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# A POLARIMETRIC SEARCH FOR CIRCUMSTELLAR ENVELOPES IN THE YOUNG CLUSTERS NGC 6611 AND NGC 225

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## RESUMEN

Usamos mediciones de la polarización lineal observada en estrellas pertenecientes a los cúmulos jóvenes NGC 6611 y NGC 225 en un intento por detectar la presencia de envolventes circumestelares. Aunque muchas de estas estrellas muestran valores relativamente altos de polarización, esta polarización tiene un origen interestelar. No se encuentra ninguna evidencia que confirme la conclusión de Reddish (1967) la cual sugiere que las estrellas más brillantes en los cúmulos jóvenes se encuentran rodeadas por envolventes circumestelares.

## ABSTRACT

Polarimetric observations of stars located in the young clusters NGC 6611 and NGC 225 are used to attempt detection of circumstellar envelopes. While many stars show relatively large polarization values, the observed polarization appears to be primarily interstellar in origin. No evidence is found to support the contention of Reddish (1967) that the most luminous members of young clusters are surrounded by circumstellar envelopes.

*Key words:* CIRCUMSTELLAR SHELLS — INTERSTELLAR EXTINCTION — POLARIZATION — YOUNG CLUSTERS.

## I. INTRODUCTION

An apparent increase of interstellar reddening with increasing stellar luminosity, first discovered by Blanco and Williams (1959) in the Cepheus IV association, has been argued to occur in most clusters and associations whose age is less than $2 \times 10^6$ years (Reddish 1967). Reddish suggests that the increased reddening is produced by circumstellar envelopes of gas and dust that surround the very young, early-type stars in these stellar aggregates. For older clusters, Reddish speculates that circumstellar envelopes may have contracted into disks. A proper understanding of the frequency of occurrence and evolution of circumstellar envelopes among early-type stars might add considerably to our understanding of the early phases of stellar evolution. For example, the spherical-collapse calculations summarized by Larson and Starrfield (1971) suggest that O and early B stars may be surrounded by infalling circumstellar envelopes which are not fully accreted until well after these massive stars reach the main sequence. Confirmation of Reddish's results would lend considerable weight to their picture. However, Bohannan (1975) and Walker (1965) have argued that the Reddish effect arises from an observational selection effect since surveys to a given limiting magnitude discriminate against the discovery of highly reddened stars of low lumi-

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nosity. Furthermore, the spectroscopic and photometric data for many of the clusters studied by Reddish are not of the highest quality (Bohannan 1975).

In view of the controversial nature of existing spectrophotometric evidence concerning the Reddish effect, we have chosen to search for circumstellar envelopes using a different technique. Breger and Dyck (1972) and Breger (1974) have shown that circumstellar envelopes may be detected by the linear polarization produced by asymmetries in the distribution of scattering elements in these envelopes. This detection method is successful so long as the envelope polarization is large compared with the polarization introduced by aligned interstellar grains in the line of sight. Even in such cases, envelopes can be detected by observing either large departures from the wavelength dependence of polarization characteristics of the interstellar medium or from rotation of the electric vector orientation with wavelength.

We report in this contribution the results of a polarimetric search for circumstellar envelopes among upper main sequence stars in two young clusters: NGC 6611 and NGC 225.

## II. GENERAL CHARACTERISTICS OF THE CLUSTERS

### *a) NGC 6611*

It is a rich open cluster with a large number of O and B stars located within an ionized hydrogen complex. This cluster is located in the plane of the galaxy at a distance of 2.5 kpc ($m - M = 12.0$; $l_{II} = 17°$; $b_{II} = 0.8°$). Extensive protoelectric and photographic UBV observations by Walker (1961) and by Hoag *et al.* (1961) show that this cluster has a color-magnitude diagram characteristic of extremely young aggregates; large numbers of stars later than type B8 are observed to lie above the main sequence. From spectroscopic and photometric observations of upper main sequence stars, Hiltner and Morgan (1969) derive a turn-off point that suggests an age of $t \simeq 1.5 \times 10^6$ years. Walker's (1961) photometric data also indicate that (*i*) the amount of extinction suffered by cluster members is highly variable and (*ii*) the amount of foreground extinction is small. The discussion by Reddish (1967) of the spectroscopic and photometric data for the cluster members selected from the proper-motion study by van Schewick (1962) suggests a strong correlation between the color excess $E(B - V)$ and the intrinsic luminosity ($V_0$) of the stars. Reddish classifies the cluster as belonging to his class (a) ("strong increase of color excess with luminosity").

### *b) NGC 225*

This cluster is located at a distance of 650 pc ($l_{II} = 122°$, $b_{II} = 11.1°$) in the Cygnus arm. Photoelectric and photographic photometry by Hoag *et al.* (1961) and the subsequent analysis of these data by Johnson *et al* (1961) indicate that NGC 225 has an upper main sequence turnoff which suggests an age somewhat greater than that derived for NGC 6611. However, the cluster is associated with a dark cloud that contains the Herbig emission star *BD* + 61°154 (Herbig 1960). This star appears to be approaching the main sequence along an equilibrium radiative track (Strom *et al.* 1972) and may not be older than $10^6$ years. Hence, the cluster may contain some extremely young stars. The stars in NGC 225 also appear to suffer highly variable extinction. Therefore, although this cluster is not among those analyzed by Reddish, the apparent youth of some of its members and the observed variable extinction suggest that it may be a suitable candidate for our polarimetric study of the Reddish effect.

## III. THE OBSERVATIONS

In order to determine the origin of the variable extinction that affects the stars in NGC 6611 and NGC 225, we have measured linear polarization for the brightest stars in these clusters. These measurements were obtained with the 1.3 m telescope and the Dyck polarimeter at Kitt Peak National Observatory. Most of the observations were made at either the Johnson *V* or *R* bandpasses. However, some stars were also observed at *U*, *B* and at λ7500 (through an interference filter whose full width at half maximum is 600 Å). The observational data obtained for stars in NGC 6611 are summarized in Tables 1 and 2.

TABLE 1

PHOTOMETRIC AND POLARIMETRIC DATA FOR NGC 6611

| Star (1) | V (2) | $V_0$ (3) | Sp. Type (4) | E(B−V) (5) | $P_R$ (%) (6) | ΔP (7) | θ (8) | Δθ (9) |
|---|---|---|---|---|---|---|---|---|
| W 125 | 10.05 | 7.74 | B1.5V | 0.74 | 3.26 | 0.08 | 73° | 0.7 |
| W 161 | 11.30 | 6.95 | O8 – O5* | 1.38 | 0.47 | 0.18 | 85 | 10.9 |
| W 166 | 10.36 | 7.48 | O9V | 0.91 | 4.11 | 0.08 | 68 | 0.6 |
| W 175 | 10.05 | 6.60 | O6 | 1.17 | 4.77 | 0.09 | 50 | 0.5 |
| W 197 | 8.77 | 6.34 | O7 | 0.79 | 3.21 | 0.08 | 69 | 0.7 |
| W 205 | 8.24 | 5.75 | O5 | 0.80 | 3.31 | 0.04 | 67 | 0.3 |
| W 207 | 12.14 | 10.10 | B2* | 0.68 | 3.04 | 0.21 | 67 | 2.0 |
| W 222 | 13.02 | 7.83 | B0 – O9* | 1.73 | 5.31 | 0.26 | 61 | 1.4 |
| W 223 | 11.22 | 8.40 | B1V | 0.89 | 4.12 | 0.13 | 64 | 0.9 |
| W 246 | 9.60 | 5.94 | O8f | 1.21 | 5.17 | 0.08 | 67 | 0.4 |
| W 254 | 10.81 | 8.59 | B2 | 0.74 | 2.53 | 0.11 | 67 | 1.2 |
| W 255 | 13.05 | ... | ... | ... | 0.94 | 0.15 | 63 | 4.6 |
| W 259 | 11.60 | 8.42 | B0.5* | 1.06 | 4.43 | 0.16 | 72 | 1.0 |
| W 275 | 11.89 | 10.39 | B2* | 0.50 | 2.92 | 0.23 | 74 | 2.3 |
| W 280 | 9.94 | 7.09 | B0 | 0.95 | 3.01 | 0.11 | 74 | 1.1 |
| W 289 | 12.67 | 10.48 | B3* | 0.73 | 3.73 | 0.25 | 67 | 1.9 |
| W 301 | 12.20 | 9.77 | B5 | 0.81 | 3.63 | 0.31 | 78 | 2.4 |
| W 314 | 9.86 | 7.07 | O9.5V | 0.93 | 3.26 | 0.09 | 79 | 0.8 |
| W 343 | 11.65 | 7.60 | B0 – O9* | 1.35 | 3.06 | 0.15 | 71 | 1.4 |
| W 367 | 9.43 | 7.69 | O9.5V | 0.58 | 2.47 | 0.08 | 74 | 0.9 |
| W 400 | 12.83 | 10.88 | A2 | 0.65 | 1.20 | 0.15 | 84 | 3.6 |
| W 401 | 8.95 | 6.67 | O8V | 0.74 | 2.91 | 0.06 | 71 | 0.6 |
| W 402 | 11.48 | 8.90 | K0II | 0.86 | 1.57 | 0.12 | 74 | 2.2 |
| W 412 | 8.30 | 6.32 | B0III – O8V | 0.66 | 0.92 | 0.08 | 79 | 2.5 |
| W 469 | 10.74 | 8.55 | B1.5V | 0.68 | 1.40 | 0.12 | 75 | 2.5 |
| W 503 | 9.69 | 7.11 | B0 – B5e | 0.86 | 1.85 | 0.09 | 91 | 1.4 |

* These spectral types were derived by applying the Q method of Johnson & Morgan (1953) to Walker's (1961) photometry. These spectral types are uncertain since this method assumes the extinction law to be normal in the region of study. The interstellar matter associated with young clusters may contain larger than average dust grains since grain growth takes place in dark clouds as shown by Carrasco, Strom and Strom (1973).

In Table 1, we list the following:

- Column 1 — Identification, where designations are those given by Walker (1961).
- Column 2 — The apparent $V$ magnitude.
- Column 3 — $V_0$, the unreddened apparent $V$ magnitude derived by assuming. $A_V = 3E(B - V)$.
- Column 4 — Spectral type as quoted by Walker (1961) or by Hiltner and Morgan (1969), unless otherwise specified.
- Column 5 — The color excess $E(B - V)$ as derived from the spectral types and the photometry by Walker (1961).
- Columns 6-7 — The polarization percentage in the $R$ bandpass and its mean error.
- Columns 8-9 — The electric vector orientation and its mean error (evaluated following Serkowski, 1962).

In Table 2, we list the polarization values measured at five wavelengths for some of the brighter members of NGC 6611. In the last column, we list the wavelength of maximum polarization as derived by fitting the observed polarization values to the "standard" interstellar curve derived by Serkowski (1973).

Table 3 is a summary of our polarimetric data for NGC 225. In column 1, we list the identification, as given either by Hoag *et al.* (1961) or assigned by us (Figure 3 — Plate 12). Columns 2-5 present our determinations of the percentage polarization

TABLE 2

WAVELENGTH DEPENDENCE OF POLARIZATION FOR NGC 6611

| Star (1) | U (2) | B (3) | V (4) | R (5) | λ7500 (6) | <θ> (7) | $\lambda_{max}$(Å) (8) |
|---|---|---|---|---|---|---|---|
| W 314 | 2.07 ± 0.18 | 2.97 ± 0.12 | 3.18 ± 0.10 | 3.26 ± 0.09 | 2.86 ± 0.19 | 78° | 6100 |
| W 205 | 2.78 ± 0.08 | 3.15 ± 0.06 | 3.48 ± 0.06 | 3.31 ± 0.04 | 3.19 ± 0.09 | 67 | 5700 |
| W 197 | 2.22 ± 0.11 | 3.10 ± 0.08 | 3.14 ± 0.08 | 3.21 ± 0.08 | 2.70 ± 0.12 | 70 | 5700 |
| W 401 | 2.16 ± 0.09 | 2.31 ± 0.09 | 2.84 ± 0.09 | 2.91 ± 0.06 | 2.45 ± 0.04 | 72 | 5700 |
| W 246 | 4.39 ± 0.18 | 5.04 ± 0.12 | 5.34 ± 0.12 | 5.17 ± 0.08 | 4.74 ± 0.14 | 67 | 5400 |

TABLE 3

POLARIZATION DATA FOR NGC 225*

| Star (1) | $P_V$ (%) (2) | ΔP (3) | θ (4) | Δθ (5) |
|---|---|---|---|---|
| H-1 | 0.70 | 0.19 | 75° | 7.8° |
| H-2 | 1.54 | 0.08 | 85 | 1.5 |
| H-3 | 1.81 | 0.11 | 87 | 1.7 |
| H-4 | 2.31 | 0.11 | 81 | 1.4 |
| H-5 | 1.16 | 0.13 | 73 | 3.2 |
| H-7 | 1.40 | 0.10 | 93 | 2.1 |
| H-8 | 2.17 | 0.12 | 90 | 1.6 |
| H-10 | 2.30 | 0.11 | 82 | 1.4 |
| H-11 | 1.52 | 0.11 | 87 | 1.9 |
| H-12 | 1.99 | 0.12 | 82 | 1.8 |
| H-13 | 0.51 | 0.15 | 36 | 8.4 |
| H-14 | 0.91 | 0.17 | 74 | 5.3 |
| H-23 | 0.94 | 0.39 | 81 | 11.9 |
| H-29 | 1.50* | 0.67 | 88 | 12.8 |
| H-33 | 0.38 | 0.17 | 64 | 12.8 |
| H-38 | 1.49* | 0.20 | 104 | 3.8 |
| H-39 | 3.60* | 0.50 | 88 | 3.8 |
| L-1 | 1.70 | 0.33 | 116 | 5.6 |

* The polarization for these stars was measured through the bandpass defined by an S-20 photocathode without filter.

and orientation of the electric vectors with their respective errors.

## IV. RESULTS

The data listed in Table 1, 2, and 3 show the following characteristics:

1) The polarization values observed for stars in both clusters are relatively large.

2) The polarization-to-extinction ratio for stars in NGC 6611 is large. This conclusion is supported by the plot of polarization (at $R$) against $E(B-V)$ presented in Figure 1. Superposed on this plot is a solid line whose slope corresponds to the maximum polarization-to-extinction value observed in the general interstellar medium. We have not presented similar data for NGC 225 since the available photometric data are not sufficiently accurate.

3) The wavelength dependence of polarization observed for the brighter stars in NGC 6611 is similar to that derived for the large and heterogeneous sample of stars discussed by Serkowski (1973). Furthermore, the observed wavelength of maximum polarization is comparable with the $\lambda_{max}$ value of 5500 Å derived by Serkowski for the general interstellar medium.

4) In both clusters, the electric vectors show a very small dispersion in orientation. For NGC 6611 the mean e-vector orientation is 73°6 with a standard deviation per star of 6°7, while for NGC 225, the corresponding values are 81°6 and 8°0, respectively. These results are illustrated more dramatically in Figure 2 (Plate 11) and Figure 3 (Plate 12). In these figures, the polarization values are represented by vectors whose length is proportional to the magnitude of the polarization observed at $V$ or $R$ while the direction of the vector indicates the observed position angle of the e-vector. With the exception of H 38 and L 1 in NGC 225 and W 175 and W 503 in NGC 6611, the stars having e-vector orientations deviating significantly from the mean are those having small measured polarization and consequently higher intrinsic errors in the derived orientation.

We should also note that the e-vector orientation observed for W 402 in NGC 6611 lies very close to the mean value for the other stars in our sample. This result provides some support for assigning

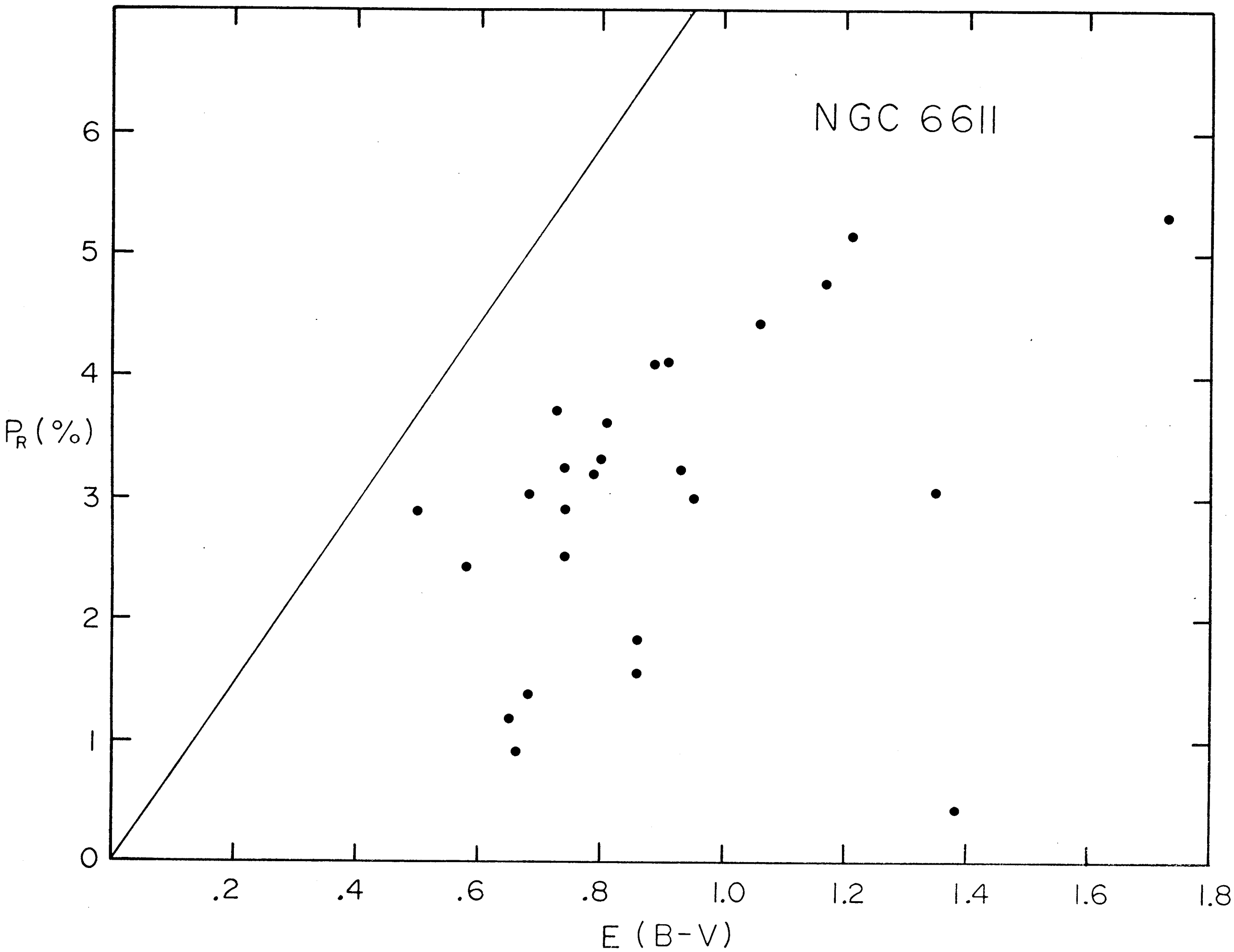


FIG. 1. The linear polarization in the R bandpass plotted against E(B − V). The polarization is well correlated with the amount of reddening. The solid line represents the maximum slope of the polarization against extinction relation observed under interstellar conditions.

membership in the NGC 6611 cluster to this luminous K0 II star. If so, W 402 is either (a) much older than other stars in the cluster and currently evolving across the Hertzsprung gap toward the red-giant domain, or (b) somewhat younger than other massive stars in the cluster and approaching the main sequence along an equilibrium radiative track appropriate to $M \simeq 100\ M_\odot$ This object is clearly worthy of detailed spectroscopic study.

## V. DISCUSSION

The results presented in §IV lead to the following conclusions:

1) Both the polarization and extinction are produced by the same agent since the amount of polarization is well correlated with the color excess. The responsible agent is most likely aligned interstellar grains located along the line of sight to the cluster stars.

2) The above conclusion is strengthened by the similarity of the observed wavelength dependence of polarization to the "universal" curve derived by Serkowski (1973).

3) For each cluster, a single cloud produces a large fraction of the observed polarization and extinction since the e-vector dispersion is small. Most probably, the dark-cloud material associated with

each cluster is responsible for both the observed polarization and extinction.

The only stars in our study which may show evidence of circumstellar envelopes are those whose e-vectors deviate significantly from the cluster means: W 175 and W 503 in NGC 6611, and L 1 and H 38 in NGC 225. In the case of W 503, the result is not unexpected since Walker (1961) has already identified this star as an emission-line object. Although W 175 is relatively luminous, it is certainly not among the most heaviliy obscured objects in the cluster. Unfortunately, there are insufficient data available to discuss the stars in NGC 225.

Our data do not appear to support Reddish's (1967) *general* conclusion that stars of high luminosity in young clusters are typically surrounded by circumstellar envelopes.

It could be argued that the high line-of-sight polarization suffered by most cluster stars obscures a possibly much smaller polarization contribution from putative circumstellar envelopes. However, the strong correlation between $p$ and $E(B\text{-}V)$ observed for stars in NGC 6611 suggests that a large fraction of the extinction occurs along the line-of-sight rather than in circumstellar envelopes.

## VI. CONCLUSIONS

The basic results of this investigation can be summarized as follows:

1) The observed polarization is well correlated with the derived extinction for stars in NGC 6611.

2) The wavelength dependence of polarization for these stars is typical of polarization arising from interstellar dust grains.

3) For both NGC 6611 and NGC 225, the electric vectors show a very small dispersion about the mean observed for the cluster.

4) A few stars in these clusters have polarization characteristics that suggest the presence of circumstellar shells. However, the occurrence of shells is far from being a general feature. Moreover, these stars are neither among the most luminous nor the most heavily reddened members of these clusters.

5) No evidence is therefore found to support Reddish's conclusion that the most luminous stars in young clusters are surrounded by circumstellar envelopes.

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