on the grounds of continuity. The loci of two sets of solution points are shown in Fig 7(a) and (b) for the data of Table 3 in which $\Lambda$ is adequately determined. For both outbursts, phase points are marked on the loci. Also shown are the phased positions of $X_2$ around its orbit for both Corbet et al. and Hutchings et al. parameters.

Assuming on physical grounds that the scattering material emerges near the periastron rather than the apastron longitude, we interpret the results as meaning that the scattering mass is either ejected around $\Lambda \approx 180^\circ$ close to the periastron encounter $\omega$ value of Hutchings et al. (Fig. 7a) or around $\Lambda = 0^\circ$ close to the $\omega$ value of Corbet et al. (Fig. 7b). Prior to outburst 99, the $\Lambda$ value is in the neighbourhood of $90^\circ$ (or $270^\circ$) which is that of a point-scattering centroid equivalent to a disc. This is not confirmatory of the model proposed, but only automatically consistent with it by our original choice of the $\phi_0$ axis. Thereafter the small pre-outburst (disc) polarization is rapidly swamped by the large polarization associated with the large enhancement of scatterers $N_1$ near the periastron point. It is also worth noting that the pre-outburst value of $fN \approx 10^{46}$ implies about $10^{47}$ electrons in the quiescent disc (again taking $f \approx 0.3$ and allowing for the factor of $1/3$ depolarization due to the averaging of scattering angles around a flat disc (cf. Brown & McLean 1977). If these disc electrons are spread throughout a volume of order $R_3^3$, the implied disc electron density is $n_e (\text{cm}^{-3}) \approx 10^{11}(10^{12}/R_3)^3$, typical of Be-star disc density estimates (Poockert & Marlborough 1978). At the phase points well after periastron in outburst 75, Fig. 7 shows a decline in $N$ back toward the origin, presumably indicating that the circumstellar material is settling back toward its quiescent state. In the pre-periastron points of outburst 99, there may also be an indication that the circumstellar material is still reverting to its pre-outburst state after outburst 98 of the previous orbit, by redistribution in both longitude and radius.

The major feature of physical interest in these results is the remarkable persistence of the mass and the direction $\Lambda$ of the scattering centroid material. Thus, although $X_2$ presumably carries off and accretes a large mass which rapidly becomes polarimetrically negligible as already discussed, a comparable mass enhancement has to persist near the Be-star, close to the periastron position for a long time (comparable to the decay time of the photometric light curve). This time is longer than the orbital time for material close to the Be-star and therefore longer than the inner Be-star disc Keplerian rotation time-scale, and more comparable to the time-scale of hydrodynamic travel across the disc $\approx R_3/v_\kappa \approx 10$ days for a temperature of $10^4$ K. Finally, it would be entirely consistent with the data if the scattering cloud were not a single material entity but rather a localized disc-density enhancement sustained by non-radial oscillations in, and mass loss from, the stellar envelope set up by its distortion at periastron. The resulting outflow speed would have to be well above escape speed so that rotation would not deflect the ejecta greatly. Secondly, the impulse delivered to the material in the disc and star near the periastron point, during the rapid fly-by of the neutron star, will be essentially
Figure 7. (a) The curves in the upper part of the figure are polar plots of the properties of the 'effective scattering centroid' inferred from the data. The radial coordinate here is $fN \times 10^{-46}$, a measure of the number of scatterers, and the polar angle $\Lambda$, their longitude, for the Hutchings et al orbit. While this cannot show where scatterers are located, increased distance from the origin in this plot indicates an increase in the optical depth of the scattering centroid while $\Lambda$ indicates its angular location. The filled circles derive from the observations of outburst 75 and 99 at the following phase points corresponding to the adjacent labels. (The first three observations which have the largest errors have not been included.)

Phase points outburst 75: $a = 0.987$, $b = 0.056$, $c = 0.101$, $d = 0.114$, $e = 0.172$, $f = 0.232$, $g = 0.286$; phase points outburst 99: $1 = 0.4$, $2 = 0.46$, $3 = 0.88$, $4 = 0.94$, $5 = 0.001$, $6 = 0.002$, $7 = 0.062$, $8 = 0.063$, $9 = 0.122$, $10 = 0.124$.

The ellipse in the lower half of the figure is a polar $(r, \lambda)$ plot of the A0538 − 66 orbit using the Hutchings et al. parameters with the location of the secondary marked for each data point. Periastron lies near point 6.

Comparison of the upper and lower panels point by point enables comparison of the evolution of the scatterer location and effective mass with the orbital motion of the neutron star.

(b) The same as (a) but for the orbital elements of Corbet et al. (1984). (Periastron lies between points a and 5 in the lower panel.) In this case the orbital ellipse is in the upper part of the diagram and the alternative scatterer longitudes $\Lambda$ (shifted 180°) have been adopted so that the scattering centroid locus lies in the lower part of the figure.

radial and along the periastron line. Thus the velocity field set up tidally in the Be-star matter will, at least initially, be in the direction of the enhancement required polarimetricaly.

5 Discussion and conclusions

While the data presented here are clearly undersampled compared to the rapidity with which the system geometry changes near periastron, our analysis shows the value of even limited
polarimetric data as a diagnostic of recurrent transient mass distribution. The analysis used here can be re-applied when more definitive orbital elements and better polarimetric data are obtained for this system. Clearly, frequent monitoring through the critical periastron encounter could be much more informative still, possibly containing the signature of the rapidly moving material accreted by the neutron star. Whatever this might reveal, we have established the necessity for there to be an additional major gas outflow from the Be-star region near the periastron point and persisting there long after the neutron star has moved away. This result is strongly suggestive that mass loss and transfer in a highly eccentric binary must be treated in terms of tidal stripping rather than as a quasi-steady Roche lobe overflow or wind accretion phenomenon as suggested by some authors (Brown & Boyle 1984; Apparao 1985). An important theoretical question is whether the tidally stripped cloud producing the polarization could also be hot enough to contribute significantly to the X-ray emission? Clearly the value of polarimetric coverage would also be greatly enhanced if good simultaneous optical and X-ray photometry were achieved.

It is unfortunate that our pre-outburst data are so scanty and, in the case of outburst 75, of low precision. Better coverage of this phase would test our interpretation that the pre-outburst polarization is that the normal Be-star disc, and elucidate how fixed the plane of the disc is, and how variable it is in extent. The well-known variability of single Be-star discs inferred from polarimetric monitoring could well play a key role in determining the ‘on-off’ behaviour of outbursts in A0538 – 66 by presenting very different gas configurations to the neutron star at its periastron passages. Indeed a period of rising polarization in the quiescent state could well presage a return of the system to its ‘on’ state.

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References