The distance and reddening of stars near the luminous blue variable AG Carinae

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Abstract. Stars of $V \lesssim 13.5$ in the region close to the Luminous Blue Variable AG Car (within 17 arcmin) have been studied in the Walraven photometric system. The observed colours are used to derive the values of $T_\text{eff}$ and $\log g$. The intrinsic colours, predicted by model atmospheres, and the absolute visual magnitudes, predicted by stellar evolutionary tracks, are used to derive the extinction and the distances of 43 stars. We find a concentration of early type stars in the direction of AG Car with distances between 1 and 10 kpc and $E(B-V)$ in the range of 0.13 to 0.68. The extinction versus distance relation suggests a distance of 4 to 10 kpc for AG Car. Combining all distance criteria for AG Car we find a distance of $6 \pm 1$ kpc, and $M_\text{bol} = -10.8 \pm 0.4$ mag. with variable $M_v$. AG Car does not belong to the Car OB1 or OB2 associations at 2.5 kpc. We did not find a cluster of luminous stars at the distance of AG Car, but we identified a few stars which may belong to the same cluster as AG Car.

Key words: stars: AG Car – dust, extinctions – Galaxy: structure

1. Introduction

The star AG Car (HD 94910) belongs to the rare class of Luminous Blue Variables (LBV). These are massive stars in a critical evolutionary stage after the main sequence. The LBV's are photometric and spectroscopic variable on a wide range of timescales from weeks to decades. The spectral type is early-B or even Ofpe/WN9 during photospheric minimum but can become as late as A or F during photospheric maximum, when the stars brighten visually by 0.5 to more than two magnitudes (Lamers 1986; Wolf 1989a). The brightening of the LBV's is usually associated with enhanced mass loss.

In addition to this variability some LBVs are known to have had large eruptions when as much as one solar mass can be ejected. The most famous ones are those of P Cygni (in 1600) and $\eta$ Car (in 1843). Although such an eruption has not been recorded in the history of AG Car, the presence of a ring nebula around the star suggests that it may have suffered at least one large outburst in the past $10^3 - 10^5$ years.

The instability of the LBV's is probably due to the fact that they are close to their opacity-dependent Eddington-limit

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2. Photometry of early type stars near AG Car

The distance of AG Car can be estimated from the relation between interstellar extinction and distance in the direction of AG Car. We try to derive this relation by determining photometric distances and reddening for stars in a small field around AG Car. To this purpose we limit ourselves to stars within about 20' from AG Car.

2.1. The selection of the program stars

Some 150 stars with $V \leq 14^{m}$ in the field near AG Car were initially selected from the ESO Sky Survey, for observations with the Walraven photometer at the Dutch 91 cm telescope at ESO. Many of these are probably foreground stars. Therefore we limited the sample to stars with $B - V \leq 0.7$. When visual examination through the telescope proved the stars to be red or visual binaries they were excluded from the program. 43 stars proved to be useful for this study. These stars are shown in Fig. 1, together with a sequence number for this program.
2.2. The photometry of the program stars

The program stars were observed with the Walraven five colour photometer at ESO in 1987 and 1988. A description of the photometer and its most important characteristics is given by Walraven and Walraven (1960), Walraven et al. (1964) and Rijf et al. (1969). The central wavelengths of the Walraven system are: $W = 323.5$ nm, $U = 362.3$ nm, $L = 383.7$ nm, $B = 429.8$ nm and $V = 544.1$ nm. The observations will be published separately (Hoekzema, 1991). The fluxes of the program stars are calibrated with respect to standard stars (Lub and Pel, 1977). We notice that in the Walraven system the magnitude is given as the $10\log$ of the calibrated intensity. To convert Walraven magnitudes into the magnitudes of the Johnson system we used the relations

$$V_j = 6.885 - 2.5(V_w + 0.030(V - B)w)$$

(1)

and

$$E(B - V)_j/E(V - B)w = 2.375 - 0.169(V - B)w$$

(2)

(Pel, 1987) where the subscripts $J$ and $W$ refer to the Johnson and Walraven systems respectively.

In this paper the magnitudes and colours in the Walraven system will be indicated by a subscript $W$. The magnitudes $V$ and the extinction $E(B - V)$ without subscripts refer to the Johnson system.

3. The extinction and the distance of the program stars

3.1. The method

The procedure used for the determination of the extinction and the distances of the stars is the same as used by Gathier et al. (1986) in his analysis of stars near Planetary Nebulae. This procedure consists of the following steps:

1. determination of the extinction-free colours.
2. determination of $T_{\text{eff}}$ and $\log g$ by comparing the extinction-free colours with those predicted by model atmospheres.
3. determination of the extinction by comparing the observed colours with those predicted by the models.
4. determination of the absolute visual magnitude from \( T_{\text{eff}} \) and 
\( \log g \) by using stellar evolutionary tracks.
5. determination of the distance from \( M_v, V \) and \( A_v \).

In this procedure the standard interstellar extinction curve of Savage and Mathis, 1979 was adopted.

The Walraven photometry provides the following extinction-free parameters (Pel, private communications).

\[
\begin{align*}
[B - U]_w &= (B - U)_w - 0.61(V - B)_w \\
[U - W]_w &= (U - W)_w - 0.45(V - B)_w \\
[B - L]_w &= (B - L)_w - 0.39(V - B)_w \\
\{B - L\}_w &= (B - L)_w - 0.64(B - U)_w
\end{align*}
\] (3)

These extinction-free colours can be used to define four two dimensional colour-colour diagrams: \([B - L]_w\) versus \([B - U]_w\); 
\([U - W]_w\) versus \([B - U]_w\); 
\([B - L]_w\) versus \([U - W]_w\); 
\([B - L]_w\) versus \([B - L]_w\). Only two of these are independent. Figures 2 and 3 show the theoretical grids of \( T_{\text{eff}} \) and \( \log g \) in these colour-colour diagrams. The grids were derived from LTE model atmospheres of solar composition (Kurucz, 1979). The observed extinction-free colours are compared with these theoretical diagrams to derive the values of \( T_{\text{eff}} \) and \( \log g \) for each star.

Stars with \( T_{\text{eff}} < 8000 \text{ K} \) were excluded from this study for three reasons: a) the flux in the W-channel of the Walraven photometry is very small; b) the intrinsic colours depend critically on the assumed abundance; c) cool stars are not important for the reddening-distance relation.
Table 1. The effect of photometric variability

<table>
<thead>
<tr>
<th>Star nr</th>
<th>V</th>
<th>Teff</th>
<th>log g</th>
<th>E(B - V)</th>
<th>Ms</th>
<th>log d</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>9.129</td>
<td>25000</td>
<td>3.5</td>
<td>0.369</td>
<td>-4.346</td>
<td>3.466</td>
<td>3</td>
</tr>
<tr>
<td>9.123</td>
<td>24900</td>
<td>3.7</td>
<td>0.369</td>
<td>-3.718</td>
<td>3.340</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.127</td>
<td>26500</td>
<td>3.7</td>
<td>0.374</td>
<td>-4.009</td>
<td>3.396</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.063</td>
<td>27200</td>
<td>3.93</td>
<td>0.383</td>
<td>-3.435</td>
<td>3.262</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9.067</td>
<td>27000</td>
<td>3.97</td>
<td>0.385</td>
<td>-3.276</td>
<td>3.229</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9.063</td>
<td>27200</td>
<td>4.00</td>
<td>0.385</td>
<td>-3.221</td>
<td>3.218</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9.062</td>
<td>27000</td>
<td>3.88</td>
<td>0.383</td>
<td>-3.551</td>
<td>3.285</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>9.090</td>
<td>26400</td>
<td>3.84</td>
<td>0.380</td>
<td>-3.600</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>0.034</td>
<td>1.020</td>
<td>0.18</td>
<td>0.007</td>
<td>0.410</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

| 40      | 11.879 | 13600 | 3.6   | 0.578    | -1.821 | 3.382 | 3      |
| 11.884 | 13000 | 3.66  | 0.576 | -1.668  | 3.353 | 3     |
| 11.893 | 13100 | 3.65  | 0.562 | -1.542  | 3.339 | 0     |
| 11.947 | 13150 | 3.65  | 0.571 | -1.555  | 3.346 | 0     |
| 11.901 | 13050 | 3.5   | 0.574 | -1.986  | 3.422 | 3     |
| 11.881 | 13100 | 3.62  | 0.576 | -1.633  | 3.346 | 2     |
| Mean    | 11.898 | 13170 | 3.58  | 0.576 | -1.790 | 3.39  |
| σ       | 0.026 | 0.220 | 0.05  | 0.001   | 0.146 | 0.03  |

1) Star 32 is a photometric variable; star 40 is not a variable star.

3.2. The effective temperatures and gravity

The values of $T_{\text{eff}}$ and log $g$ for each program star were derived by comparing the location of the star in the extinction-free colour-colour diagrams with the theoretical grids of LTE model atmospheres in the same diagram (Fig. 2).

The signal of the stars in the W-filter is smaller than in the other filters and hence the uncertainty in the W-magnitude is larger than that of other filters. For this reason the value of log $g$ derived from colour-colour diagrams containing the W-filter is much more uncertain than that derived from other $T_{\text{eff}}$ filters. Therefore the values of log $g$ in Table 3 were only derived from the photometry in the $V, B, L$ and $U$ filters, i.e. the $[B - L]$ vs $[B - U]$ and the $[B - L]$ vs $[B - L]$ diagrams. The values of log $g$ derived from the colours with the W-magnitudes are only used to estimate the accuracy of the determination of log $g$.

Most program stars were observed on more than one night. A few program stars turned out to be variable. This is not surprising, considering the fact that most of these stars are giants or supergiants. For this reason we determined the values of $T_{\text{eff}}$ and log $g$ of a star for each night separately, rather than averaging all observations and determining the stellar parameters from the mean photometry. Our approach has the advantage that the independent determinations of $T_{\text{eff}}, \log g, M_*, E(B - V)$ and distance for each observation provide a good estimate of the effect of variability on the accuracy of the final values of $E(B - V)$ and distance.

In Table 1 we list two examples of this approach. The consistency of the values of $T_{\text{eff}}$ and log $g$ derived from the different colour-colour relations is indicated by a weight (Sect. 3e and Table 2). Star number 32 was observed 7 times during 3 nights and nr 40 was observed on 6 nights. The analysis of nr 32 shows that the values of $T_{\text{eff}}$ and log $g$ vary in the range of 24900 $\leq T_{\text{eff}} \leq 27200$ and $3.5 \leq \log g \leq 4.0$ and the resulting value of the extinction is in the range of $0.369 \leq E(B - V) \leq 0.385$. The resulting values of $M_*$ and log $d$ (to be described in Sect. 3c) are in the range of $-3.22 \leq M_* \leq -4.35$ and $3.218 \leq \log d \leq 3.466$. These wide ranges are due to the photometric variability of the star.

On the other hand, the ranges and the standard deviations of $T_{\text{eff}}$ are much smaller: $13050 \leq T_{\text{eff}} \leq 16600$, $3.5 \leq \log g \leq 3.65$, $0.562 \leq E(B - V) \leq 0.578$, $-1.54 \leq M_* \leq -1.82$ and $3.339 \leq \log d \leq 3.422$. This star shows no clear photometric variations so the derived stellar parameters, distance and extinction are defined more accurately.

3.3. The extinction

The values of $T_{\text{eff}}$ and log $g$ were derived for each night a program star was observed, and the intrinsic colour $(V - B)_{0}$ was determined from the corresponding model atmosphere. To this purpose the Walraven colors of the grid of Kurucz model atmospheres were interpolated in steps of $\Delta T_{\text{eff}} \approx 200$ K and $\Delta \log g \approx 0.1$. The extinction in the Walraven system was derived from the difference between $(V - B)_{0}$ and the observed value of $(V - B)$, and expressed in the Johnson system by means of Eq. (2).

3.4. The absolute visual magnitude and the distance

Gathier (1985) constructed two analytical expressions describing $M_v$ as a function of $T_{\text{eff}}$ and log $g$ for log $g \geq 4.3$ and log $g > 4.3$.

$$M_v = a_1 + a_2 x + a_3 x^2 + a_4 x^3 + a_5 \log g - a_6$$

with $x = \log T_{\text{eff}}$ and the values of $a_1$ to $a_6$ are:

$$a_1 = 1243.38, a_2 = -882.225, a_3 = 210.617, a_4 = -16.9169, a_5 = 0$$

and $a_6 = 0$ if log $g > 4.3$ and

$$a_1 = 1467.73, a_2 = -1038.54, a_3 = 246.663, a_4 = -19.6725, a_5 = 3.05$$

and $a_6 = 4.20$ if log $g \leq 4.3$. These expressions are derived from the stellar evolutionary tracks calculated by Hejlesen (1980). They are valid in the region of 8000 $\leq T_{\text{eff}} \leq 25000$ and $3.0 \leq \log g \leq 4.5$.

We compared the $M_v(T_{\text{eff}}, \log g)$ relation of Gathier with those derived from more recent and improved evolutionary calculations by Maeder and Meynet (1987). In the region of 8000 $\leq T_{\text{eff}} \leq 9500$ K and log $g \geq 3.0$ the values of $M_v$ derived from the tracks of Maeder and Meynet are slightly more
Table 2. The weights of the determination of $E(B-V)$ and $d(\text{pc})$

<table>
<thead>
<tr>
<th>Weight</th>
<th>$\Delta \log g$</th>
<th>$\Delta \log d$</th>
<th>$\Delta E(B-V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$\leq 0.065$</td>
<td>$\leq 0.033$</td>
<td>0.007</td>
</tr>
<tr>
<td>2</td>
<td>$\leq 0.18$</td>
<td>$\leq 0.10$</td>
<td>0.010</td>
</tr>
<tr>
<td>1</td>
<td>$\leq 0.27$</td>
<td>$\leq 0.15$</td>
<td>0.015</td>
</tr>
</tbody>
</table>

negative than those of Gathier by about $-0.05$ (ranging from $-0.14$ to $+0.04$ with no clear trend in $\log g$ or $T_{\text{eff}}$). In the region of $10000 \leq T_{\text{eff}} \leq 25000$ and $\log g \geq 3.0$ the values of $M_e$ from Maeder and Meynet are slightly less negative than those of Gathier by $+0.05$ (ranging from $-0.05$ to $+0.14$). These differences in $M_e$ are small and would correspond to differences in the derived distances of $\Delta \log d \approx 0.01$. Therefore we adopted equ. (4) for the determination of $M_e$ in the range of $8000 \leq T_{\text{eff}} \leq 25000$ K and $\log g \geq 3.0$.

For the four program stars with $\log g < 3.0$ we adopted the relation between $T_{\text{eff}}, \log g$ and $M_e$ from Maeder and Meynet. These values of $M_e$ are about $-0.20$ smaller than given by Eq. (4).

The distance of each star was derived for each night the star was observed from $V, M_e$ and $E(B-V)$ in the standard way.

3.5. The accuracy of $E(B-V)$ and distance

The determination of $E(B-V)$ and distance depends on the accuracy of the determination of $T_{\text{eff}}$ and $\log g$. The value of $E(B-V)$ is mainly sensitive to $T_{\text{eff}}$ and the value of $\log d$ is mainly sensitive to $\log g$, because $M_e$ depends critically on $\log g$. The accuracy of the determination of $T_{\text{eff}}$ and $\log g$ from the observations of a star on one night can be estimated from the agreement between their values derived from the different colour-colour diagrams. This agreement is expressed by means of a weight $W$, from 0 (low weight) to 3 (high weight). The relation between these weights and the accuracy of $E(B-V)$, $\log g$, and $\log d$ is given in Table 2.

For stars which were observed on three or more nights we determined the accuracy of $E(B-V)$ and $\log d$ from the scatter of the determinations of the different nights, taking into account the weights $W$. For stars which were observed on two nights the difference between the two determinations is used to derive the accuracy of $E(B-V)$ and $\log d$. For stars which were observed on one night only the internal consistency between the values of $\log g$ derived from different colour-colour diagrams, including those containing the W-filter, was used as an indication of the accuracy of $E(B-V)$ and $\log d$.

3.6. The results

The resulting values of $E(B-V)$ and $\log d$ of the program stars are listed in Table 3, in order of increasing visual magnitude, for 43 stars. For five of these the uncertainty is either unknown or too large, so they will not be used for the distance-extinction relation.

The standard errors listed in Table 3 are based on the internal consistency of the derived values of the parameters. External errors may also occur. The most important ones are due to possible errors in the relation between $M_e$ and $(T_{\text{eff}}, \log g)$ and the possibility of a non-standard extinction curve.

The agreement between the values of $M_e$ derived from the evolutionary tracks of Hejlesen (1980) and Maeder and Meynet (1988) suggests that the external error in the $M_e$-calibration is less than 0.15 magn., which corresponds to an error of only 0.03 in $\log d$. The reliability of the use of the standard extinction curve can be checked from the internal consistency of the stellar parameters derived from the four colour-colour relations. If the extinction curve in the direction of a star would deviate strongly from the adopted standard curve, the stellar parameters from the colour-colour relations would show a poor agreement. In this case the derived extinction and the distance would not be reliable. On the other hand, if the star is non-variable the night-to-night variations of the determinations of $E(B-V)$ and $\log d$ would be small, and so the standard deviations in Table 3 which indicate the internal errors could be small, despite the fact that the extinction and distance are not reliable. For this reason we listed a weight-factor $W$ in Table 3, which is a measure of the external accuracy, with $W = 3$ corresponding to the high accuracy and small uncertainty.

Seven of our program stars turned out to be photometric variables and two are suspected ones, because their magnitudes vary by more than the accuracy of the observations. Their variability will affect the accuracy of the extinction and distance determination. To investigate this effect we show in Fig. 4 the variation of $M_e$ against the variation of $\log d$. This was done for some stars for which two or three observations with weight 3 were available and the observations were at least one month apart. The figure shows the existence of a correlation between $\Delta M_e$ and $\Delta \log d$ of variable stars. This implies that the derived distances of the photometric variables are not very reliable. The possible uncertainty is given by the standard deviation of $\log d$. It is not unlikely that some of the stars which were observed only once or twice are also variable.

Four of our program stars are listed in the HD or SAO catalogue. The magnitudes and spectral types listed in these catalogues are compared with our results in Table 4. There is a reasonable agreement between our $V$ magnitude and $m_{bp}$ from the catalogues, except for star nr 62. However, the spectral types listed in the catalogues give only a very crude indication of the temperature of the stars.
## Table 3. The extinction and distance of program stars

<table>
<thead>
<tr>
<th>V-range</th>
<th>Star nr</th>
<th>V</th>
<th>( T_{\text{eff}} )</th>
<th>( \log g )</th>
<th>( E(V-B) )</th>
<th>( M_{V} )</th>
<th>( \log (d/pc) )</th>
<th>Weight</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 - 10</td>
<td>32 7</td>
<td>9.090±0.028</td>
<td>2660±800</td>
<td>3.84±0.18</td>
<td>0.38±0.01</td>
<td>-3.60±0.41</td>
<td>3.30±0.08</td>
<td>3 V</td>
<td></td>
</tr>
<tr>
<td>10 - 10.5</td>
<td>92 4</td>
<td>10.316±0.005</td>
<td>1070±100</td>
<td>2.33±0.10</td>
<td>0.68±0.02</td>
<td>-5.06±0.33</td>
<td>3.65±0.03</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>10 - 11</td>
<td>94 1</td>
<td>10.529</td>
<td>18500</td>
<td>2.8</td>
<td>0.53±0.01</td>
<td>-5.54</td>
<td>3.88±0.10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>11 - 11.5</td>
<td>468 3</td>
<td>11.078±0.014</td>
<td>14500±200</td>
<td>3.48±0.07</td>
<td>0.33±0.01</td>
<td>-2.38±0.20</td>
<td>3.49±0.03</td>
<td>3 V</td>
<td></td>
</tr>
<tr>
<td>11.5 - 12</td>
<td>55 3</td>
<td>11.500±0.016</td>
<td>19700±300</td>
<td>4.29±0.12</td>
<td>0.31±0.01</td>
<td>-1.04±0.21</td>
<td>3.32±0.07</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>12 - 12.5</td>
<td>12 2</td>
<td>12.105±0.033</td>
<td>11500</td>
<td>3.4</td>
<td>0.44±0.02</td>
<td>-1.85</td>
<td>3.52±0.15</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>12.5 - 13</td>
<td>12 2</td>
<td>12.615±0.005</td>
<td>17300±200</td>
<td>4.1±0.4</td>
<td>0.59±0.02</td>
<td>-1.16±0.23</td>
<td>3.39±0.23</td>
<td>3 V, O</td>
<td></td>
</tr>
<tr>
<td>&gt; 13.5</td>
<td>8 1</td>
<td>13.582</td>
<td>16600</td>
<td>4.15</td>
<td>0.47±0.02</td>
<td>-0.81</td>
<td>3.59±0.15</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

1) If the value of \( \sigma \) is not given, only one observation could be used to give a reliable estimate of \( T_{\text{eff}}, \log g \) or \( M_{V} \).
2) If only one observation was used for the determination of \( T_{\text{eff}} \) and \( \log g \), the value of \( \sigma (E(V-B)) \) was derived from the values of \( E(V-B) \) from different colour–colour relations.
3) The final value of \( \log d \) is the weighted mean of the determinations from different observations (see Sect. 3.0). Therefore this distance is not necessarily in agreement with the mean values of \( V, (E(V-B)) \) and \( M_{V} \).
4) \( V \) = variable in magnitude or colour; \( O \) = omitted from the final analysis because of low weight.
4. The extinction and distance of AG Car

4.1. The extinction-distance relation

The extinction of the program stars is plotted versus distance (log \(d\)) in Fig. 5. We added the data of five Wolf-Rayet stars within 1' from AG Car, which are listed in Table 5 (van der Hucht, 1988). These five stars are outside the program area of 20' around AG Car but they may give some indication about the extinction at large distances.

The extinction distance relation shows a gradual trend of increasing \(E(B - V)\) with distance. At any distance there is a considerable scatter in \(E(B - V)\). The major part of this scatter is probably real and due to inhomogeneous extinction near AG Car. An inspection of the ESO Sky Survey plates in the area close to AG Car and even the finding chart given by Hoekzema (1991) shows that there is considerable structure in the extinction on angular scales as small as one or two arcminutes. We tried to make a distinction between star-rich (probably clear) and star-poor (probably clouded) areas. This distinction is shown in Fig. 6. Although this distinction is crude and somewhat subjective it serves for the discussion of our results.

Below the distance of 1.5 kpc there is no clear distinction in the \(E(B - V) - d\) relation of the two types of regions. At distances larger than 1.5 kpc the difference is obvious. AG Car itself is in a star-rich area and is surrounded at small angular distances by the relatively low extinction/large distance stars nrs 33, 18B, 32 and 36 with \(\{E(B - V), \log d\} = \{0.26, 3.27\}, \{0.33, 3.22\}, \{0.38, 3.30\}\) and \{0.55, 4.01\} respectively. So AG Car is probably in a relatively clear, low extinction area.

4.2. The interstellar extinction of AG Car

The total extinction of AG Car has been determined from a study of the UV and visual energy distribution (Lamers et al., 1989). The same value of \(E(B - V) = 0.60\) to 0.67 was derived from observations at different photometric phases when the star varied in magnitude between \(V = 6.23\) and \(V = 8.04\) and in spectral type between B0.5Ia and B5Ia. The mean value of \(E(B - V)\) derived by taking into account the accuracy of the determinations is \(E(B - V) = 0.63 \pm 0.02\). We did not find evidence for an anomalous extinction curve: i.e. the energy distributions corrected for the standard extinction curve of Savage and Mathis (1979) agree very well with the intrinsic energy distributions predicted by model atmospheres.

Part of the total extinction of \(E(B - V) = 0.63\) will be of interstellar origin, and part of it may be of circumstellar origin. For the comparison of the extinction of AG Car with that of the stars in the same direction, studied in this paper, we have to estimate the circumstellar contribution to the total extinction.

There is evidence for a substantial amount of circumstellar dust in the ring nebula of AG Car. IUE observations of the nebula by Viotti et al. (1988) show a nearly constant nebular/stellar continuum ratio between 2000 and 3000 Å which suggests that the nebular UV radiation is mainly due to scattering of stellar light by dust particles in the nebula. However, this dust is distributed highly asymmetrically. McGregor et al. (1988) found evidence for two peaks in the far-IR, located at about 9 arcsec from the star in the SW and NE direction. Parese and Nota (1989) observed a helical jet in the SW and a knot in the NE direction, with a total...
The high spatial resolution observations of AG Car by Paresce and Nota (1989) show that the area inside the ring away from the jet has an average surface brightness of $V = 19.2 \pm 0.05$ magn arcsec$^{-2}$. At the time of these observations AG Car had a visual magnitude of $V = 7.7$ magn. We assume that the circumstellar nebula has a mean diameter of 35″ (in reality it has an elliptical shape of 39″ × 30″) and that it contains a sphere with a homogeneous dust density outside the SW jet and the NE knot. In that case the total amount of visual radiation scattered in the direction of the observer is about $\pi (35/2)^2$ $F_V$, where $F_V$ is the flux corresponding to $V = 19.2 \pm 0.05$ magn arcsec$^{-2}$. The total magnitude of the visual radiation scattered by the homogeneous dust sphere is $11.7 \pm 0.05$ magn, which is 4.0 magn fainter than the star. This implies that the dust sphere has an optical depth for scattering of only $\tau \approx 0.025$. Assuming a normal albedo of $a \approx 0.70$ (Savage and Mathis, 1979) and isotropic scattering we find a total optical depth due to scattering and absorption by circumstellar dust of $\tau_\nu \approx 0.035$ which corresponds to $A_V \approx 0.04$ and $E(B - V)_{CS} \approx 0.01$. This rough estimate indicates that the circumstellar contribution to $E(B - V)$ is very small, and that we can assume an interstellar extinction of $E(B - V)_{IS} \approx E(B - V)_{local} = 0.63 \pm 0.02$.

4.3. The distance of AG Car

Since AG Car is in a low extinction region we can compare its distance and extinction with those of star nr 32 at $E(B - V) = 0.38$ and log $d = 3.30$ and star nr 36 at $E(B - V) = 0.55$ and log $d = 4.01$. This implies a distance of AG Car of $d > 3$ kpc with a probable range of $4 \leq d \leq 10$ kpc. This range agrees with the distance of 5.6 to 7.6 kpc derived from the radial velocity of AG Car (Humphreys et al., 1989).
Table 5. Wolf-Rayet stars within 1° from AG Car

<table>
<thead>
<tr>
<th>WR-nr</th>
<th>Type</th>
<th>$V$</th>
<th>$I_H$</th>
<th>$b_H$</th>
<th>$M_v$</th>
<th>$E(B-V)$</th>
<th>log $d$(pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>WN7</td>
<td>12.65</td>
<td>288.59</td>
<td>-1.01</td>
<td>-6.6</td>
<td>0.91</td>
<td>4.10</td>
</tr>
<tr>
<td>30</td>
<td>WC4+O4</td>
<td>13.70</td>
<td>288.90</td>
<td>-1.38</td>
<td>-6.0</td>
<td>0.91</td>
<td>4.19</td>
</tr>
<tr>
<td>31</td>
<td>WN4+O8V</td>
<td>10.69</td>
<td>288.50</td>
<td>+0.02</td>
<td>-5.0</td>
<td>0.61</td>
<td>3.64</td>
</tr>
<tr>
<td>32</td>
<td>WC5</td>
<td>17.3</td>
<td>289.36</td>
<td>+0.02</td>
<td>-3.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>WN4.5</td>
<td>14.50</td>
<td>290.03</td>
<td>-1.39</td>
<td>-4.6</td>
<td>1.02</td>
<td>3.98</td>
</tr>
<tr>
<td>35</td>
<td>WN6</td>
<td>13.83</td>
<td>289.97</td>
<td>-1.18</td>
<td>-5.3</td>
<td>1.03</td>
<td>3.98</td>
</tr>
<tr>
<td>AG Car</td>
<td>LBV</td>
<td></td>
<td>289.18</td>
<td>-0.70</td>
<td>var</td>
<td>0.63</td>
<td>3.80</td>
</tr>
</tbody>
</table>

With an apparent bolometric magnitude of $m_{bol} = 3.05 \pm 0.06$ (Lamers et al., 1989) and a total extinction of $E(B-V) = 0.63$ the value of $M_{bol} = -10.1$ at 4 kpc, -10.8 at 6 kpc, -11.5 at 8 kpc and -11.9 at 10 kpc. The empirical luminosity-amplitude relation for LBV’s derived from LBV’s in the LMC (Wolf, 1989b) suggests a value of $M_{bol} \approx -10.4$ for AG Car, which is just inside the most probable range derived from the extinction-distance relation. Van Genderen et al. (1989) derived a characteristic time of $P \approx 13.8$ days for the micro-variations of AG Car. Using the empirical relation between the characteristic time of the micro-variations and the bolometric magnitude they find that AG Car’s value of $M_{bol} \approx -10$ to -11. This also agrees with our value derived from the extinction distance relation. In summary, the different distance determinations provide a consistent estimate:

- from $E(B-V) - \log d$ relation: $4 \leq d \leq 10$ kpc
- from $V_{rad}$: $5.6 \leq d \leq 7.6$ kpc
- from $\Delta B - M_{bol}$ relation: $d \approx 5.0$ kpc
- from $P - M_{bol}$ relation: $4.1 \leq d \leq 6.5$ kpc
- Mean value: $d = 6 \pm 1$ kpc

5. Discussion and conclusions

The extinction in the direction of AG Car is inhomogeneous on a small scale of arcminutes. AG Car is in a star-rich region of low extinction. The total extinction of AG Car is $E(B-V) = 0.63$ with an interstellar contribution in the range of 0.61 to 0.63 magn. This extinction suggests a distance in between that of star nr 32 at 2 kpc and star nr 36 at 10 kpc, which are both in the same star-rich region as AG Car, with a most probable range between 4 and 10 kpc. Combining four independent methods for distance determinations we find that $d = 6 \pm 1$ kpc and $M_{bol} = -10.8 \pm 0.4$ magn.

The region around AG Car is rich in luminous stars. Within the region of 20 arc min around AG Car we found a large number of 50 to 100 luminous stars. For 23 of these we derived a distance larger than 2 kpc and $M_v < -1"$. This high concentration is due to the fact that the line of sight to AG Car is almost tangentially into the Carinae spiral arm. This richness is also found in the distribution of Wolf-Rayet stars. There are six WR stars within 1 degree from AG Car at distances between 4 and 15 kpc (Van der Hucht, 1988). Some of the stars may belong to a cluster with AG Car as a member.

It is interesting to study the region close to AG Car with deep CCD-photometry in order to confirm the presence of a cluster near AG Car and to determine its stellar content and age.

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References

Van der Hucht, K.A., Hidayat, B., Admiranto, A.G., Supelli, K.R.,
Van Genderen, A.M., Thé, P.S., Augusteijn, T., Engelsman, E.C.,
Wolf, B.: 1989a in “Physics of Luminous Blue Variables”, eds. K.
Davidson et al. (Dordrecht: Kluwer), p. 91.

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\textbf{Note added in proof:} In Table 3 star nr 76B with }\textit{V = 11.600}
should be star nr 76 BA