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A PHOTOMETRIC STUDY OF THE ORION OB 1 ASSOCIATION. II. PHOTOMETRIC ANALYSIS

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ABSTRACT

The procedures adopted for analysis of the photometric data of Paper I (Warren and Hesser 1977) in terms of color excesses, intrinsic color indices, absolute visual magnitudes, and rotational-velocity effects are discussed in detail for Orion association B-, intermediate (I)-, and AF-type stars. The effects of the nebular environment and a comparison of various calibrations of Balmer-line and four-color indices are considered for the determination of individual absolute magnitudes for B-type stars. When absolute magnitudes of stars in the region of the Orion Nebula are determined from the β index, emission mechanisms appear to spuriously brighten them. A detailed comparison of absolute magnitudes derived from Balmer-line indices and MK spectral-type calibrations is presented.

The *uvby*β data are also examined with regard to the effects of polarization and infrared excesses. The results suggest a complex combination of intracluster and circumstellar origins for these processes.

Subject headings: absolute magnitudes--associations: stellar--nebulae: Orion Nebula--photometry

I. INTRODUCTION

Prior to undertaking a comparative analysis of the individual subgroups of the Orion OB 1 association using the photometric data of Paper I (Warren and Hesser 1977), we examine in this paper the methods adopted for reduction of the observed data to intrinsic indices and the derivation of absolute visual magnitudes and distance moduli. We also examine the extent to which such derived parameters may be dependent upon errors or inconsistencies in the calibrations, stellar axial rotation, and emission mechanisms resulting in polarization and ultraviolet- and infrared-excesses for certain stars in the association.

Analysis of the *uvby*β photometric data divides naturally (Strömgren 1966) into three stellar groups and we will follow that pattern here. In turn we discuss in § II the early group (O- and B-type stars); in § III the intermediate (I) group (∿A0-A2); and in § IV the late group (A, F and early G stars). Each of these sections is further divided into discussions of the standard procedures, absolute-magnitude calibrations, and effects of axial rotation on the observed parameters. In § V we review previous work on the effects and interpretation of infrared excesses and polarization in young stellar groups before presenting some relationships found among our new photometric observations and the above data. The detailed results of the photometric analysis presented here will be deferred until Paper III, where our final analyses of the Orion OB 1 subgroups in terms of distances, color excesses, and ages will be given.

II. B-TYPE STARS

a) Color Excesses

The color excesses and intrinsic photometric indices are determined from the *uvby* photometry by an iterative procedure described by Crawford and Barnes (1970*a*). A preliminary calibration of the four-color indices in terms of intrinsic color (Crawford 1970*b*) is used to find a first approximation to $(b-y)_0$: $(b-y)_0' = -0\overset{m}{.}116 + 0.097c_1$. Preliminary values of $E(b-y)$ and $E(c_1) = 0.2E(b-y)$ then yield a first approximation to c_0 which is substituted back into the $(b-y)_0'$ relation to obtain $(b-y)_0$. After calculating $E(b-y)$ from $E(b-y) = (b-y) - (b-y)_0$, the other reddening-free indices are found from the following relations:

$$c_0 = c_1 - E(c_1) = c_1 - 0.2E(b-y) \ , \qquad (1)$$

$$m_0 = m_1 - E(m_1) = m_1 + 0.3E(b-y) \ , \qquad (2)$$

$$(u-b)_0 = (u-b) - E(u-b) = (u-b) - 1.6E(b-y) \ , \qquad (3)$$

where

$$(u-b) = c_1 + 2[m_1 + (b-y)]. \qquad (4)$$

A modified *Q* method for calculating color excesses from the *UBV* photometry is used in the reduction program as a cross-check. The expression $(U-B)_0 = 1.242(U-B) - 0.894(B-V)$, valid for a linear reddening line of slope $E(U-B)/E(B-V) = 0.72$ (Crawford 1958) is used to find $E(U-B) = (U-B) - (U-B)_0$ for each star having *UBV* photometry.[1] Since $E(U-B) = 0.72E(B-V)$

[1]We note that no evidence for appreciable differences from the *normal* reddening ratio has been found in any part of the Orion association (Sharpless 1954, Lee 1968). A more recent expression derived by Heintze (1973) has also been checked and appears to give the same results to within the errors of the determination.

and $E(b-y) = 0.73E(B-V)$, these quantities should check well for individual stars. Figure 1 shows the $E(b-y)$, $E(U-B)$ relation for all B-type program stars in Orion. A tendency for stars of high color excess to lie above the unit slope line may be due to differential effects of blue continuum emission on the *B* filter for stars in the vicinity of the nebula; this will be discussed in further detail in Paper III.

b) Absolute Magnitudes and MK Spectral-Type Relations

i) β, $M_V(\beta)$

For the determination of absolute magnitudes and thence distance moduli for individual B-type program stars, we use Crawford's (1973) preliminary β, M_V calibration *without* applying corrections for evolutionary effects[2] (Crawford 1970*a*,*b*).

[2]Evolutionary corrections will not be necessary or perhaps even desirable here since we are dealing with a young group where the only stars expected to deviate to any extent from the zero-age main sequence (ZAMS) are emission objects for which the calibration is not appropriate due to anomalously

low β indices. [This may not be strictly true for the extreme upper main sequence of the Orion 1a subgroup, but very few stars are contained in this region of the color-magnitude (c-m) diagram and we shall deal with those individually.]

In order to measure the deviation of a star from the ZAMS we compute a quantity $\delta\beta = \beta[c_0] - \beta$, where $\beta[c_0]$ is the value of β for a given c_0.[3] Since emission decreases the β index and produces a large positive δβ value, the quantity δβ is very useful for picking out emission stars for which the β, $M_V(\beta)$ calibration is not valid. Fortunately, the *uvby* colors of many Orion O and B stars are free of emission effects (cf. Paper III), and hence a $(b-y)_0$, M_V relation can be used to find M_V (ZAMS) for them.

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[3]The β, c_0 calibration is non-linear, hence a four-point Lagrangian interpolation routine was incorporated into the reduction program to calculate δβ. Values of δβ are generally found to agree within a few thousandths of a magnitude of those derived from a linear interpolation.

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ii) $M_V(\alpha,\beta,\gamma)$ *Comparisons*

Considering the difficulties encountered in past attempts to calibrate Balmer-line intensities for absolute magnitude, and the general problem of possible continuum and line emission in our Orion program stars, it was decided to compare our β indices with measurements of Hα and Hγ made by other workers, and also to compare the absolute magnitudes derived from the β calibration with those derived from other Balmer lines and from MK spectral types. This comparison is not intended to be complete, but is made principally to investigate possible systematic errors and/or adverse effects resulting from working in an association containing a large number of objects affected by various types of emission and nebulosity problems.

In order to compare the Balmer-line measures, photoelectric Hα indices from Andrews (1968) and Hγ equivalent widths from Crampton, Leir and Younger (1973) have been used for all Orion stars in common with our program.[4] The relation

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[4]About two dozen program stars have also been measured photoelectrically on different Hγ systems by Beer (1964) and by Bappu *et al.* (1961), but most of these are in the Victoria catalogue. Photoelectric measures of bright stars have been made by Tebbe (1969) on a narrow-band α system, but he has far fewer stars in common with our program than does Andrews. Recently, Feinstein (1974) observed a large number of normal, Be, Am, and He-weak stars, determining photoelectric α, β, and γ indices simultaneously; he has observed only two of our Orion program stars for which his β indices agree well with our values.

between Andrews' Rα index and β, Figure 2, is seen to be fairly tight for dwarfs, while high-luminosity and emission stars are well-separated from the main-sequence locus. A smooth transition to emission occurs at $\beta \lesssim 2^{m}.59$, in agreement with theoretical predictions by Mihalas (1972); this transition can be seen more clearly in a similar plot of Crawford, Barnes and Perry (1975), which contains many more stars. The absolute visual magnitudes plotted in Figure 3 scatter rather uniformly about the unit-slope line with a correlation coefficient, r, of 0.96 for 37 stars. The principal deviants are seen to be at B0 V ($M_V \sim -4$), where two stars are found well below the line. One of these stars is υ Ori which, according to our photometry, appears to be an O star. This star is stated by Heintze (1973) to be O9.5 V in the *UBV* two-color diagram and its T_{eff} is discussed as being more representative of the O9.5 V type according to the NLTE models of Auer and Mihalas (1972). Since Andrews' M_V calibration includes corrections for He II λ6560 for O but not B main-sequence stars, we can presume that no correction was applied for υ Ori. The absence of such a correction results in an Rα value indicating a stronger Hα line and hence greater (algebraically) $M_V(\alpha)$, as seen in the diagram. A similar situation may prevail for the other star (HD 36960), for which the β value is more representative of an O-type star, although its spectrum has been noted as possibly composite (Murphy 1969) with emission.

The Hγ equivalent widths are plotted against β in Figure 4 and again the agreement is excellent. The mean line is expressed by the relation $\beta = 0.022W(H\gamma) + 2^{m}.516$ (51 stars, r=0.91). For comparison of the absolute magnitudes predicted by $W(H\gamma)$ and β, we have derived an expression relating $W(H\gamma)$ and $(b-y)_0$, analogous to the calibration equation of Balona and Crampton (1974) for $W(H\gamma)$ and $(B-V)_0$. Using the $(B-V)$, $(b-y)$ [Fig. 5] and $(U-B)$, $(u-b)$ [Fig. 6] diagrams derived from the union of *UBV* (Johnson and Morgan 1953, Johnson and Harris 1954) and *uvby* (Crawford and Barnes 1970*b*) photometric standards we find the following relations:

$$(B-V) = 1.668(b-y) - 0^{m}.030\ , \quad (b-y) = 0.598(B-V) + 0.019\ ; \qquad \text{(94 stars, r=0.999)} \tag{5}$$

$$(U-B) = 0.727(u-b) - 0.984\ , \quad (u-b) = 1.371(U-B) + 1.355\ . \qquad \text{(96 stars, r=0.998)} \tag{6}$$

[These transformations are valid for both reddened and unreddened stars, as can be seen in the $(u-b)$, $(U-B)$ diagram for B stars given by Crawford, Barnes and Golson (1971).] The calibration equation of Balona and Crampton now becomes

$$M_V(\gamma) = -\,9^{m}.50 - 11.98(b-y)_0 + 9.59\log W + 16.11(b-y)_0 \log W. \tag{7}$$

Using this relation we have calculated $M_V(\gamma)$ values for all Orion stars having $W(H\gamma)$ data; these values are plotted against $M_V(\beta)$ in Figure 7. Here we find that the $M_V(\beta)$ values are systematically brighter by about $0^m.5$ or more. Although values in the range $-2 \leq M_V(\gamma) \leq -1$ appear to agree, this should not be the case when a comparison of the $W(H\gamma)$ and β calibrations is considered. The average difference in the calibrations between B2 V and B5 V is such that the $W(H\gamma)$ calibration is about $0^m.7$ brighter, a difference that should cause most points in this range to lie below the line of unit slope in the diagram. A similar diagram, Figure 8, for field dwarfs composed of late O and early B stars with classifications on the new MK† system (Morgan and Keenan 1973) confirms this expectation. Clearly, something is affecting the relationship between the absolute magnitudes of the Orion stars as derived from their β and $W(H\gamma)$ indices, and a closer examination is desirable.

iii) *Possible Detrimental Effects on $M_V(\beta)$*

To examine possible effects on $M_V(\beta)$, the list of stars in Figure 7 has been investigated using MK types and predicted values of β and c_0 as tabulated by Crawford (1973). If the deviations are in $M_V(\beta)$ then the β values are systematically low, thus decreasing the absolute magnitudes (brightening the stars). A comparison of tabulated β values for each spectral type with our measured values yields a mean difference of only $+0^m.005 \pm 0^m.012(\sigma)$ for 33 stars, corresponding to an increase of only $0^m.2$ in $M_V(\beta)$ at B0 V. The difference in the diagram is $0^m.5$ in M_V at B0; hence we cannot attribute the discrepancy exclusively to $M_V(\beta)$, although some brightening may be present.

The effect of using photometric colors to compute $M_V(\gamma)$ values with the calibration of Balona and Crampton can be assessed by using the MK types and corresponding integer S values in their alternate expression. The resulting relationship shown in Figure 9 differs little from that of Figure 7. However, when we use only the spectral types with the MK calibration of Balona and Crampton (Fig. 10) the diagram is altered significantly, the points in the range B2 V to B5 V ($M_V \sim -1$ to -3) having moved down to the positions expected from the differences in the $W(\mathrm{H}\gamma)$ and β calibrations in this range. On the other hand, while the earlier and peculiar stars remain above the unit slope line, they lie much nearer to it than before. Unfortunately the problem is not yet solved and it is not clear why the color- and S-relations do not give better agreement with the MK calibration table and the predictions for field stars.

Some of the absolute-magnitude effects encountered here appear to agree with the suggestion of Strom, Strom and Yost (1971) and Smith (1972) that small residual core emission at Hγ and Hβ is affecting the derivation of absolute magnitudes from these lines. This effect is predicted to be about 5 percent in line depth or $0^{\mathrm{m}}.01$ in a line-centered photometric system at Hγ and increases to $0^{\mathrm{m}}.03$ in the β index (Smith 1972). The average decrease in β for stars in the Trapezium region, if occurring, is accompanied by a corresponding decrease in the c_0 index due to continuum emission in the blue region, thus c_0 predicts an earlier type while β predicts a brighter value for $M_V(\beta)$. These two motions would combine to move stars upward along the main sequence but not away from it, hence δβ values remain small. The slightly decreased equivalent widths of Hγ would also predict brighter $M_V(\gamma)$ values, but the magnitude of the effect is smaller at Hγ and stars are moved upward in the $M_V(\beta)$, $M_V(\gamma)$ plane. A decrease of $0^m.03$ in β at B0 corresponds to a decrease of about $0^m.07$ in c_0 on the ZAMS and a brightening of $1^m.7$ in $M_V(\beta)$ if δβ remains near zero. Referring to Figure 7, we find the following distances above the unit slope line for the nebula stars: θ^1 A (O7 V) - $2^m.2$; θ^1 B (B0.5 V) - $1^m.0$; θ^1 C (B0.5 V, O8 Vn) - $1^m.8$; θ^1 D (B0 V) - $1^m.4$; θ^2 A (O9 V, O9.5 V) - $0^m.8$; θ^2 B (B1 V, B0.5 V) - $1^m.8$. The photometric spectral types predicted by the observed c_0 indices for the latter five stars are O9, B0, B2, O8, O9 respectively, confirming the suggestion that these stars look earlier photometrically than their MK types. The c_0 index for θ^1 A (= $-0^m.201$) is much too blue for any MK type and θ^1 D (= BM Ori) is a very peculiar object predicted to lie well above the main sequence ($\delta\beta = +0^m.053$).

As a final check for adverse effects on the δβ index, we have determined absolute visual magnitudes from the four-color photometry alone using the computed $(b-y)_0$ values and standard $(b-y)_0$, $M_V(\beta)$ relation for the ZAMS. The difference $M_V(\beta) - M_V[(b-y)_0]_{ZAMS}$ is plotted against $\delta\beta = \beta[c_0] - \beta$ in Figure 11. This diagram supports the conclusion that as β decreases ($\delta\beta$ increases) the corresponding change in absolute visual magnitude is accurately predicted by $\delta\beta$. The solid line is given by $M_V(\beta) = M_V[(b-y)_0]_{ZAMS} - 31\delta\beta$, but the supergiants are seen to follow a separate relation. This indicates that separate correction factors, $\delta\beta$, are needed for high-luminosity stars in order to derive absolute magnitudes using the intrinsic colors and $\delta\beta$ indices. It also shows qualitatively why a correction factor $\delta\beta$ is not necessary when deriving absolute magnitudes for supergiants from the $M_V(\beta)$ calibration. The change in gravity for high luminosity stars is compensated for nicely by the change in β at a given color, hence reliable absolute magnitudes are predicted from β alone. This will be seen even more clearly in the ensuing discussion.

iv) *Detailed Comparison of Absolute Magnitudes*

Since we have been unable to produce any definite conclusions concerning systematic effects on the absolute magnitudes for the Orion stars as derived from β, other than the fact that stars in the nebula region appear considerably brighter due to probable continuum and line emission effects, it seems instructive at this point to present a detailed comparison of absolute visual magnitudes as derived from the various parameters discussed. We therefore list in Table 1 all stars for which the $M_V(\alpha,\beta,\gamma)$ comparison has been made. Using *preliminary* mean distance moduli <dm> for the various subgroups and V_0 values derived from reduction of the four-color photometry (Paper III), we also compare $M_V(\langle dm\rangle)$ values.

These are not expected to be very accurate due to the large spread in distance,[5] both within some subgroups and among

[5]For this reason we have not corrected the V_0 data for duplicity for the spectroscopic binaries (these corrections would only amount to $0^m.1-0^m.2$), although for visual binaries we have applied corrections to V_0 according to the individual magnitudes of the components. Nor have we assumed, for this comparison, any increase over the standard value of $R = A_V/E(b-y) = 4.3$ in the Trapezium region.

all subgroups, but they do provide a rough estimate of the values expected. The columns labeled "Calibrations" list the M_V(MK) data found from empirical calibrations made by the authors cited at the end of the table.[6]

[6]In order to make the comparison as complete as possible, we have not attempted to evaluate "best" MK types, but instead present individual values for all spectral classifications for each star given in Table 2 of Paper I. Broadline (n, nn) and normal types are not distinguished here since the calibrated M_V(MK) values are the same for both.

Overall, the agreement between Balmer-line and MK absolute magnitudes seems quite good, and certainly within the differences expected from having multiple classifications for most stars and from the quantized nature of the spectral classification scheme. We do note, however, that in most cases where $M_V(\gamma)$, as calculated from $(b-y)_0$, $(B-V)_0$, or S, is considerably fainter than $M_V(\beta)$, $M_V(\beta)$ agrees more closely with the MK calibrations, including the one by Balona and Crampton (1974). This indicates that the $M_V(\gamma)$ values for the Orion stars are systematically fainter than M_V(MK) and $M_V(\beta)$ values, as previously deduced from Figures 7, 9 and 10. We have seen from Figure 8 that this is not the case for field stars, indicating that the young stars in the Orion association have strong hydrogen lines relative to field stars and lie very near the zero-age line in the HR diagram. The differences are not considered large enough to produce serious systematic errors in the derived mean distances to the association subgroups when $M_V(\beta)$ values are used, although a more detailed comparison of the calibrations is clearly desirable.

v) *Comments on Independent $M_V(\beta)$ Calibrations*

Having compared absolute magnitudes as derived from various measures of Balmer lines, we now turn to a comparison of absolute magnitudes as determined from two independent calibrations utilizing the β index, and to four-color and β relations relating to MK spectral types. As has been mentioned previously, the preliminary $M_V(\beta)$ calibration (Crawford 1973) is a one-dimensional calibration, although a two-dimensional calibration using $\delta\beta$ is contemplated for the final relationship. [A preliminary $M_V(\beta)$ correction of $8\delta\beta$ (Crawford 1970*b*) has not, because of the unevolved nature of the program stars, been applied here.] Recently, however, Eggen (1974) has published a new two-dimensional calibration whereby the absolute magnitudes of B-type stars are determined from β and Strömgren's (1966, 1967) bracket index $[u-b] = (u-b) - 1.84(b-y) = [c_1] + 2[m_1]$, where $[c_1] = c_1 - 0.2(b-y)$ and $[m_1] = m_1 + 0.18(b-y)$. These are defined such that they are independent of interstellar reddening according to the normal law. Eggen's calibration uses a standard ZAMS relation between $[u-b]$ and M_V to find a correction factor Δβ which is then used to compute $\Delta M_V([u-b], \beta)$ for each star. The ZAMS relation is based upon a large number of observations of clusters, associations and wide binary systems, all made by Crawford and his associates. The resulting luminosities should be quite accurate since a factor which varies according to the $[u-b]$ value is used with Δβ when calculating ΔM_V.

Figure 12 shows the relation between $M_V(\beta)$ and $M_V([u-b], \beta)$ for all Orion program stars having non-peculiar MK types. It is immediately evident that the absolute magnitudes agree very well except for an M_V-dependent shift such that $M_V([u-b], \beta)$ values are systematically brighter toward later spectral types, from $0\overset{m}{.}6$ at $M_V = -2$ to about $0\overset{m}{.}8$ at $M_V = 0$. The direction of this systematic difference and the uniformity of the relation suggest that the cause resides in the calibrations themselves, probably resulting from Eggen's use of more stars in evolved aggregates and visual binary systems.[7] Such an

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[7]The importance of using unevolved stars in (Balmer-line, M_V) calibrations has been s'ressed by Bappu *et al.* (1961) in connection with their Hγ photometry.

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explanation would also account for the increase in the width of the main-sequence band as we approach the late B stars, as well as for the good ag ,ement for stars of $M_V \lesssim -4$, where the earliest main-sequence stars used in both calibrations belong to young unevolved groups. (The good agreement for the supergiants tends to confirm our earlier statement that $\delta\beta$ corrections appear unnecessary for these high-luminosity stars when using the [β, $M_V(\beta)$] technique.)

As a further check on our understanding of the $M_V(\beta)$ calibration, a new calibration using *uvby*β photometry and MK† spectral types of field dwarfs has been derived (Warren 1976). In Figure 13 the β, c_0 relation from that calibration is used to show the deviation of the new mean relation for the general field from that for Crawford's ZAMS. (The indicated spectral types are valid for both the field and ZAMS relations along the horizontal axis because of the excellent agreement of our mean c_0 values with those of Crawford (1973) for MK types earlier than B7 on the ZAMS.) The figure clearly shows the break at spectral type B4 as found in the W(Hγ), MK-type relation of Balona and Crampton (1974).

For direct comparison with the absolute-magnitude calibration of Eggen, we have subdivided the Orion 1 program stars according to MK type. Unlike the procedure used in Table 1, we have now had to choose a "best" MK type for each star having multiple classifications in order to derive a mean for each type. The mean β and c_0 values derived for each spectral type for the Orion stars are shown as filled triangles in Figure 13. The Orion points are seen to fall very nearly along the ZAMS except at A0 where the lower turn-up moves the point upward to the field-star relation. The horizontal deviations of the Orion points from the field-star group may be due to the small samples for each spectral type or possibly to systematically lower c_0 values, which would indicate smaller Balmer jumps for these young stars. In Figure 14 we compare the absolute magnitude calibrations. To simplify the diagram, separate symbols are used for each calibration and we have not attempted to fit smoothed relations through the data. Comparison between the empirical and theoretical calibrations is effected by including the ZAMS determined from model-atmosphere calculations by Morton and Adams (1968). All calibrations agree for the upper main sequence; but as expected, the unevolved Orion association stars lie closer to the theoretical relation when the $M_V(\beta)$ calibration is used. For the late B stars, however, the $M_V([u-b], \beta)$ calibration of Eggen places the group nearer to the expected top of the main-sequence band, resulting in a significantly brighter calibration. As mentioned earlier, this probably results from the inclusion of a higher percentage of evolved stars in the calibration sample. While Eggen's calibration may be more appropriate for older field stars, we feel that Crawford's $M_V(\beta)$ calibration gives much better agreement with both the MK relation and that expected for unevolved aggregates. We will therefore derive our absolute visual magnitudes strictly from that $M_V(\beta)$ calibration except in situations discussed earlier when there are obvious emission effects present. In these cases the four-color photometry can sometimes be used in terms of a $(b-y)_0$, $M_V(\beta)_{ZAMS}$ relation since the color indices often are not affected by the emission.

c) Axial Rotation

The effects of stellar axial rotation on the *uvby*β indices for B-type stars have been discussed in detail by Warren (1975, 1976) and the results need only be summarized here. The β index appears to be affected by projected rotational velocity in B-type stars, *but only in the region* $v_e \sin i \gtrsim 250$ *km* s^{-1}. The deviations for rapid rotators appear to be in reasonably good agreement with those predicted from the model-atmosphere calculations of Hardorp and Strittmatter (1968*a*,*b*) [see Fig. 4 of Warren 1976] in that they show the $(v_e \sin i)^2$ dependence expected from gravity darkening and rotational distortion. Although there is an inherent spread in absolute magnitudes as determined from the β index, the mean correction appears to be not far from zero (Maeder 1972). In any case, since the deviations ($\delta\beta$) do not become pronounced below about 250 km s^{-1}, and since only a small percentage of our Orion program stars show rotational velocities above this value (many of these being peculiar and emission objects for which derived $M_V(\beta)$ values are not used in our analysis), we do not consider rotation to have a significant effect on the mean distances of the Orion subgroups as determined from the $M_V(\beta)$ values of their individual members. Possible detrimental effects for individual stars will be discussed further in notes to our tables in Paper III.

III. INTERMEDIATE-GROUP STARS

a) Color Excesses

The problems associated with calibrating the *uvby*β indices for effective temperature and luminosity for stars in the region of the Balmer maximum have been discussed by Strömgren (1966), who developed a method for unreddened stars by forming new indices defined as linear combinations of the four-color and β indices. As an effective temperature indicator which is virtually independent of log g throughout the range, a combination of $(u-b)$, sensitive to T_{eff} for B stars, and $(b-y)$, the T_{eff} indicator for A and F stars, is formed. As an indicator of luminosity a linear combination of $[c_1] = c_1 - 0.2(b-y)$, the luminosity parameter for the late group (A and F), and β, the luminosity parameter for the early group (O and B), is defined as $r = 0.35[c_1] - (\beta - 2^{m}.565)$, where the constants have been chosen such that r remains nearly zero on the ZAMS throughout the range, increasing to about $0^{m}.1$ at the top of the main-sequence band.

For reddened stars the situation is complicated by the fact that the luminosity indicators β and c_1 turn over in the I range and solutions are therefore two-valued. This is also the case for $(u-b)$, hence it becomes difficult to determine the intrinsic index a_0. The approach adopted by Strömgren (1966) uses the $[m_1]$ index to derive an independent expression for a_0 which will yield an intrinsic value with an accuracy of about $\pm 0^{m}.02$ (m.e.). This expression $\{a_0 = 0.80r + 2.0([m_1] + 0^{m}.179)\}$ takes luminosity effects into account by including r, which for a standard reddening law, is reddening-free as defined. The most modern form of these equations (Glaspey 1972) is:

$$\begin{aligned} a_0 &= 0.80r + 2m_1 - 0^{m}.358 + 0.36(b-y) \ , \\ r &= 0.35c_1 - (\beta - 2^{m}.565) - 0.07(b-y) . \end{aligned} \qquad (8)$$

Strömgren has also developed criteria for segregating stars into correct reduction groups according to their $[u-b]$, β and $[m_1]$ indices. This separation is necessary due to the individual reduction procedures used for the OB, I and AF groups. In the past, difficulties have been encountered in categorizing I-group stars properly (see e.g. Perry and Hill 1969), a problem to which we were not immune. However, in spite of considerable effort[8] (Warren 1975), we were unable

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[8]The attempts described elsewhere (Warren 1975) involved an analysis of field-star data from the catalogue of Lindemann and Hauck (1973), both in terms of a refined Strömgren-type analysis and in terms of the K-line index (Henry 1969, Henry and Hesser 1971, Hesser and Henry 1971). In the latter case, it was found that $(b-y)_0 = 0.216(\pm 0.010)k - 0^m.036(\pm 0^m.003)$ s.e. (114 field stars). In cases where k indices exist for the Orion 1 program stars (Hesser and Henry 1971), we will predict $(b-y)_0$ values from both the $[m_1]$, r and k methods.

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to improve significantly upon the situation, and in Paper III derived indices will be reported for all likely classifications when a choice could not be unambiguously made.

b) Absolute Magnitudes

The a_0, r diagram has been calibrated by Strömgren (1966) using stars of the intermediate group having trigonometric or cluster parallaxes. He finds that the linear expression $M_V = 1^m.5 + 6.0a_0 - 17.0r$ produces M_V values with a mean error of $\pm 0^m.2$. The same accuracy is obtained by Eggen (1972) using independent M_V values found from space motions for members of the Hyades group. This expression will therefore be used to compute absolute visual magnitudes for the I-group stars in the present program.

c) Axial Rotation

A detailed examination of rotational-velocity effects on the photometric parameters of the intermediate group has not been made here because: (*i*) they constitute less than 5 percent of the program stars; (*ii*) the uncertainty in the reddening corrections and therefore the intrinsic indices for the Orion I-group stars is larger than for the other groups and; (*iii*) as noted by Hardorp and Strittmatter (1968*a*, *b*), the effects of rotation on indices of stars near the Balmer maximum are difficult to evaluate theoretically. Additional complications arise in the observed *uvby*β indices due to the large width of the main sequence (up to $0^m.100$) in the parameter r (Strömgren 1966) and to the turning over of the β and c_1 indices in the I-group region. For all the above reasons, attempts to directly evaluate effects of axial rotation on our photometric data do not seem justified, except to note that Abt, Muncaster and Thompson (1970) found abnormally high rotational velocities among a sample of Nebula-region stars; it is therefore plausible that the location of many I-group stars of the Nebula region above the main sequence in an a_0, r diagram (to be shown in Paper III) may be partially attributable to effects of axial rotation.

Nevertheless, having chosen a large number of nearby I-group stars for the examination of the reduction method and evaluation of the *k*-index technique alluded to in

§ III(a) above, we collected $v_e \sin i$ data from the catalogues of Bernacca and Perinotto (1970) and Uesugi and Fukuda (1970) in order to look for any qualitative effects on the indices.

Figure 15 shows the r, $v_e \sin i$ relation for some 190 luminosity class V stars of these lists having distance moduli $\leq 6^{m}.0$. The expected scatter in r appears similar to that found in the standard a, r diagrams of Strömgren (1966) and Eggen (1972) except that a number of class V stars of intermediate rotational velocity fall well above the upper main-sequence limit of r ($=0^{m}.100$). This effect is not seen for the fastest rotators, however, and may be due to higher luminosity (many of the stars have multiple classifications). A definite zone of avoidance does appear for fast rotators in the lower right corner of the diagram, indicating that rotation above about 200 km s^{-1} tends to increase r. Since r increases with an increase in c_1 and/or a decrease in β, we plot c_1, ($b-y$) and β, ($b-y$) diagrams in Figures 16, segregating the stars according to $v_e \sin i$. Although the stars are rather evenly mixed in the c_1, ($b-y$) diagram, higher $v_e \sin i$ stars appear generally shifted toward lower β in the β, ($b-y$) relation. Such a shift is compatible with the models of Collins and Harrington (1966) and Hardorp and Strittmatter (1968b) and expected if there is a decrease in effective surface gravity with increasing rotation as suggested by Abt and Osmer (1965).

It is pertinent to note here that Jaschek (1970), in a study of rotational-velocity effects among I-group stars classified by Cowley *et al.* (1969), found no changes in color indices as a function of v_e sin i. This of course is in agreement with the even distribution of field stars in our c_1, $(b-y)$ diagram; however, contrary to the β, $(b-y)$ diagram, Jaschek found no dependence of β on rotation. The numbers of stars used by Jaschek in the spectral range A1 V to A3 V are too small ($\leq$ 10 in each type) to produce any definitive conclusion and this is even the case here. It is obvious that a detailed study using all available data for stars in aggregates and in the field will be needed to produce any quantitative answers to these important questions.

IV. A AND F STARS

a) Color Excesses

The standard method for deriving intrinsic colors and absolute magnitudes for Strömgren's "late group" has been outlined by Crawford and Barnes (1974). The procedure is slightly different for A- and F-type stars since small luminosity and abundance terms are needed in the F-star expressions. In both groups, however, the physical parameters measured by the photometric indices are reversed with respect to the O and B stars, i.e. the β index is now an effective temperature indicator closely related to intrinsic color, while c_1 measures luminosity differences. The index m_1

becomes even more sensitive to changes in chemical composition (blanketing) as the Hδ line weakens. For the A stars ($\beta > 2^{m}.720$) we iteratively compute the intrinsic color from

$$(b-y)_0 = 2^{m}.943 - \beta - 0.1(\delta c_0 + \delta m_0) , \qquad (9)$$

where $\delta c_0 = c_0 - c_0(\beta)$, $\delta m_0 = m_0(\text{Hyades}) - m_0$. The standard relations are given in tabular form by Crawford and Barnes (1974). For the F stars ($\beta \leq 2^{m}.720$) a slightly revised procedure has been developed by Crawford (1975) since the constant -0.1 in equation (9) changes toward later types due to luminosity and blanketing effects. A quantity $\Delta\beta = 2^{m}.720 - \beta$ is first computed using the observed β index. The intrinsic color $(b-y)_0$ is then found iteratively from

$$(b-y)_0 = 0^{m}.222 + (1^{m}.11 + 2.7\Delta\beta)\Delta\beta - 0.05\delta c_1 - (0^{m}.10 + 3.6\Delta\beta)\delta m_1 . \qquad (10)$$

Other useful quantities can now be readily found: $(u-b)_0 = (u-b) - 1.6E(b-y)$; the ultraviolet excess $\delta(u-b)_0 = (u-b)_0\{\beta\} - (u-b)_0$, where $(u-b)_0\{\beta\}$ is the standard value of $(u-b)_0$ for the observed β; and $\delta(b-y)_0 = (b-y)_0 - (b-y)_0\{\beta\}$. The above quantities can often be used to find discrepancies between the four-color and β observations, while δc_0 and δm_0 are physically meaningful since they measure luminosity and blanketing differences, respectively. Finally, a value for the visual absorption is computed from $A_V = 4.3E(b-y)$.

b) Absolute Magnitudes

The absolute-magnitude calibration for A and F stars is straightforward and has been described in detail by Crawford (1973) [for the F-type stars see Crawford 1975]. The general expression is $M_V = M_V(\mathrm{ZAMS}) - f\delta c_0$, where the second term is applied to correct for evolutionary effects. From observations of evolved cluster and trigonometric parallax stars the factor f has been determined as 8 for A stars and 11 for F stars.

c) Axial Rotation

No attempt will be made here to analyze the effects of rotational velocity on the photometric parameters for the Orion A and F stars, mainly because the program contains very few of these stars having existing $v_e \sin i$ data and because many of the A and F stars observed in this program are foreground field stars. Rotational-velocity effects have recently been examined in some detail for the α Persei cluster (Crawford and Barnes 1974), which contains a large percentage of fast rotators among its A-star members. They detect a possible effect on δc_0; the δc_0, $v_e \sin i$ diagram shows considerable scatter, however, and it even appears that the relation may be different for early and late A stars. The effects of rotation on both the β and c_1 indices of A and F stars have also been examined by Hartwick and Hesser (1974), who find a correlation between $\Delta\beta$ ($=\beta-\beta_{\mathrm{ZAMS}}$)

and v_e sin i which only seems to appear for v_e sin $i \geq 180$ km s^{-1}. A similar threshold effect was found above for the B stars (§ II(c) and Warren 1976). Hartwick and Hesser also found a clear separation between slow and fast rotators in a c_0, $(b-y)_0$ diagram for field dwarfs. Rotational-velocity effects on c_1 and $(b-y)$ had also been found earlier by Kraft and Wrubel (1965). An apparent effect on the m_1 index (Strömgren 1963, Slettebak, Wright, and Graham 1968, Danziger and Faber 1972, Hartwick and Hesser 1974) is such that fast rotators appear to have systematically smaller m_1 indices for a given $(b-y)$ color.

The trend in the c_0 index for the α Persei cluster members caused Crawford and Barnes to set $\delta c_0 = 0$ in Equation 9 for the A stars on the supposition that the cluster is about the right age to have neither pre- nor post-main-sequence members in this region of the HR diagram. This assumption would certainly not be valid for the Orion 1 association members since we know the pre-main-sequence turn-up to be near A0 for stars in the Trapezium region. In addition, the vanishing δc_0 term would not be valid for the numerous field A and F stars on the program. We have therefore chosen to reduce all A- and F-type stars with the correction term included.

The effects of rotation have been studied theoretically for members of the late group by Maeder and Peytremann (1970, 1972). This work has been summarized by Maeder (1972, 1973), where the effects on color index and on the c_1, $(b-y)$

diagram are discussed. Rotational tracks in this diagram, as presented by Maeder (1973), appear similar to those for B stars in the M_V, $(B-V)$ diagram of Hardorp and Strittmatter (1968*a*). Quantitative corrections for color index are given as f(v_e sin i) by Maeder (1972) and the variation is stated to depend essentially on v_e sin i and not on the individual indeterminate quantities v_e and i. On the other hand, changes in M_V induced by rotation depend on both v_e and i and may reach $\pm 0\overset{m}{.}5$; the mean of the corrections is not far from zero, however. Unfortunately, the effects on the β index and on the combined diagrams used for photometric analysis of the A and F stars are not clear and quantitative assessment must await a comprehensive study.

V. ULTRAVIOLET AND INFRARED EXCESSES AND POLARIZATION

Before the final photometric analyses may be carried out, one further aspect of the presence of both circumstellar and intracluster material in the Orion-Nebula region must necessarily be discussed, namely the processes that conspire to produce blue continuum emission, infrared (IR) excesses, and polarization effects. We will first review some of the (extensive) past work, and then show how the effects of such material are manifested in the photometric indices of the Orion stars on our program. As we shall see, it is somewhat unclear to what extent circumstellar or intracluster processes are responsible, and whether some of the effects are due to free-free emission by electron scattering or to radiation by circumstellar dust grains.

a) Background

i) *Blue Continuum Emission*

In our earlier discussions of absolute magnitudes (see § II(*b*), we noted that residual core emission at Hβ and blue continuum emission may be affecting the photometric indices for stars in the nebula region. The continuum emission is present shortward of the Balmer jump and in the blue, extending into the range of the *B* filter; it is thought to originate in circumstellar gas envelopes surrounding rapidly rotating B stars, and possibly Be, Ae and other young objects (Herbig 1962, 1970).

In the theoretical picture of pre-main-sequence (PMS) evolution presented by Larson (1969, 1972; see also Strom 1972), the core of a protostar collapses rapidly enough that the outer parts of the parent cloud are left as remnants in the circumstellar region. The computations suggest that while stars later than B5-B8 have detectable shells only during their PMS lifetimes, earlier types should still retain their shells upon reaching the ZAMS, after having very thick shells in their PMS phases; these shells may contain dust as well as gas. During a period of initial main-sequence burning these shells are probably dissipated gradually by radiation pressure or stellar winds and/or an infall of material occurs and the inner parts of the shell are accreted[9] onto the stellar surface until the optical

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[9]Evidence for the accretion process is provided by Conti's (1972) observations of an inverse P Cygni profile for the He II λ4686 line in the spectrum of θ^1 Orionis A; he has also (Conti 1973) interpreted the comparison of observational data with the non-LTE models of Auer and Mihalas (1972) as indicative of the presence of extended envelopes around many (but not all) O stars.

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depth of the shell approaches zero. At this point the normal main-sequence lifetime of a young star begins.

ii) *IR Excesses*

Stein and Gillett (1969) have observed the Trapezium region from 7 to 14 μ and found excess emission very similar in spectral distribution to that observed for cool stars such as μ Cephei and the Mira variables. Ney and Allen (1969) have also found IR excesses for objects in the Trapezium

Observations of Penston (1973) in Orion and of Strom *et al.* (1972*a*) in NGC 2264 indicate that O and early B stars do not show near-IR excesses, suggesting either that: (*i*) radiation pressure holds the dust particles at such great distances from the stars that the grain temperature is lowered and emission occurs at $\lambda > 3.5\ \mu$; or (*ii*) these stars have been on the main sequence long enough that most of the remnant dust has either been accreted onto the stellar surface or been blown away. Stars not on the main sequence long enough for these mechanisms to obtain would be seen as Herbig Be stars. Indeed, Cohen (1973*a*) has observed several of these objects in Orion out to 18 μ and finds that the 10-μ dust feature appears in some of them. Observations (Cohen 1973*a*; Ney, Stecker and Gehrz 1973) of early-type stars in Orion support the view that distant dust clouds are present around many of these objects; for instance, a shell size of 25" (equivalent to a linear diameter of > 0.5 pc) is estimated for NU Orionis.

Penston, Hunter and O'Neill (1975) have observed many fainter Orion-Nebula cluster stars and find a uniformly mixed distribution of reddened and unreddened stars in their [$(I-K)_0$, spectral type] diagram, although almost all stars appear to have higher than normal $(I-K)_0$ indices indicative of IR emission.

iii) *Polarization*

Polarization data for ∿190 stars in the Trapezium region have been obtained by Breger (1976), who finds that the incidence of polarization in Orion is higher than it is for NGC 2264 (Breger and Dyck 1972): 47 of 191 Orion stars (25 percent) measured show polarization effects, versus 4 of 35 NGC 2264 stars (11 percent). In the case of NGC 2264, Breger and Dyck found that polarized stars always show IR excesses, but IR-excess stars do not always show polarization. Dyck and Milkey (1972) and Smith (1973) have suggested that IR and optical excesses in A and F stars may originate from free-free emission in circumstellar gas envelopes, a view supported by the polarization data for NGC 2264 (although it should also be noted that many NGC 2264 stars show no polarization, IR excesses or light variability indicative of shells). On the other hand, Breger (1973, 1976) has interpreted much (but not all) of the polarization in the nebula region as due to aligned intracluster dust, on the basis of the observed patchiness, non-random position angles, and lack of correlation with variability. We will show shortly, however, that even if the distribution is somewhat patchy, stars displaying no polarization are interspersed in these areas in a majority of cases. Also, the reddening is very non-uniform over small areas and, on close examination, over half of the stars displaying polarization are either known or suspected variables. Thus, although we may be able to attribute some polarization to intracluster dust, the evidence suggests a fairly high incidence of circumstellar shells also.

iv) *Models*

As already implied by the preceding discussion, no completely satisfactory model exists that can account for the wealth of observed UV- and IR-excess and polarization phenomena in the Orion-Nebula stars; it seems likely that both intracluster dust as well as circumstellar shells play important roles. A plausible model for many of the UV- and IR-excess observations would consist of a near circumstellar region containing ionized gas that produces the blue continuum emission and near-IR excesses, while a remote region containing cooler dust particles produces IR emission longward of 3.5 μ (see Cohen 1973*b*).

The free-free and dust hypotheses are not easily distinguishable because both mechanisms place stars into the same area of the near-infrared two-color diagrams (Allen 1973). It is clear, however, that while the free-free model must attribute all reddening to interstellar or intracluser absorption (except in the case of an electron cloud optically thick to scattering, a case not considered here), the dust model predicts a contribution from the circumstellar shell as well, except in cases where a shell is in the form of a disk and not oriented in the line of sight. This implies that cluster stars which are considerably more reddened than the cluster mean are candidates for the dust mechanism; furthermore, stars with high excesses both in the visual and infrared and displaying polarization (possibly due to aligned dust grains in the shell) are even stronger candidates. An attempt to correlate the aforementioned quantities should therefore be made for possible distinction between the models:

1. High visual absorption should correlate with infrared excess but be independent of polarization if spherical dust shells are present;
2. High visual absorption should correlate with polarization but infrared excess should be negligible if circumstellar disks are oriented in the line of sight; for orientations tilted toward the plane of the sky the infrared excess should increase (due to greater disk area seen) but polarization should decrease (due to spherical symmetry), while visual absorption should also decrease since we are then not looking through the disk;
3. The free-free model of Dyck and Milkey (1972) can produce all of the above except (in the present discussion) the circumstellar visual absorption;
4. The presence of an inner shell of ionized gas and an outer shell of dust in any of the above configurations might make detection of infrared emission at longer wavelengths possible;
5. If the dust hypothesis is operative, a correlation might also be expected between optical variability, IR excess, and/or polarization, as suggested by the

work of Penston (1973) and Cohen (1973*b*). (The correlations of the cited authors indicate that non-variability implies an absence of IR excess and that variability is related to visual absorption.)

Additional evidence for circumstellar grains in Orion comes from a comparison of absorption as determined from early-type stars against that determined from normal stars later than G (which presumably contain no circumstellar material); Isobe (1971, 1973) concluded that most absorption in the Orion association is due to circumstellar grains around O, B, A and F stars. The correlation between luminosity and absorption can be interpreted in terms of Larson's model as due to the fact that the more luminous stars have condensed from more massive clouds and thus have left larger shell remnants. An earlier suggestion (Reddish, Lawrence, and Pratt 1966; Reddish 1967) that remnant shells also contain dust was based upon a suspected correlation between luminosities and color excesses in young clusters; existence of such a correlation has been controversial (see, e.g. Schild, Neugebauer and Westphal 1971; Strom 1972; Voelcker and Elsässer 1973; Bohannan 1975; Carrasco *et al.* 1975). On the other hand, Poveda (1965), Méndez (1967), Mezger (1970), Strom, Strom and Yost (1971), Strom *et al.* (1972*b*) and Breger (1972*b*) have all presented convincing evidence regarding the role played by circumstellar dust around young stars.

The anomalously high ratios of total-to-selective absorption for parts of the Orion association (Johnson 1968; Lee 1968) might also be influenced by or be attributable to emission from circumstellar and/or intracluster dust since *R* has been demonstrated to be abnormally high for dust shells (Strom *et al.* 1972*a*).

The evidence reviewed in the preceding discussion implies that in the Orion association we probably are dealing with a complex mixture of circumstellar gas and dust shells with a probable contribution from intracluster dust. The free-free processes in the near-photospheric environment contribute to the observed polarization and near-infrared, blue continuum and line emission, and possibly even to reddening, while more distant dust shells may produce infrared emission, polarization due to aligned grains, and reddening. In addition, for any or all stars we may have superimposed contributions from intracluster dust.

b) Results From the New Photometry

Several interesting relationships found among the polarization, optical and IR data that bear on the preceding discussion will now be discussed briefly. Before doing so, however, we wish to note that the polarization data indicate no adverse effects on the intrinsic *uvby*β colors or on the distance moduli other than the related emission effects discussed in § II(*b*).

i) *Polarization*

About 100 of Breger's (1976) stars measured for polarization are included in the present program and several relations found using them do appear to confirm effects previously found by others (e.g. Strom, Strom and Yost 1971; Smith 1972) with regard to the blue continuum emission.

Figure 17 displays the relation between the color indices $(b-y)$ and $(B-V)$ (uncorrected for reddening). The dispersion among unpolarized stars is comparable to that for standard stars (Fig. 5). Stars displaying polarization, however, appear to form a separate sequence.[10] The only unpolarized stars lying along the polarized "sequence" are those within the nebula. This appears to agree with the suggestion that blue continuum emission may be affecting the $(B-V)$ index, since we are unaware of a reasonable explanation for a differential reddening of $(b-y)$ for polarized stars. [Although a change in effective wavelengths of the filters in the two

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[10] In Fig. 17 the polarized sequence lies approximately $0^m.05$ blueward at $(B-V) = 0^m.0$, the separation appearing to increase slightly with $(B-V)$. A similar diagram for NGC 2264, made using the data of Strom *et al.* (1971) and Breger and Dyck (1972), shows a blueward shift of about $0^m.07$ in $(B-V)$ [at $(B-V) = 0^m.15$] for W90, the only definitely polarized star having all the required data.

systems for reddened stars may be causing some of these effects (Breger 1972*a*), it seems doubtful that the polarized "sequence" would be so uniformly shifted due to this cause, since stars of many different color excesses are included in the diagram.] If the (*B-V*) index is being affected by continuum emission from circumstellar gas and/or dust, then we would expect this differential effect on (*B-V*) to increase toward later spectral types due to the proportionately increasing importance of shells at lower T_{eff} (Strom *et al.* 1971). The same diagram for the indices (*u-b*) and (*U-B*) is present in Figure 18 and indicates that the differential effect is not present for these indices.

Figure 19 shows an areal diagram for stars having polarization data; variable-star designations and certain star names are included for orientation purposes. Although the polarized stars appear to clump somewhat, in most cases there are unpolarized stars nearby. Most of the stars plotted are considered to be association members. A check on the dependence of variability with polarization reveals that of 47 polarized stars, 16 are designated variables and an additional seven are suspected of variability, as noted by Kukarkin *et al.* (1971). Three of these suspected variables and another four polarized stars appear variable in four-color and/or β photometry, hence a total of 27 polarized stars are likely variables. This percentage is high enough to suggest shell effects, since these are known to be connected with variability, but also low enough to indicate that intracluster dust may play a role.

Figure 20 shows a plot of percentage polarization against color excess $E(b-y)$ for all stars having polarization data and color excesses determined from the $uvby\beta$ photometry. The solid line is the mean relation found by Hiltner (1956) and by Mathewson and Ford (1970) between interstellar polarization and visual absorption A_V; A_V has been transformed to $E(b-y)$ assuming the normal ratio $A_V/E(b-y) = 4.3$. The stars of substantial color excess (up to $0^m.25$) lying along the interstellar relation are the two components of θ^2 Orionis and three of the four brightest members of the Trapezium stars θ^1 Orionis ABC. Their positions reinforce the idea that the most luminous stars in the region have dissipated their remnant dust shells by radiation pressure and that their color excesses are high due to foreground intracluster material exclusively. This also suggests that the intracluster dust results in a P, $E(b-y)$ dependence similar to that of the general interstellar medium and that the ratio of total-to-selective absorption might be normal for the luminous stars within the nebula. On the other hand, the great majority of reddened stars fall well above the mean interstellar relation, again indicating the possible presence of circumstellar dust shells around the less luminous, polarized stars in the region, and also that the grain sizes, alignment, temperature and/or other physical conditions in these shells are different from those of the interstellar medium. That a change in grain alignment or the full contribution of extinction particles to the polarization would imply an increase in the ratio $P/E(b-y)$ is discussed by Aannestad and Purcell (1973).

ii) *IR Excesses and Polarization*

To examine the near-infrared excesses and their relation to polarization, we show in Figure 21 the $(V-K)$, $(B-V)$ relation for stars having polarization and the other required quantities. The $(V-K)$ data are taken from Penston (1973) and from Lee (1968). The near-infrared excesses $\Delta(V-K)$ are determined as the vertical distances of stars from the standard relation (solid line) of Johnson (1968) at constant $(B-V)$. A blueward shift in $(B-V)$ tends to increase $\Delta(V-K)$ somewhat but the increase is small compared to most of the $\Delta(V-K)$ values. It is readily seen that all stars whose light is polarized, with the exception of π 1044 at $(B-V) = 0$, have significant $[\Delta(V-K) > 0^{m}.3]$ near-infrared excesses. The converse is not true, however, and many stars having near-infrared excesses are not polarized. As mentioned earlier the same result has been found by Breger and Dyck (1972) for young stars in NGC 2264. On the basis of the free-free model, disk geometries having various orientations with respect to the observer fail to explain this diagram since, if a disk is in the line of sight, high polarization is expected due to asymmetry, while marginal infrared excess is expected because of the small disk area seen. Orientations in the plane of the sky would produce the filled circles, since large disk area produces infrared excess while spherical symmetry produces no significant polarization. Another problem with the free-free model here is that Figure 20 clearly shows all stars having significant polarization to be appreciably reddened, i.e. significant polarization implies both near-infrared excess *and* abnormally high visual absorption. These results seem to be readily explainable in terms of the dust model or a combination gas/dust (multiple-shell) model.

iii) *Summary*

In summary, it is clear that the situation regarding the presence of circumstellar and intracluster material around stars in the Orion-Nebula region is very complicated and that additional observations at longer wavelengths will be needed to help solve the problem. It appears that several classes of objects may exist, some stars displaying the existence of circumstellar gas and/or dust shells, while others show the effects of the nebular dust environment.

As far as the effects on the reddening and distance determinations from $uvby\beta$ photometry are concerned, we have shown that the color excesses are not likely to be affected greatly by the blue continuum emission, at least for B-type stars. This is probably not the case for the later (I and AF) groups, since the methods for these stars use both c_1

and β in a way more likely to adversely affect the resulting $(b-y)_0$ values. The absolute magnitudes of stars as derived from β values have been shown to be considerably brighter than expected when the stars display core emission and these will require careful evaluation in the final analysis.

The challenge of discriminating uniquely between dust and free-free models may be unanswerable, but the observations evaluated here indicate a possible combination of these mechanisms for many stars in the nebula region. In any case, a conservative approach will be adopted for Paper III in that stars located within the nebula will not be used to derive the distance to the nebula; rather, this distance will be inferred from apparently normal stars just outside the nebular boundaries. It should then be possible to use the known and derived distances to assess in more detail the effects of the nebula, and peculiarities of the stars embedded within it, on the photometric parameters of the *uvby*β systems, and perhaps on the *apparent* values of *R* for the nebula cluster members.

VI. SUMMARY

In the second of a series of papers on the Orion OB 1 association, we have outlined the procedures used for analysis of our *uvby*β photometry presented in Paper I. The reduction of the observational data to derive color excesses, intrinsic photometric indices, absolute visual magnitudes, and photometric distances for individual stars have been treated in terms of the three natural groups of stars analyzed using the four-color and Hβ photometric systems. In addition, we have examined the effects of different calibrations and emission mechanisms on the derived absolute magnitudes, especially for the B-type stars which constitute the largest population group in the vicinity of the main-sequence locus of the association. The absolute visual magnitudes, $M_V(\beta)$, derived for B-type stars in the present study (see Fig. 7) are found to be systematically brighter than those obtained from the $W(H\gamma)$ calibration of Balona and Crampton (1974). For the Orion-Nebula stars both calibrations yield systematically brighter absolute magnitudes with respect to MK spectral types, probably because of the degrading effects of line and possibly continuum emission on the Balmer-line indices. The effects appear to be larger for the β index, however, a result expected for line emission.

For stars outside the nebula, comparison of the derived absolute magnitudes with those given by MK spectral types (Table 1) reveals that $M_V(\beta)$ values show somewhat better agreement in most cases where $M_V(\gamma)$ is significantly fainter than $M_V(\beta)$. This result also holds for the MK calibration of Balona and Crampton (1974).

The β, $M_V(\beta)$ calibration used in the present work appears more appropriate for young stars near the zero-age main sequence than does the two-dimensional β, $M_V([u-b], \beta)$ calibration of Eggen (1974). This appears due to the inclusion of older aggregates and wide binary systems in Eggen's calibration data, since the calibrations agree well for stars near the top of the main sequence.

The photometric indices of the *uvbyβ* systems appear affected by stellar axial rotation. For the B-type stars (Warren 1976), the effects do not become significant until velocities above 250-300 km s^{-1} are reached. Fortunately, this is not a serious problem for the Orion OB 1 stars, but it may present difficulties in analyses of other stellar aggregates. Rotational-velocity effects are probably present in the indices for intermediate (I)- and AF-group stars also, but no quantitative assessments have been attempted in the present study because of the relatively small number of Orion stars having the necessary data.

An analysis of optical, infrared and polarization data suggests a complex mixture of interstellar, intracluster and circumstellar origins for emission, infrared excesses and optical polarization. Blue continuum emission appears to adversely affect $(B-V)$ indices (Fig. 17) and polarization shows a significantly higher dependence on color excess than expected for the interstellar case (Fig. 20). Additional observations at longer wavelengths and analyses of polarization data in terms of wavelength dependence and other differences between the intracluster and circumstellar cases will probably be needed to disentangle these effects (cf. Breger 1976).

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TABLE 1

ABSOLUTE-MAGNITUDE COMPARISON

Star No.	Name	Sub-group	MK Type	$\langle V_0 \rangle$	dm	M_V(dm)	$M_V(\beta)$	$M_V(\gamma)$	$M_V(\alpha)$	MK Calibrations*† 1	2	3	4	Note
1	HR 1646	A	B5 IV	$6^{m}.0$	$7^{m}.8$	$-1^{m}.8$	$-1^{m}.3$	$-1^{m}.3$	---	$-1^{m}.8$	---	$-1^{m}.0$	$-1^{m}.8$	
18	HR 1748	A	B1.5 V	6.0	7.8	−1.8	−2.5	−3.1	−3.15	(−3.0)	−2.7	−2.8	−2.8	
24	22 Ori	A	B2 IV B2 IV-V	4.6	7.8	−3.2	−3.1	−2.8	−3.0	−3.3 ---	−2.9 ---	−3.0 −2.4	−3.1 ---	
27	23 Ori A	A	B1 V B1 IV	4.7	7.8	−3.1	−3.3	−2.9	−3.0	−3.6 −4.1	−2.7 −3.5	−3.5 −3.8	−3.2 −3.7	
34	HR 1781	A	B1 V B1.5 V B2 V	5.6	7.8	−2.2	−2.8	−2.9	−2.1	−3.6 (−3.0) −2.5	−2.7 −2.7 (−2.2)	−3.5 −2.8 −2.2	−3.2 −2.8 −2.5	
37	η Ori AB	A	B0.5 V B1 V	3.5	7.8	−4.3	−3.9	−2.8	−3.3	−4.0 −3.6	−3.6 −2.7	−4.0 −3.5	−3.5 −3.2	1
49	ψ Ori AB	A	B1 V B2 IV	4.5	7.8	−3.3	−3.0	−2.9	−2.9	−3.6 −3.3	−2.7 −2.9	−3.5 −3.0	−3.2 −3.1	
51	HD 35730	A	B3 V: B5 IV	7.1	7.8	−0.7	−1.4	−1.0	---	−1.7 −1.8	--- ---	−1.3 −1.0	−2.0 −1.8	
53	HD 35762	A	B2 V	6.6	7.8	−1.2	−1.6	−1.7	−1.3	−2.5	(−2.2)	−2.2	−2.5	
54	HD 35777	A	B2 V	6.5	7.8	−1.3	−2.0	−1.6	−2.0	−2.5	(−2.2)	−2.2	−2.5	
67	HD 35899	A	B5 V	7.4	7.8	−0.4	−1.1	−1.1	---	−1.0	---	−0.9	−1.3	
79	HD 36013 A	A	B1.5 V B3 V:	6.8	7.8	−1.0	−1.6	−1.6	---	(−3.0) −1.7	−2.7 ---	−2.8 −1.3	−2.8 −2.0	
91	HD 36133 A	A	B2 V B5 V	7.0	7.8	−0.8	−1.4	−1.2	---	−2.5 −1.0	(−2.2) ---	−2.2 −0.9	−2.5 −1.3	
113	HR 1840	C	B1.5 V B2 IV-V	6.2	8.1	−1.9	−2.3	−2.4	---	(−3.0) ---	−2.7 ---	−2.8 −2.4	−2.8 ---	

TABLE 1 (continued)

Star No.	Name	Sub-group	MK Type		$\langle V_0 \rangle$	dm	M_V(dm)	$M_V(\beta)$	$M_V(\gamma)$	$M_V(\alpha)$	MK Calibrations*† 1	2	3	4	Note
140	HR 1851 C	B3	B2 B2	V IV-V	6^m.7	7^m.9	−1^m.2	−1^m.8	−1^m.7	−2^m.5	−2^m.5 ---	(−2^m.2) ---	−2^m.2 −2.4	−2^m.5 ---	
141	δ Ori A	B3	09.5	II	2.0	7.9	−5.9	−5.9	−5.2	−5.5	−5.7	−5.9	---	−5.1	
147	υ Ori	C	09.5 B0	V V	4.6	8.1	−4.5	−4.3	−3.1	−2.5	(−4.6) −4.4	−4.1 −3.6	−4.9 −4.2	−4.1 −3.8	2
184	VV Ori	B2	B1 B1.5	V III	5.1	8.0	−2.9	−3.1	−2.7	−3.1	−3.6 −4.0	−2.7 −4.2	−3.5 −3.7	−3.2 −3.9	3
193	HR 1871	A	B2	V	6.5	7.8	−1.3	−1.2	−1.6	−2.0	−2.5	(−2.2)	−2.2	−2.5	
219	HD 36824	A	B3	V	6.6	7.8	−1.2	−1.7	−1.9	−1.8	−1.7	---	−1.3	−2.0	
265	HR 1886 B	C4	B1	V	5.6	8.4	−2.8	−3.0	−2.5	---	−3.6	−2.7	−3.5	−3.2	
266	HR 1887 A	C4	B0 B0.5	V Ve	4.7	8.4	−3.7	−4.2	−3.7	−2.8	−4.4 −4.0	−3.6 −3.6	−4.2 −4.0	−3.8 −3.5	
278	θ[1] Ori D	D	B0	V	6.7	8.4	−1.7	−3.5	−2.2	---	−4.4	−3.6	−4.2	−3.8	
279	θ[1] Ori C	D	08 B0.5	V Vp	5.8	8.4	−2.6	−5.0	−3.2	---	−5.2 −4.0	−4.4 −3.6	−5.9 −4.0	−4.8 −3.5	4
280	θ[1] Ori A	D	07	V	4.3	8.4	−4.1	−6.9	−4.7	−5.6	−5.4	−4.8	−5.9	−5.1	4
284	HR 1891 AB	C1	B2 B2.5 B3	IV V V	6.7	7.8	−1.1	−1.2	−1.4	−1.4	−3.3 (−2.1) −1.7	−2.9 −1.6 ---	−3.0 −1.9 −1.3	−3.1 (−2.2) −2.0	5
285	HR 1890	C1	B1.5 B2 B2	V Vp IV	6.4	7.8	−1.4	−2.5	−1.7	−3.0	(−3.0) −2.5 −3.3	−2.7 (−2.2) −2.9	−2.8 −2.2 −3.0	−2.8 −2.5 −3.1	
292	θ[1] Ori B	D	B0.5	Vp	5.6	8.4	−2.8	−3.7	−2.7	---	−4.0	−3.6	−4.0	−3.5	

TABLE 1 (continued)

Star No.	Name	Sub-group	MK Type	$\langle V_0 \rangle$	dm	M_V(dm)	$M_V(\beta)$	$M_V(\gamma)$	$M_V(\alpha)$	MK Calibrations*† 1	2	3	4	Note
295	42 Ori AB	C2	B1 V B2 III	$4^m.5$	$8^m.5$	$-4^m.0$	$-3^m.4$	$-3^m.5$	$-3^m.0$	$-3^m.6$ -3.6	$-2^m.7$ (−3.5)	$-3^m.5$ -3.3	$-3^m.2$ -3.7	6
296	θ^2 Ori A	D	O9 V O9.5 Ve	4.4	8.4	−4.0	−4.6	−3.8	---	−4.8 −4.6	−4.3 −4.1	−5.4 −4.9	−4.5 −4.2	
297	θ^2 Ori B	D	B0.5 V B1 V	5.9	8.4	−2.6	−4.2	−2.4	---	−4.0 −3.6	−3.6 −2.7	−4.0 −3.5	−3.5 −3.2	
301	ι Ori AB	C4	O9 III	2.6	8.4	−5.8	−5.3	−5.2	---	−5.7	−5.7	−5.6	−5.0	
302	HR 1900 AB	C	B3 V B3 IV	6.3	8.1	−1.8	−0.9	−1.6	−1.1	−1.7 −2.5	--- ---	−1.3 −1.7	−2.0 −2.6	
303	HR 1898 AB	C1	B2 IV B2.5 V	6.5	7.8	−1.3	−1.5	−1.5	−1.8	−3.3 (−2.1)	−2.9 −1.6	−3.0 −1.9	−3.1 (−2.2)	7
304	V359 Ori	C2	B2 Vp	7.2	8.5	−1.3	−2.1	−1.6	---	−2.5	(−2.2)	−2.2	−2.5	
307	NU Ori	D1	B0.5 V B1 V	5.2	8.4	−3.2	−3.7	−3.3	---	−4.0 −3.6	−3.6 −2.7	−4.0 −3.5	−3.5 −3.2	
328	ε Ori	B2	B0 Ia	1.3	8.0	−6.7	−7.5	−6.9	−6.7	−6.2	−7.0	−6.6	−7.0	8
335	HD 37129	C1	B2V, B2Vp	7.0	7.8	−0.8	−1.5	−2.1	---	−2.5	(−2.2)	−2.2	−2.5	
350	HR 1911 AB	C	B1 V B2 IV	5.7	8.1	−2.4	−3.1	−2.7	---	−3.6 −3.3	−2.7 −2.9	−3.5 −3.0	−3.2 −3.1	9
374	HR 1918	C	B1 V B1.5 V B2 V	5.9	8.1	−2.2	−3.4	−2.4	---	−3.6 (−3.0) −2.5	−2.7 −2.7 (−2.2)	−3.5 −2.8 −2.2	−3.2 −2.8 −2.5	
381	HD 37334	C	B1.5 V	7.0	8.1	−1.1	−2.0	−1.9	---	(−3.0)	−2.7	−2.8	−2.8	

TABLE 1 (continued)

Star No.	Name	Sub-group	MK Type	$\langle V_0 \rangle$	dm	M_V(dm)	$M_V(\beta)$	$M_V(\gamma)$	$M_V(\alpha)$	MK Calibrations*†				Note
										1	2	3	4	
390	HR 1923	C	B1.5 V	$5^{m}.6$	$8^{m}.1$	$-2^{m}.5$	$-3^{m}.1$	$-2^{m}.0$	$-3^{m}.4$	$(-3^{m}.0)$	$-2^{m}.7$	$-2^{m}.8$	$-2^{m}.8$	
			B2 IV-V							---	---	-2.4	---	
			B2 IV							-3.3	-2.9	-3.0	-3.1	
397	HD 37397	B2	B2 V	6.7	8.0	-1.3	-1.8	-1.7	-2.05	-2.5	(-2.2)	-2.2	-2.5	
			B3 V							-1.7	---	-1.3	-2.0	
415	σ Ori AB	B1	O9.5 V	4.0	8.2	-4.2	-3.9	-4.4	-3.7	-4.6	-4.1	-4.9	-4.2	10
419	HR 1933 A	C	B1 V	5.9	8.1	-2.2	-2.6	-2.5	---	-3.6	-2.7	-3.5	-3.2	
			B1.5 IV							(-3.7)	(-3.5)	-3.5	-3.4	
458	HR 1950	B1	B1 V	6.1	8.2	-2.1	-2.9	-2.3	-2.8	-3.6	-2.7	-3.5	-3.2	
			B1.5 V							(-3.0)	-2.7	-2.8	-2.8	
460	ζ Ori AB	B1	O9.7 Ib	1.7	8.2	-6.5	-6.1	-6.2	-6.6	-5.9	-6.2	---	-5.7	11
463	HR 1952	B1	B2 IV-V	4.9	8.2	-3.3	-2.8	-3.5	-3.0	---	---	-2.4	---	
			B3 V							-1.7	---	-1.3	-2.0	
			B3 III							-2.9	---	-2.2	-3.1	
507	κ Ori	C?	B0.5 Ia	1.7	8.1	-6.4	-6.1	-4.9	---	-6.4	-7.0	(-6.7)	-7.0	
526	HR 2058	C	B1.5 V	6.4	8.1	-1.7	-2.2	-2.0	---	(-3.0)	-2.7	-2.8	-2.8	
			B2 V							-2.5	(-2.2)	-2.2	-2.5	

*MK Calibration References

1. Blaauw (1963)
2. Walborn (1972, 1973)
3. Lesh (1968)
4. Balona and Crampton (1974)

TABLE 1 (continued)

† An additional independent calibration by FitzGerald (1969) derived from clusters is not included separately here. For main-sequence stars, this calibration is intermediate between those of Walborn and Blaauw for types earlier than O9.5, agrees reasonably well between B0 and B5 with the four calibrations used, and deviates brightward from the others from B7 to A0. At A0 it is $0\overset{m}{.}7$ brighter than the mean of all other calibrations considered. The calibration of Schmidt-Kaler (1965) is almost identical to Blaauw's.

TABLE 1 (continued)

Notes

1. V_0 corrected by $0^m.4$ for duplicity.
2. Inclusion of the O9.5 V classification is based on the present *uvby* photometry and on the discussions by Heintze (1973).
3. This is a spectroscopic tertiary system (Beltrami and Galeotti 1970) but no correction to V_0 has been made here since secondary spectrum has only been observed as a trace and tertiary spectrum has not been seen.
4. $M_V(\beta)$ affected by emission and/or nebulosity.
5. V_0 corrected by $0^m.5$ for duplicity.
6. V_0 corrected by $0^m.1$ for duplicity.
7. V_0 corrected by $0^m.2$ for duplicity.
8. Emission has been noted at Hα by Rosendhal (1973) and possible filling-in of absorption lines is discussed by Lamers (1972). A two-dimensional Hα calibration has been applied by Andrews (1968). $M_V(\beta)$ appears affected by the emission while $M_V(\alpha)$ does not, but variability is quite possible here.
9. V_0 corrected by $0^m.1$ for duplicity.
10. V_0 corrected by $0^m.4$ for duplicity.
11. V_0 corrected by $0^m.2$ for duplicity.

FIGURE CAPTIONS

FIG. 1.— The $E(b-y)$, $E(U-B)$ relation for B-type program stars in Orion. The solid line is the unit slope relation. The tendency for stars displaying high color excesses to lie above the line may be due to adverse emission effects (see text).

FIG. 2.— The relation between Andrews' (1968) photoelectric Hα index (Rα) and the β index for Orion 1 B-type program stars. The square near the top of the diagram is the shell star HD 34959. The symbol 2 indicates two overlapping points, and normal stars are indicated in this and subsequent diagrams by filled circles.

FIG. 3.— A comparison of absolute visual magnitudes as derived from the Rα and β indices using the calibration of Andrews (1968) and the preliminary β, $M_V(\beta)$ calibration of Crawford (1973), respectively.

FIG. 4.— The relation between β and Hγ equivalent width on the Victoria system as catalogued by Crampton *et al.* (1973). No deviations are apparent in this diagram when luminosity classes are considered. The regression line gives a correlation of r = 0.91 (51 stars) and represents the relation $\beta = 0.022W(H\gamma) + 2^{m}.516$.

FIG. 5.– The $(b-y)$, $(B-V)$ relation for standard stars common to both systems. Open circles represent stars that have been omitted from the solution and are identified by their HD numbers.

FIG. 6.– The $(u-b)$, $(U-B)$ relation for standard stars common to both systems. Open circles represent stars that have been omitted from the solution and are identified by their HD numbers.

FIG. 7.– The relation between $M_V(\beta)$ derived from Crawford's preliminary calibration used in the present study, and $M_V(\gamma)[W(H\gamma), (b-y)_0]$ calculated from the $(B-V)_0$ relation of Balona and Crampton (1974) transformed to $(b-y)_0$, as described in the text.

FIG. 8.– The $M_V(\beta)$, $M_V(\gamma)$ relation for field dwarfs having new MK† classifications. The differences in the calibrations show up more clearly here than when only Orion association stars are plotted, as in Fig. 7. The symbol 2 indicates two overlapping points.

FIG. 9.– The relation between $M_V(\beta)$ and $M_V(\gamma)$ for Orion 1 stars, as calculated from the alternate expression of Balona and Crampton (1974) where an integer value S is assigned according to MK type and used in the calculation. This relation differs little from that of Fig. 7, showing that the two expressions of Balona and Crampton yield comparable $M_V(\gamma)$ values

and that the photometric colors are not significantly altering the latter figure.

FIG. 10.— The relation between $M_V(\beta)$ and $M_V(\gamma)$[MK type], as derived directly from the MK calibration table of Balona and Crampton (1974). Here the agreement with the field-star diagram (Fig. 8) and with the known differences between the calibrations themselves is more satisfactory.

FIG. 11.— The relationship between the difference in absolute magnitude as predicted from β and the ZAMS value derived from the intrinsic color $(b-y)_0$, and the photometric measure of this difference δβ. The high-luminosity program stars are identified.

FIG. 12.— A comparison of absolute magnitudes predicted for the Orion 1 B-type program stars from the β, $M_V(\beta)$ calibration and from the $M_V([u-b], \beta)$ calibration of Eggen (1974). The systematic difference appears attributable to the types of stars defining the ZAMS relationships, as discussed in the text. The solid line represents the unit-slope relation.

FIG. 13.— A comparison of the mean β, a_0 relations for Crawford's ZAMS and for the field stars compiled here. Filled triangles represent the mean values for the Orion 1 program stars and are seen to follow the ZAMS relation closely for stars earlier than A0.

FIG. 14.— A comparison of various M_V calibrations with MK spectral types. The filled triangles represent the theoretical ZAMS of Morton and Adams (1968).

FIG. 15.— The r, $v_e \sin i$ relation for approximately 190 unreddened dwarfs. The diagram shows an absence of r values near zero for stars rotating faster than about 200 km s^{-1}, suggesting an increase in r for the fastest rotators.

FIG. 16.— c_1, $(b-y)$ and β, $(b-y)$ diagrams for intermediate-group field stars. Filled symbols have $v_e \sin i \leq 100$ km s^{-1}; open symbols have $v_e \sin i \geq 175$ km s^{-1}; solid lines represent the ZAMS relations derived by Glaspey (1971). Although the stars appear evenly mixed in c_1, a systematic decrease in β appears to be present for rapid rotators.

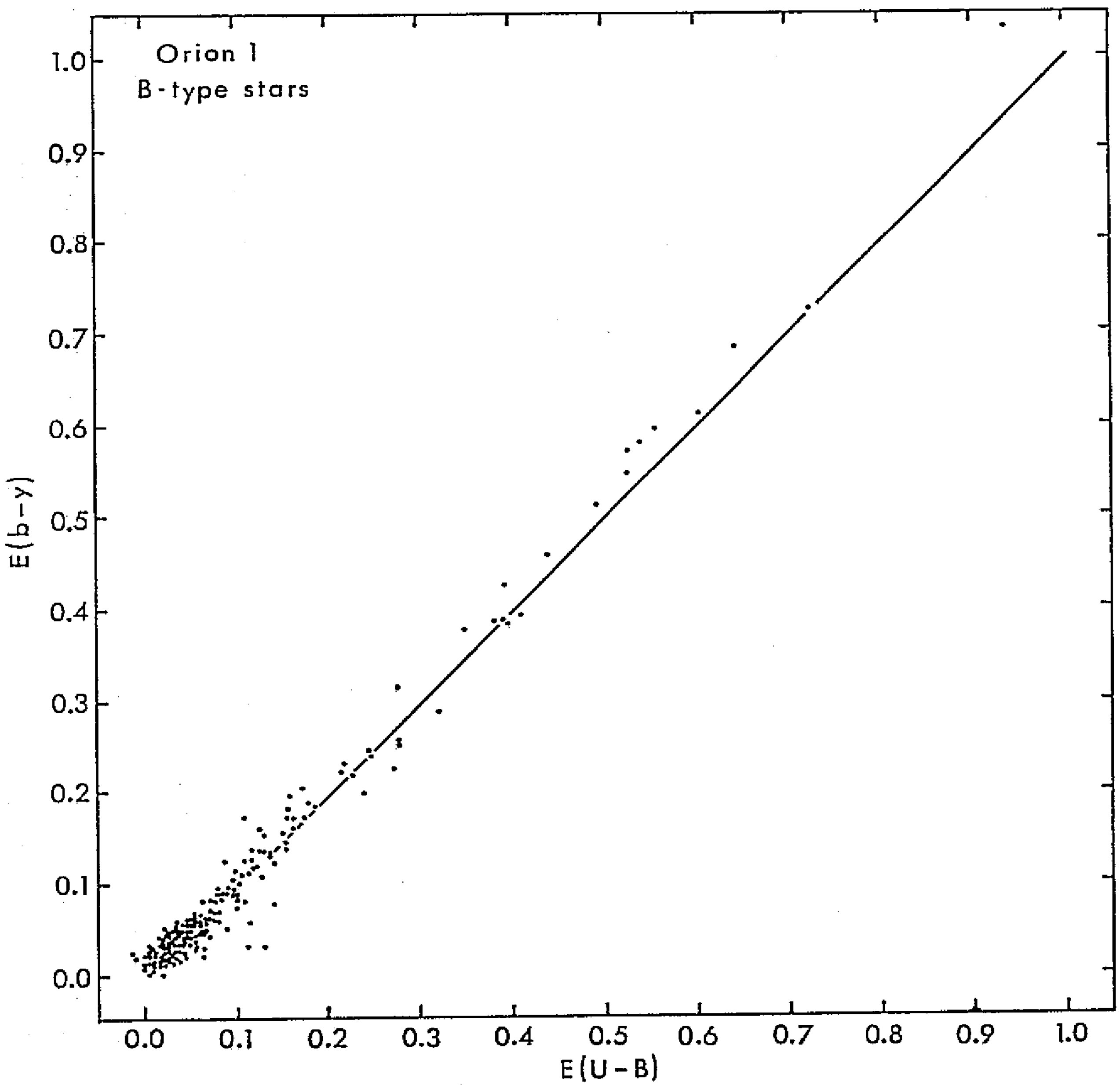
FIG. 17.— $(b-y)$, $(B-V)$ [uncorrected for reddening] relation for Orion 1 stars having polarization data. Almost all polarized stars are shifted horizontally in $(B-V)$, indicating that blue continuum emission in these stars is brightening their B magnitudes.

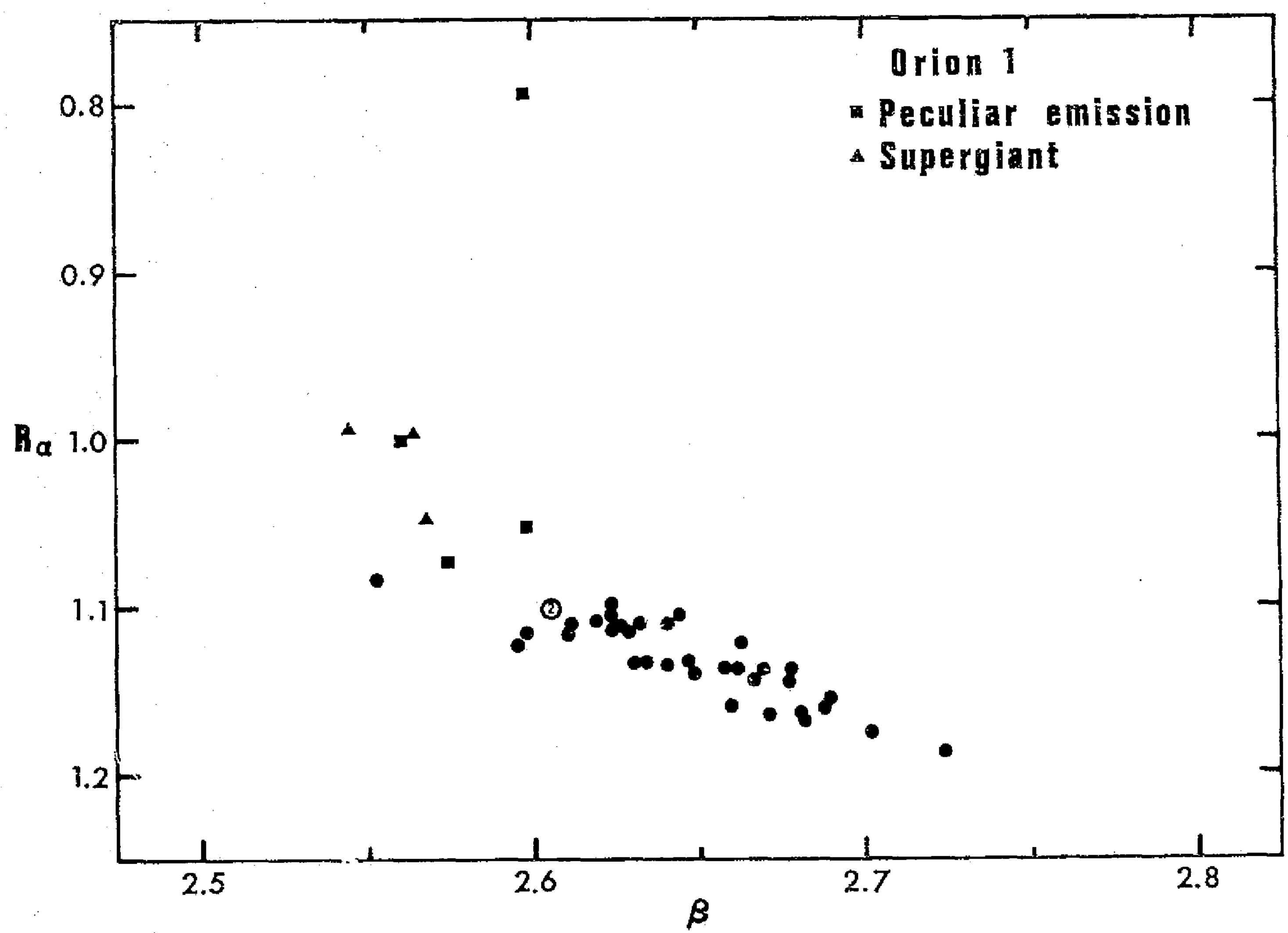
FIG. 18.— $(u-b)$, $(U-B)$ relation for Orion 1 stars having polarization data. The polarized and unpolarized stars are much more uniformly distributed in this diagram than in Fig. 17, indicating that both indices are affected to approximately the same degree by the blue continuum emission.

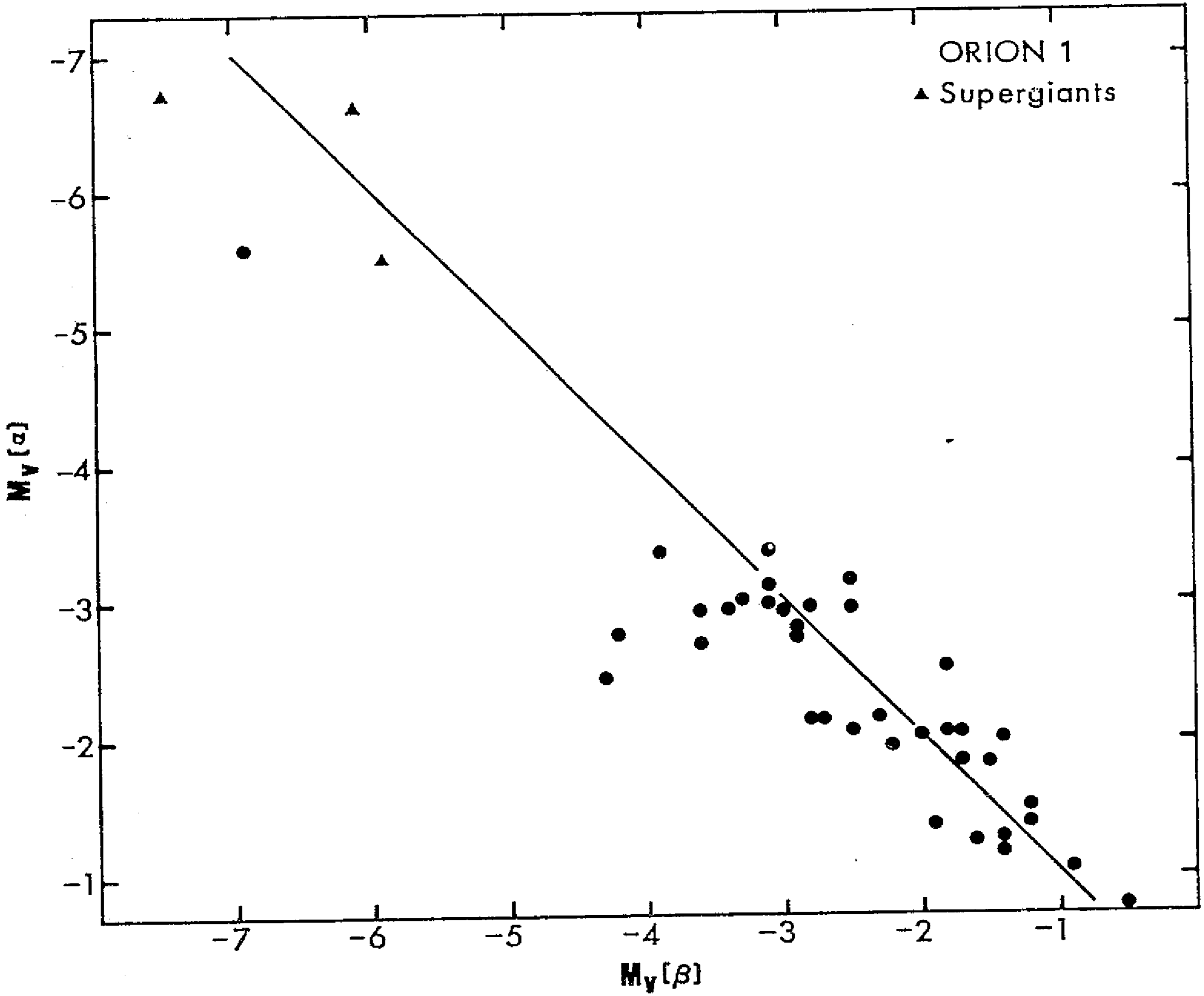
FIG. 19.— Areal diagram for program stars with polarization data. The distribution of polarized stars (open symbols) is somewhat patchy, but in most cases there are unpolarized stars nearby.

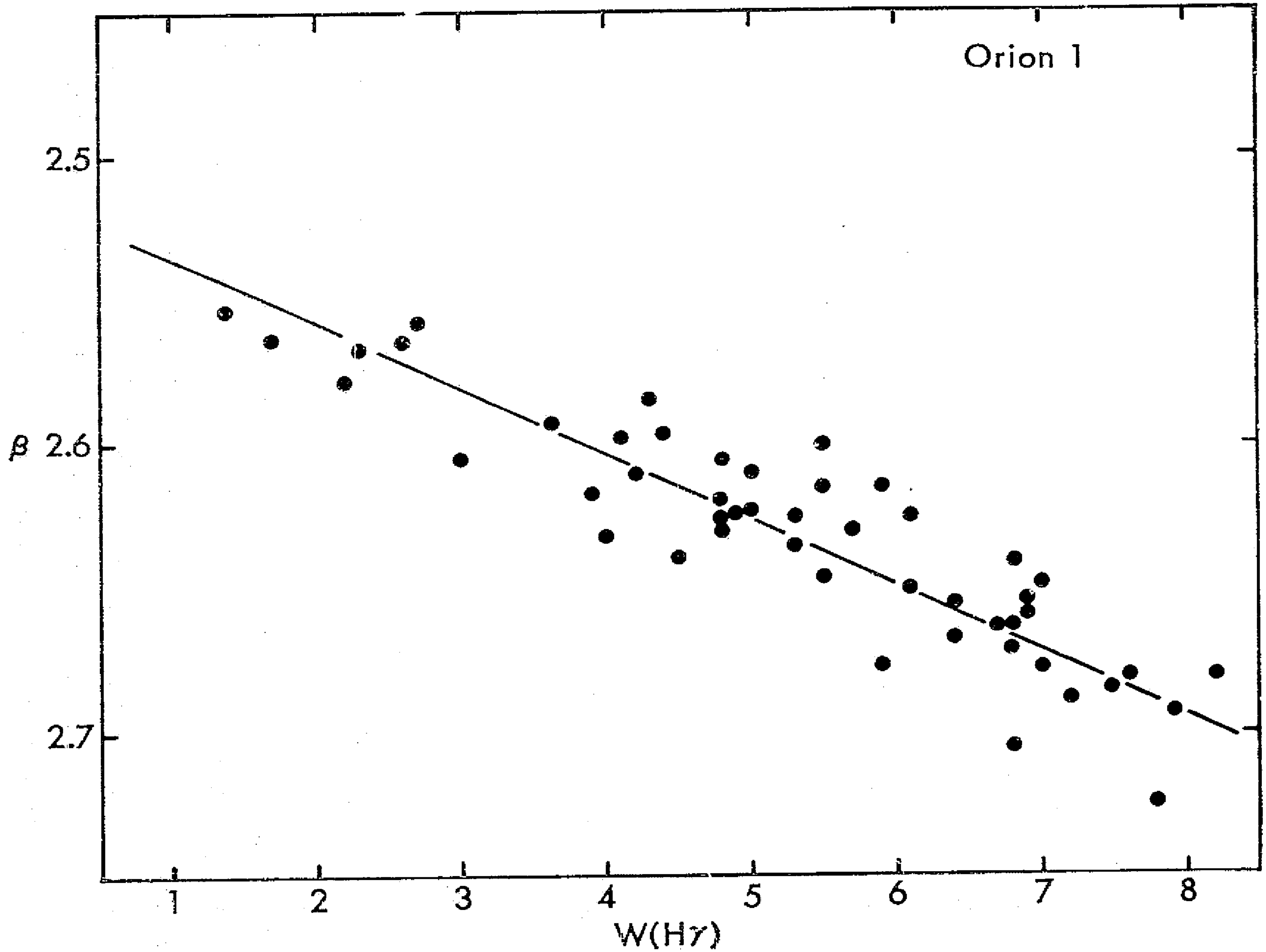
FIG. 20.— Relation between percentage polarization and color excess $E(b-y)$. The solid line shows the dependence expected for interstellar polarization.

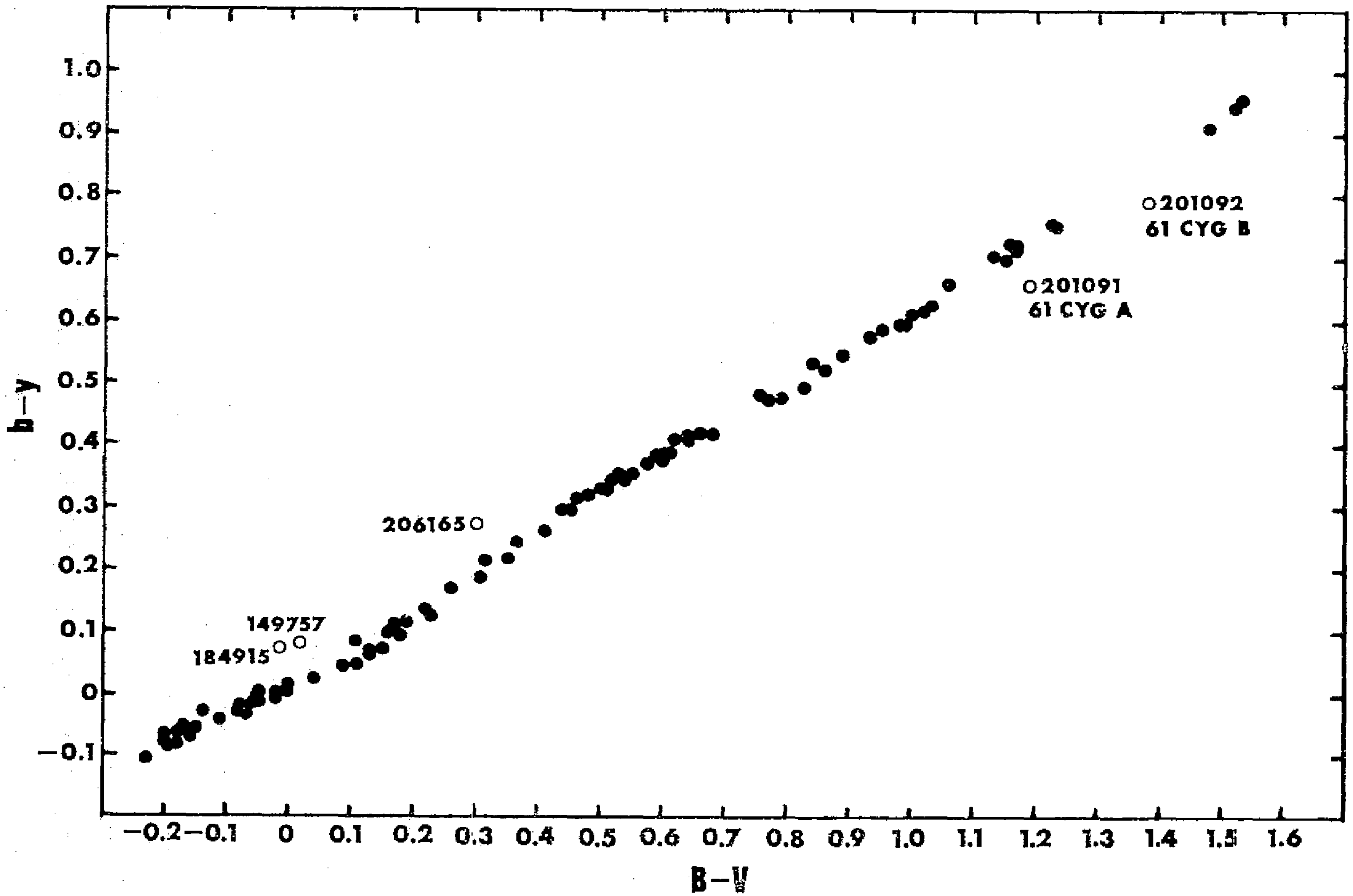
FIG. 21.— The $(V-K)$, $(B-V)$ relation for stars having polarization and $(V-K)$ data. The excess $\Delta(V-K)$ is measured as the vertical distance from the standard line of Johnson (1968).


Orion 1
B-type stars
E(b−y)
E(U−B)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

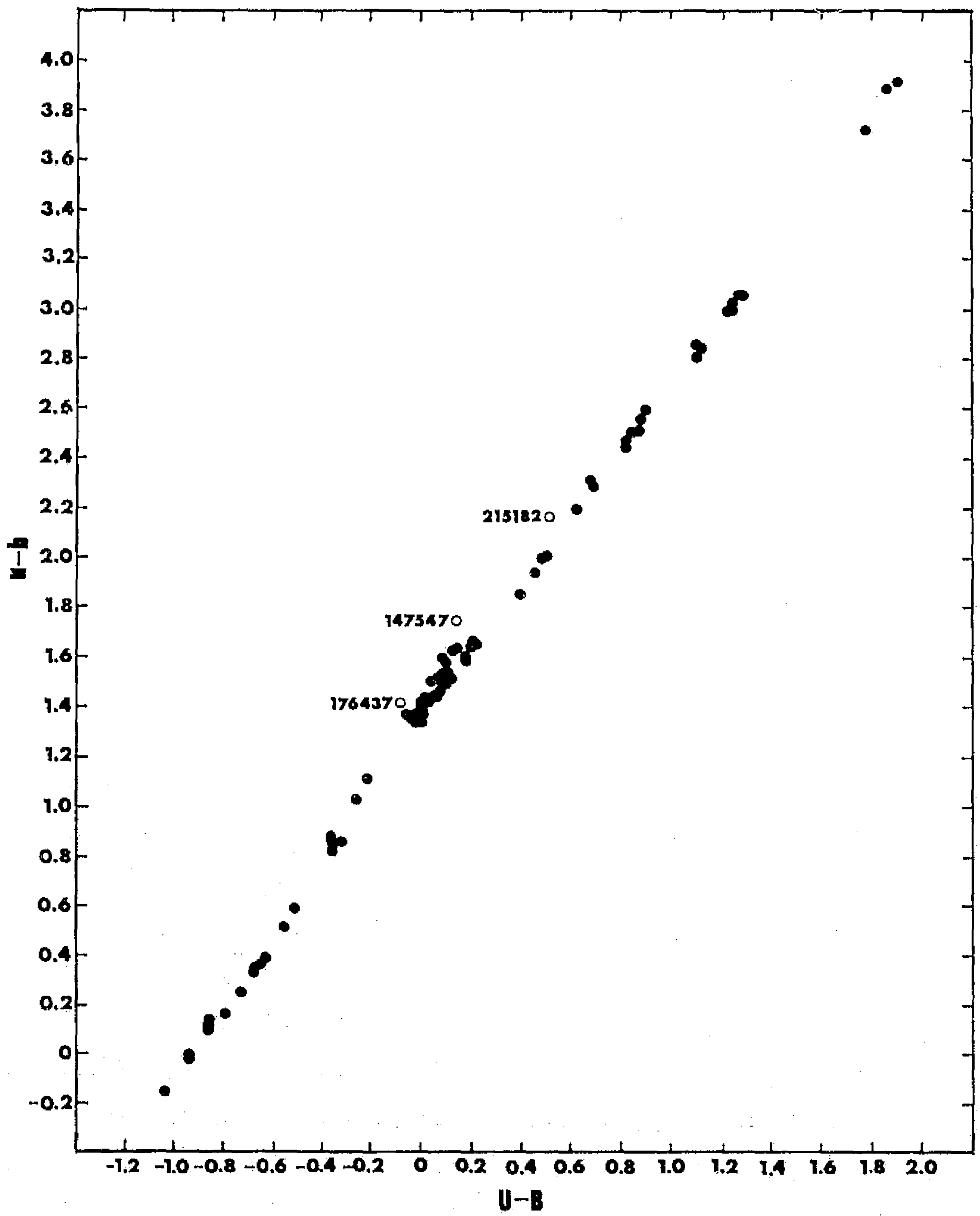

Orion 1
Peculiar emission
Supergiant
0.8
0.9
1.0
1.1
1.2
Rα
2.5
2.6
2.7
2.8
β


ORION 1
Supergiants
-7
-6
-5
-4
-3
-2
-1
$M_V[\alpha]$
$M_V[\beta]$

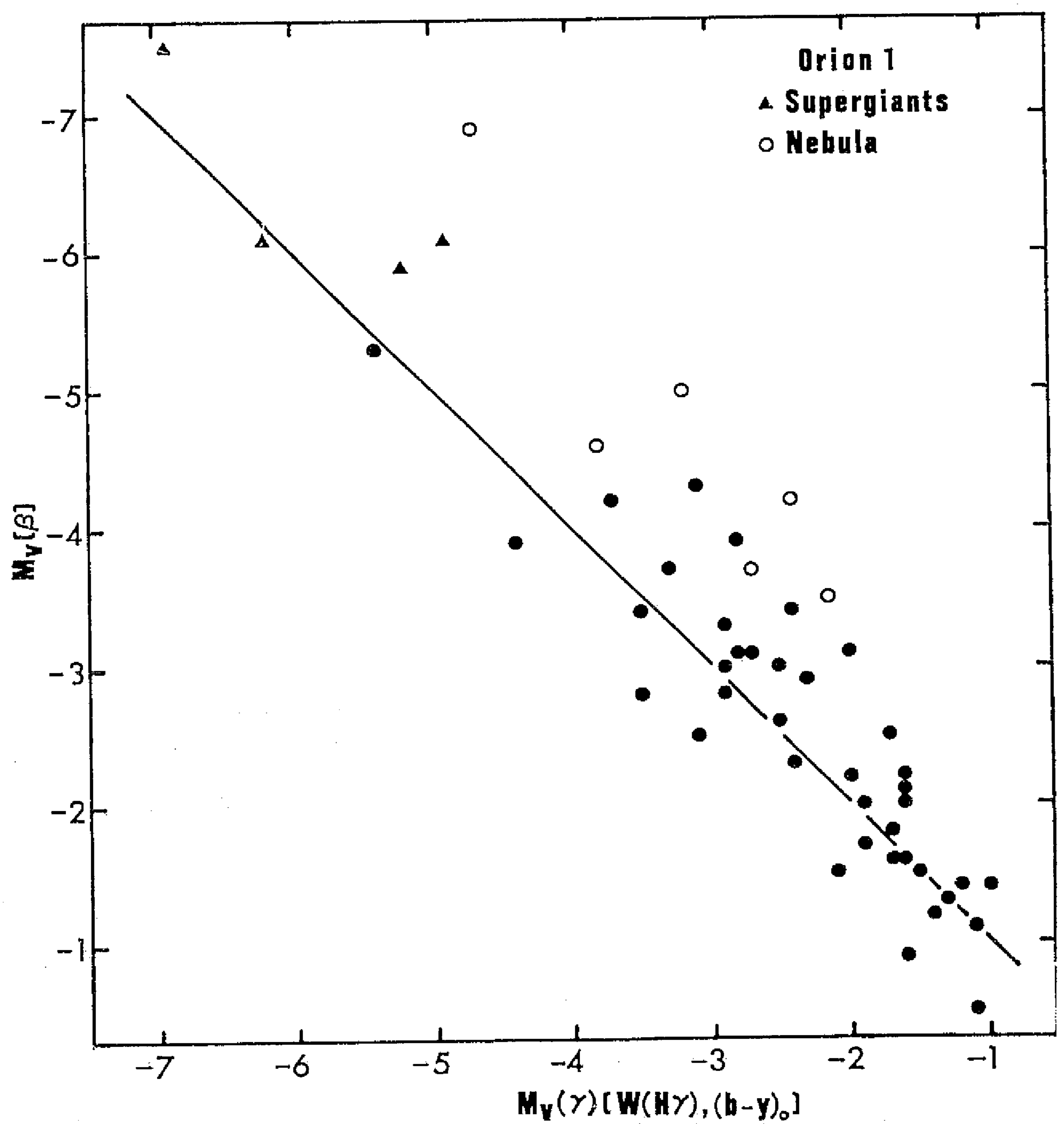

Orion 1
β
2.5
2.6
2.7
1
2
3
4
5
6
7
8
W(Hγ)



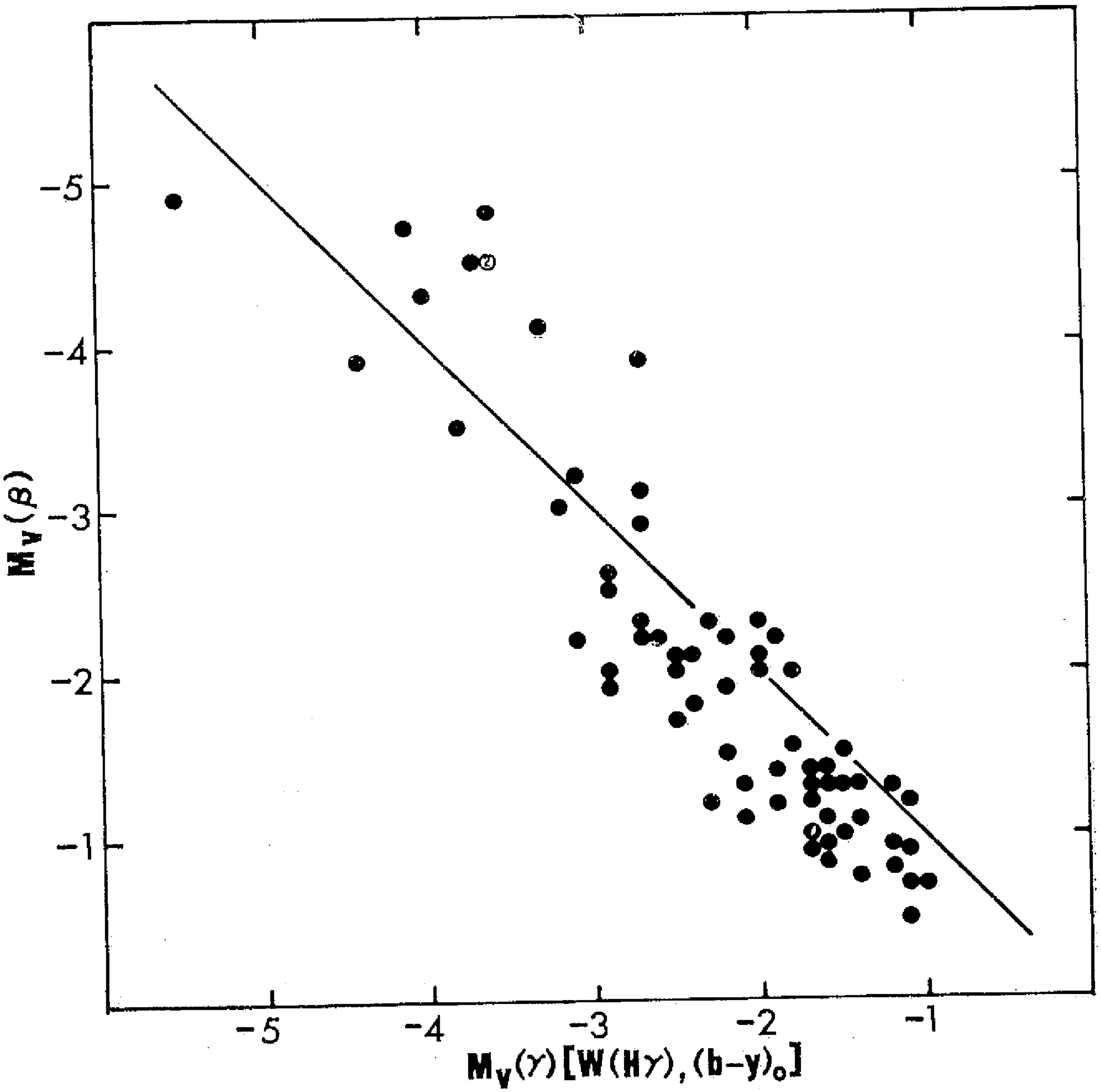
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
b−y
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
B−V
149757
184915
206165
201091
61 CYG A
201092
61 CYG B



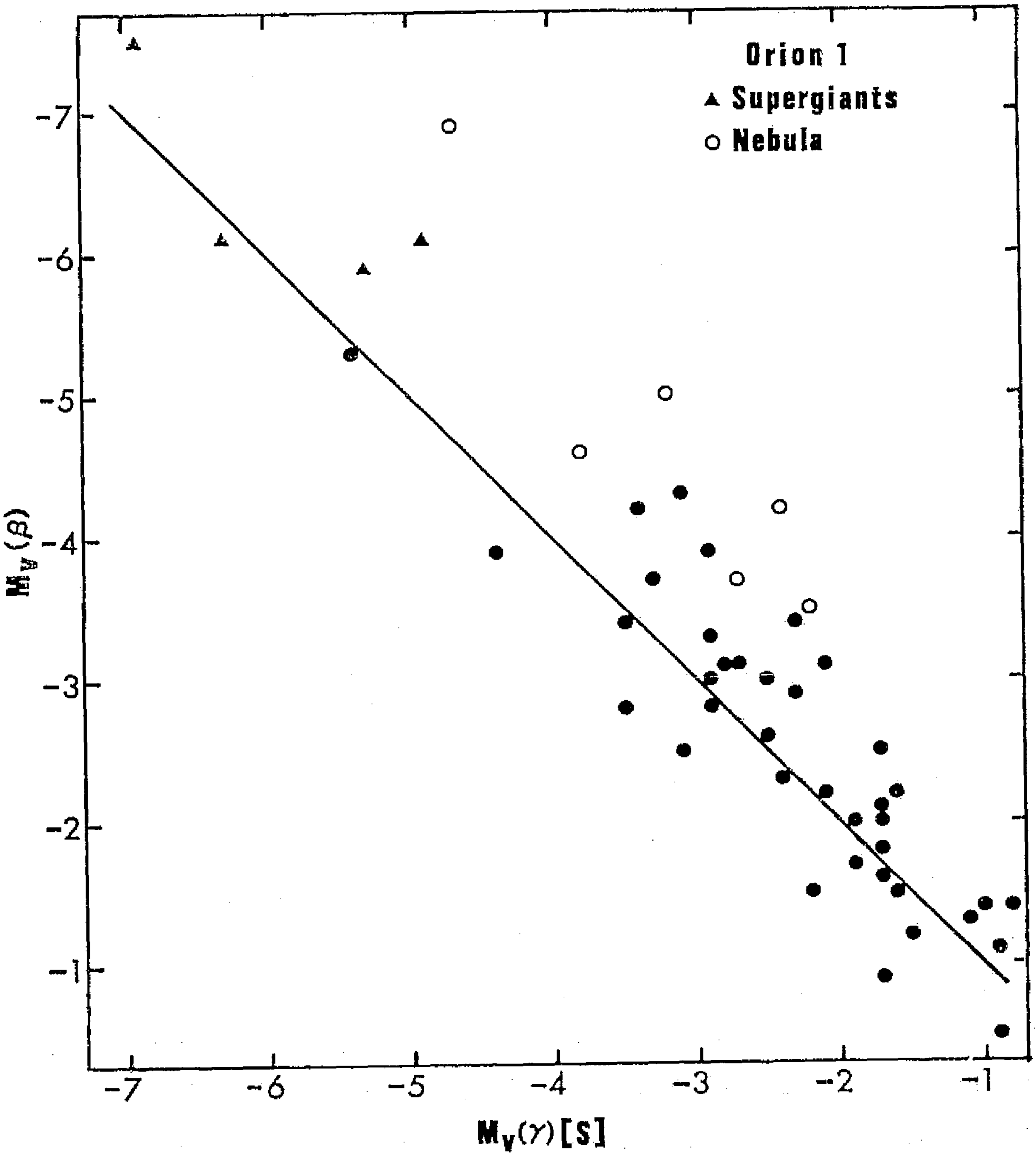
u−b
U−B
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
215182
147547
176437



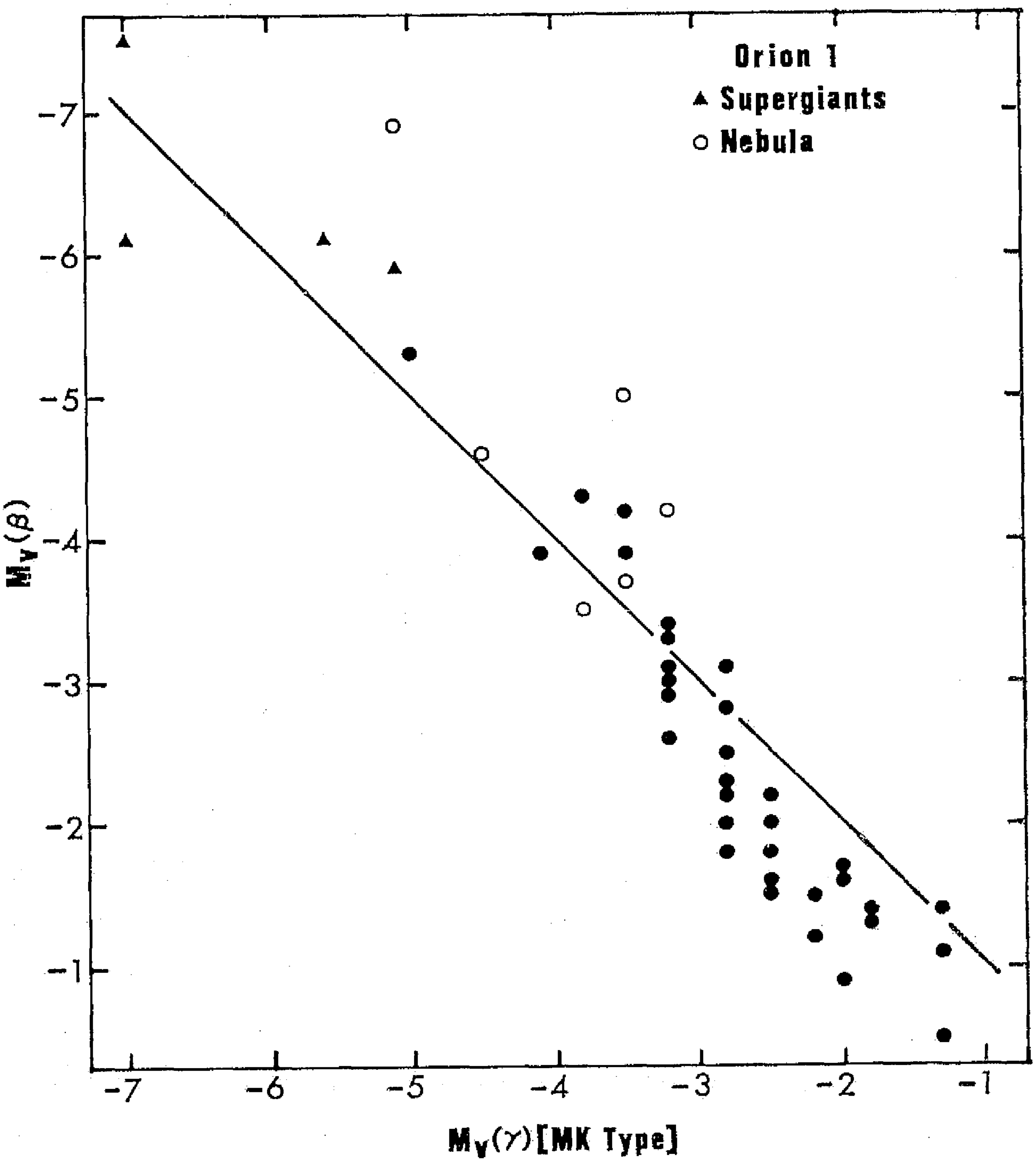
Orion 1
Supergiants
Nebula
-7
-6
-5
-4
-3
-2
-1
$M_V[\beta]$
$M_V(\gamma)[W(H\gamma),(b-y)_o]$



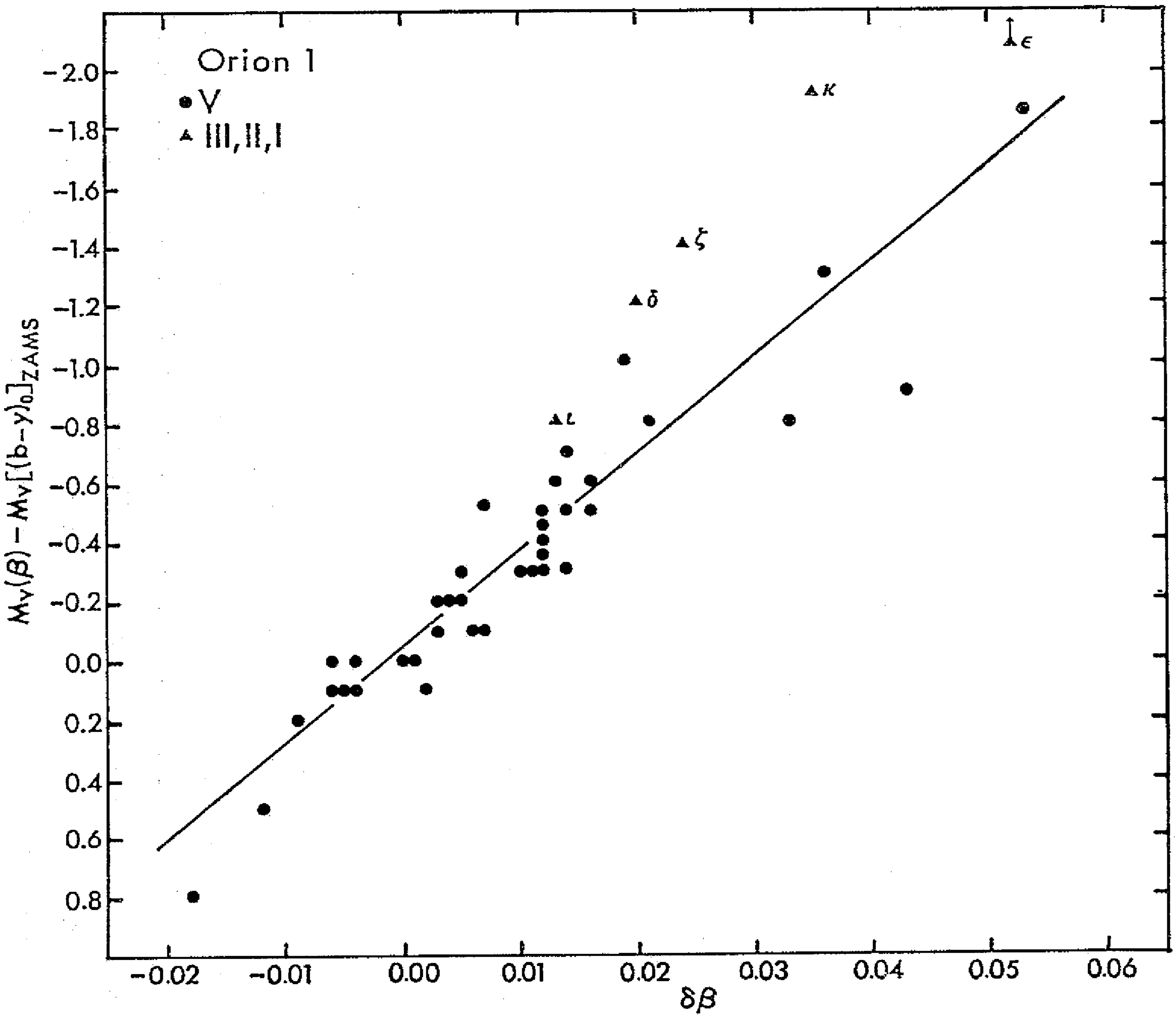
-5
-4
-3
-2
-1
$M_V(\beta)$
$M_V(\gamma)$[W(Hγ), $(b-y)_o$]



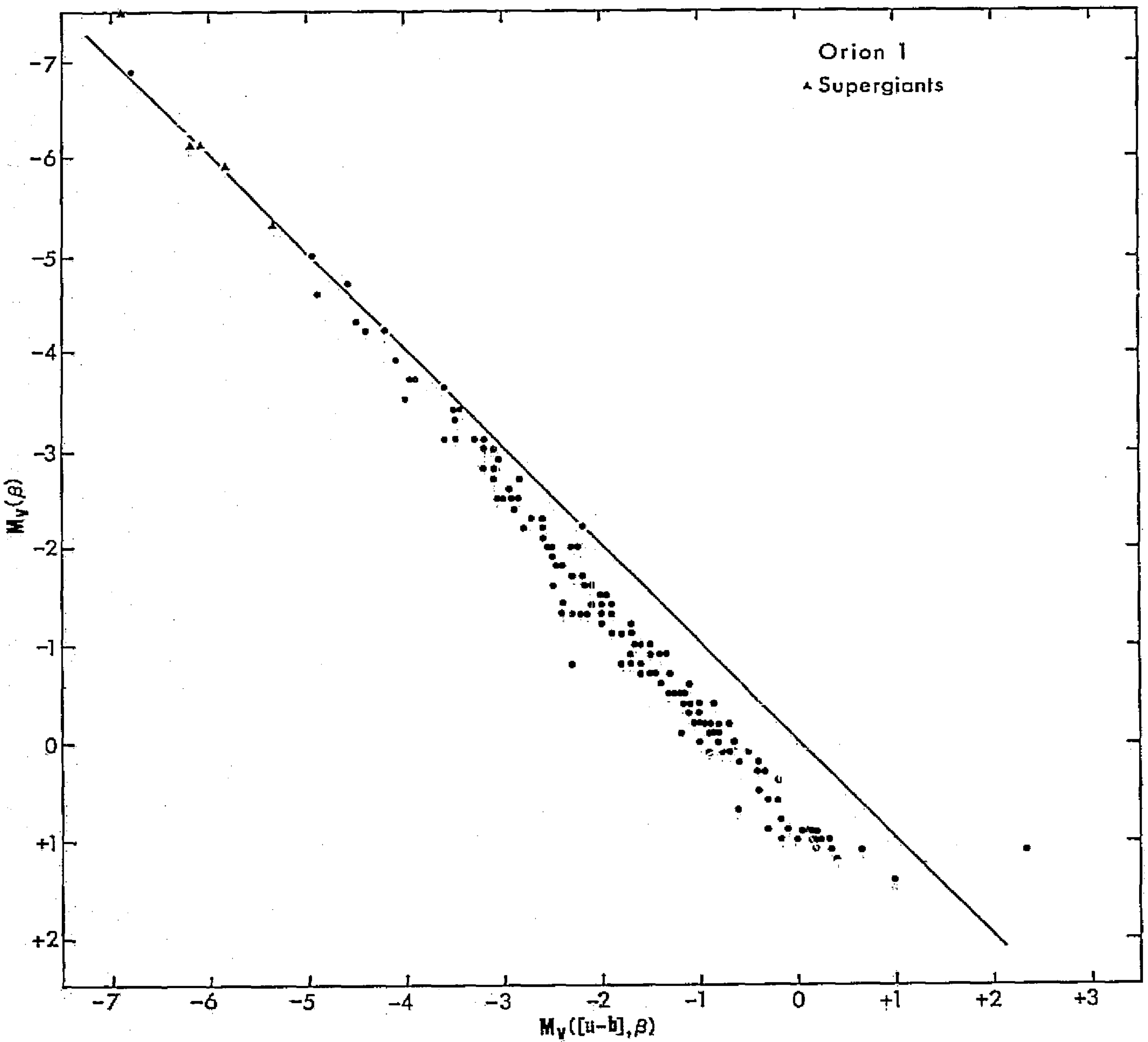
Orion 1
Supergiants
Nebula
$M_V(\beta)$
$M_V(\gamma)[S]$
-7
-6
-5
-4
-3
-2
-1

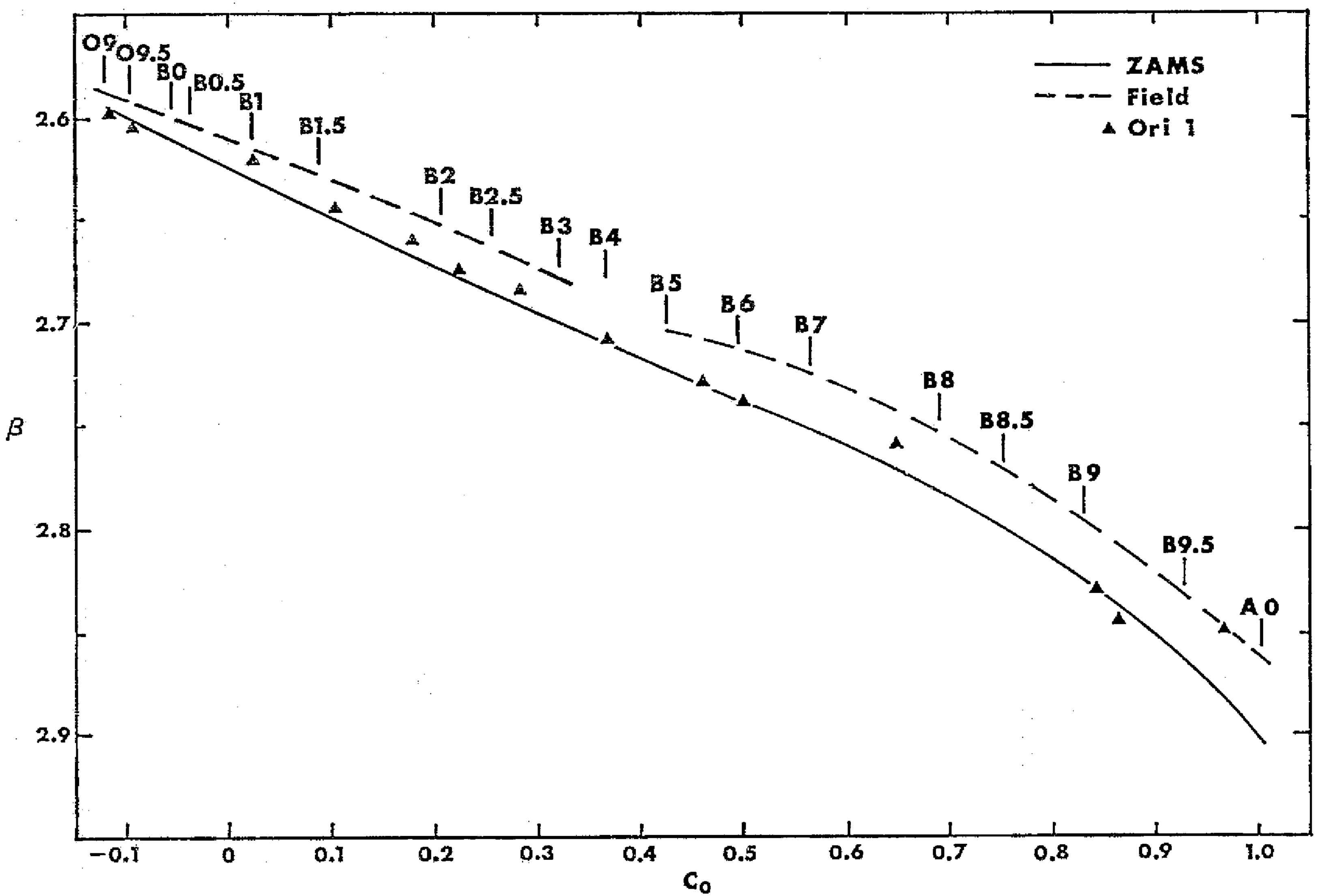


Orion 1
Supergiants
Nebula
$M_V(\beta)$
$M_V(\gamma)$[MK Type]
-7
-6
-5
-4
-3
-2
-1

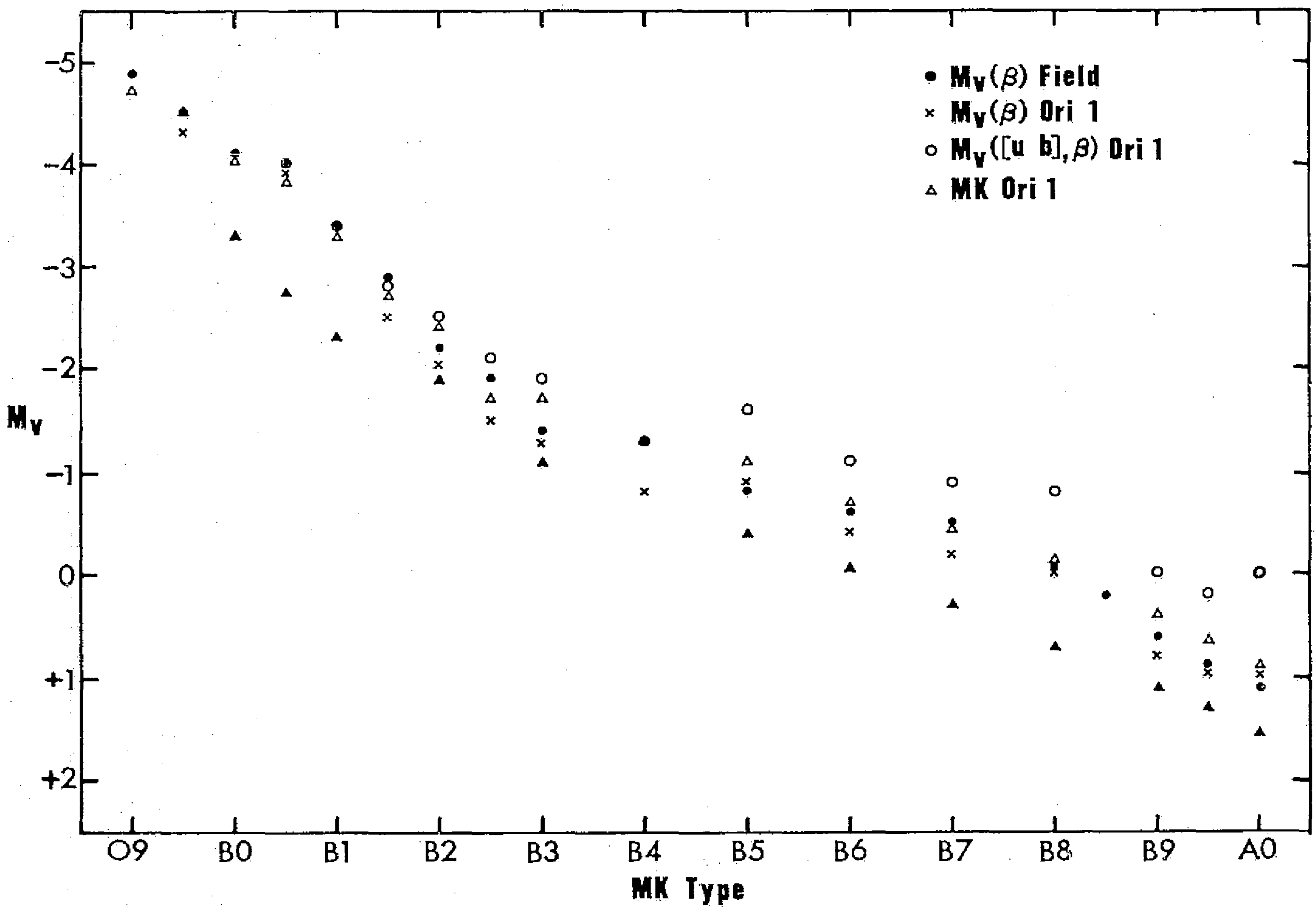


Orion 1
V
III, II, I
ε
κ
ζ
δ
ι
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
$M_V(\beta) - M_V[(b-y)_0]_{ZAMS}$
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
0.06
$\delta\beta$

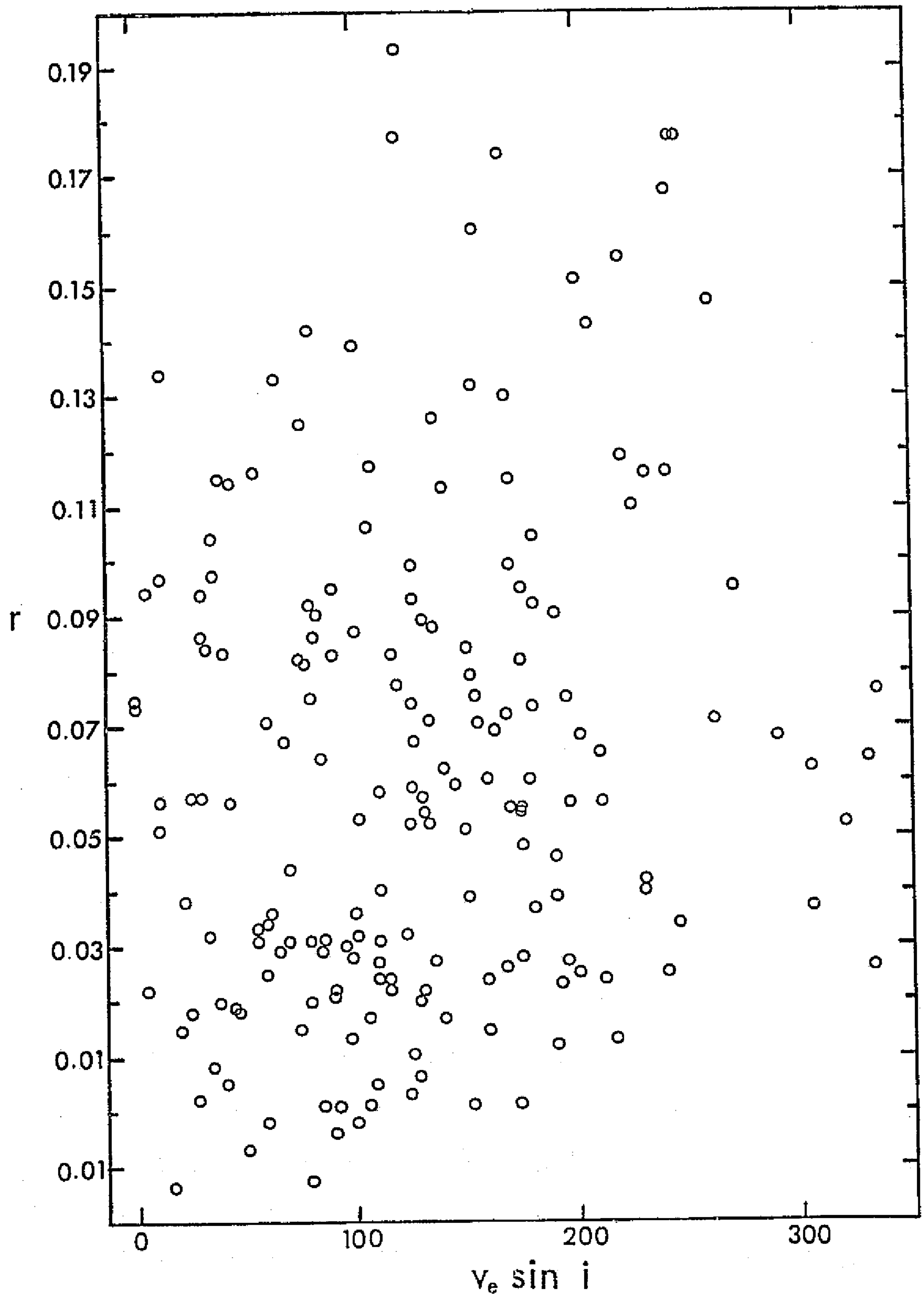

Orion 1
Supergiants
$M_V(\beta)$
$M_V([u-b],\beta)$
-7
-6
-5
-4
-3
-2
-1
0
+1
+2
+3



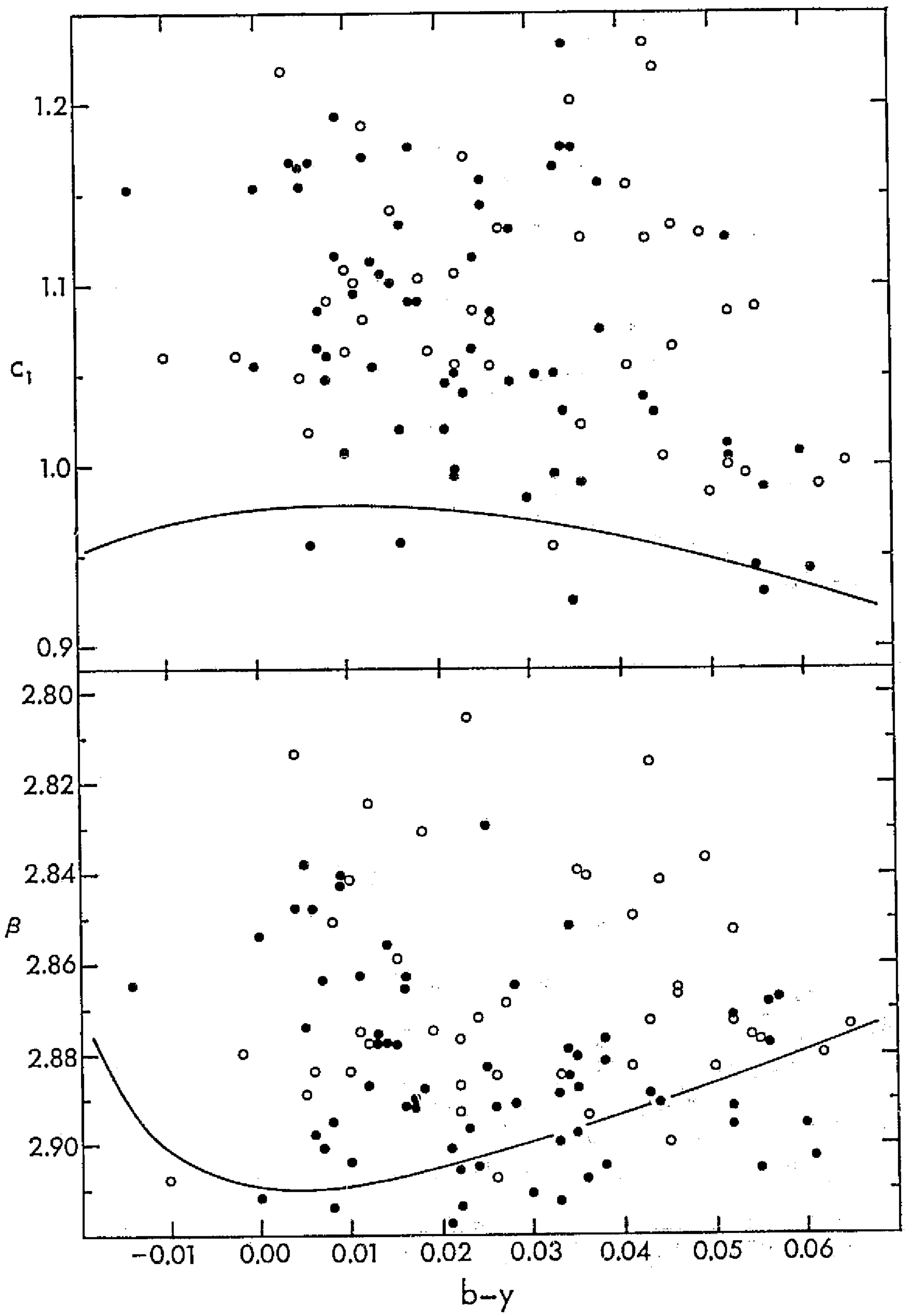
ZAMS
Field
Ori 1
O9
O9.5
B0
B0.5
B1
B1.5
B2
B2.5
B3
B4
B5
B6
B7
B8
B8.5
B9
B9.5
A 0
2.6
2.7
2.8
2.9
β
−0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
c_0



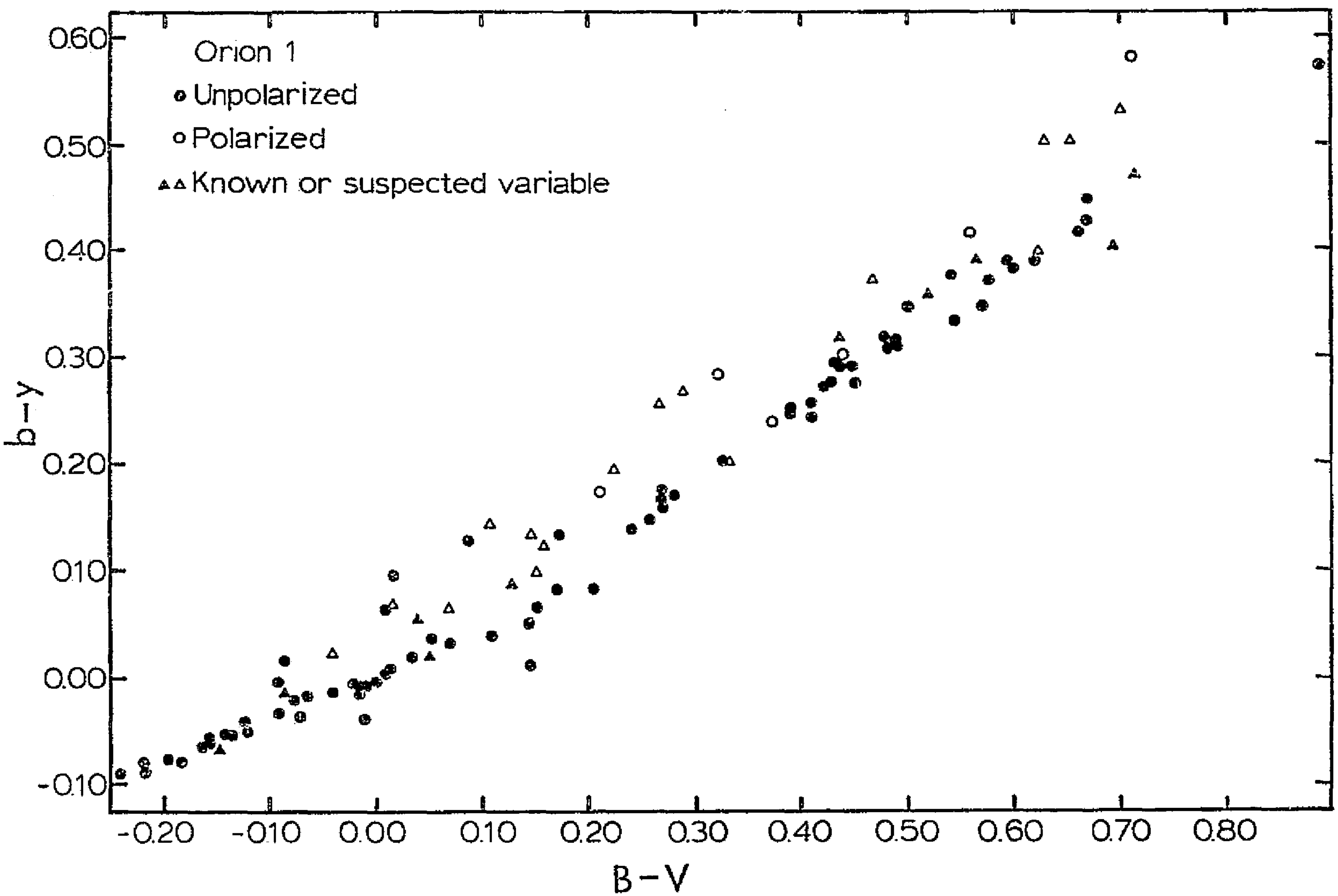
-5
-4
-3
-2
-1
0
+1
+2
M_V
$M_V(\beta)$ Field
$M_V(\beta)$ Ori 1
$M_V([u\ b],\beta)$ Ori 1
MK Ori 1
O9
B0
B1
B2
B3
B4
B5
B6
B7
B8
B9
A0
MK Type

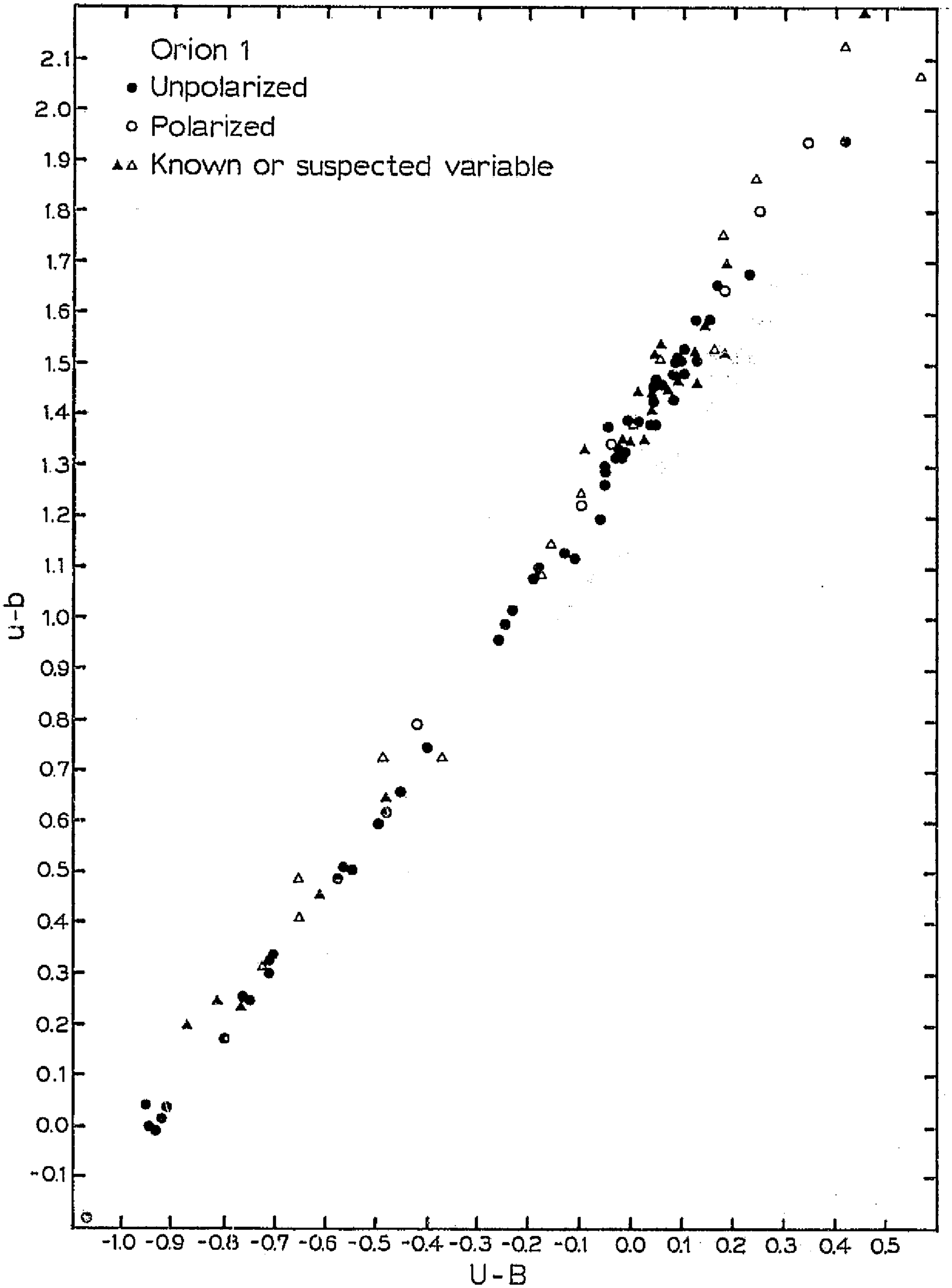


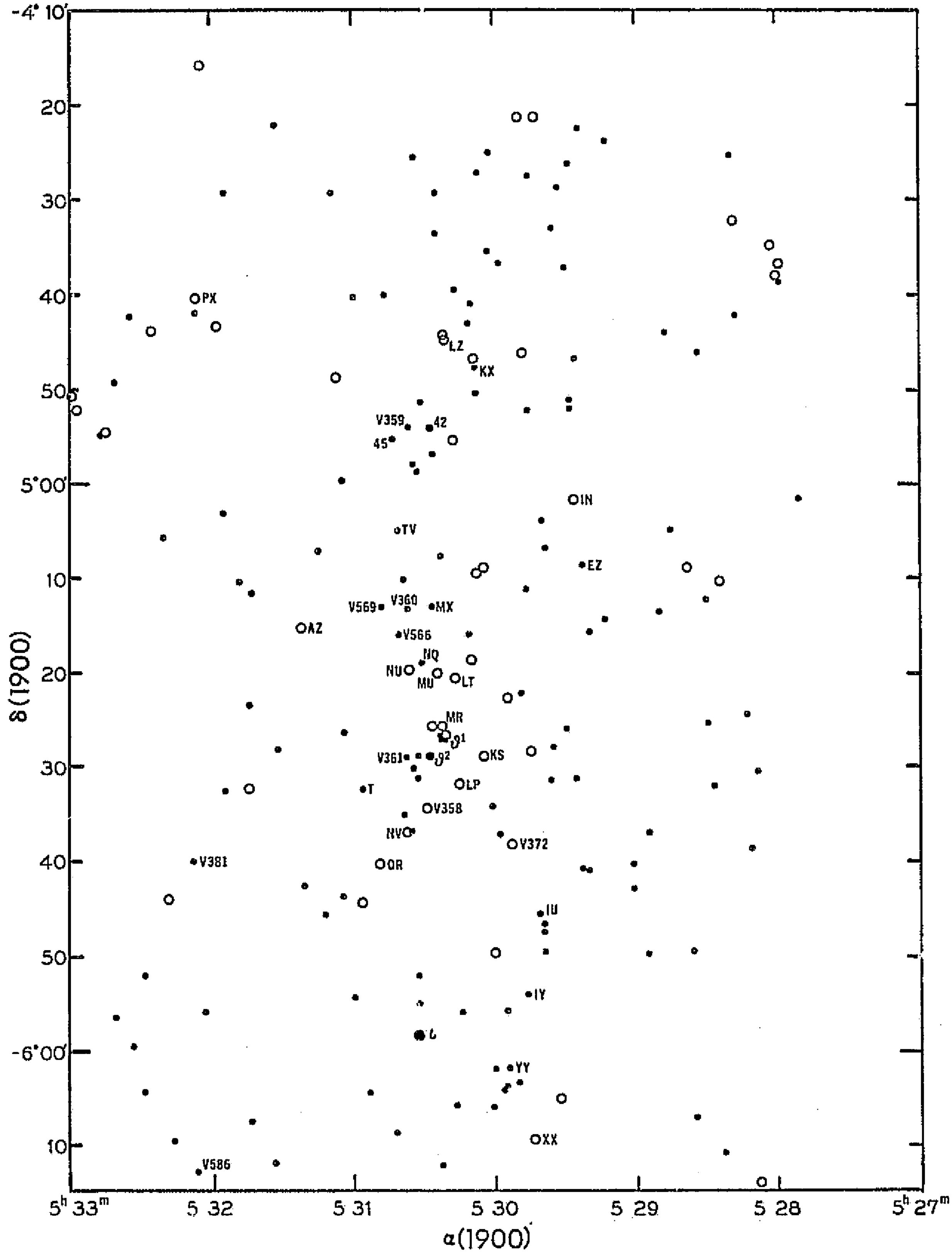
0.19
0.17
0.15
0.13
0.11
r
0.09
0.07
0.05
0.03
0.01
0.01
0
100
200
300
$v_e \sin i$

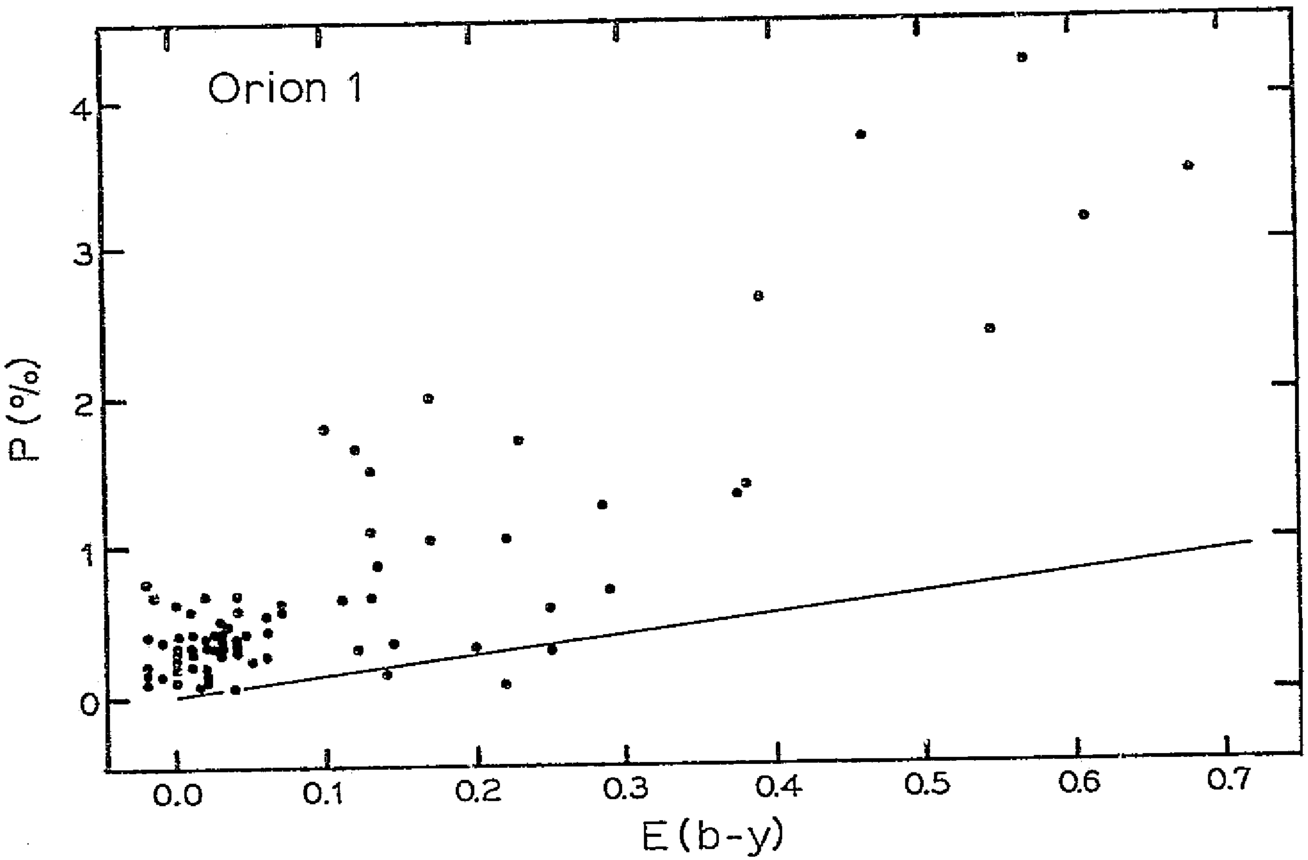


1.2
1.1
1.0
0.9
c_1
2.80
2.82
2.84
2.86
2.88
2.90
β
−0.01
0.00
0.01
0.02
0.03
0.04
0.05
0.06
b−y

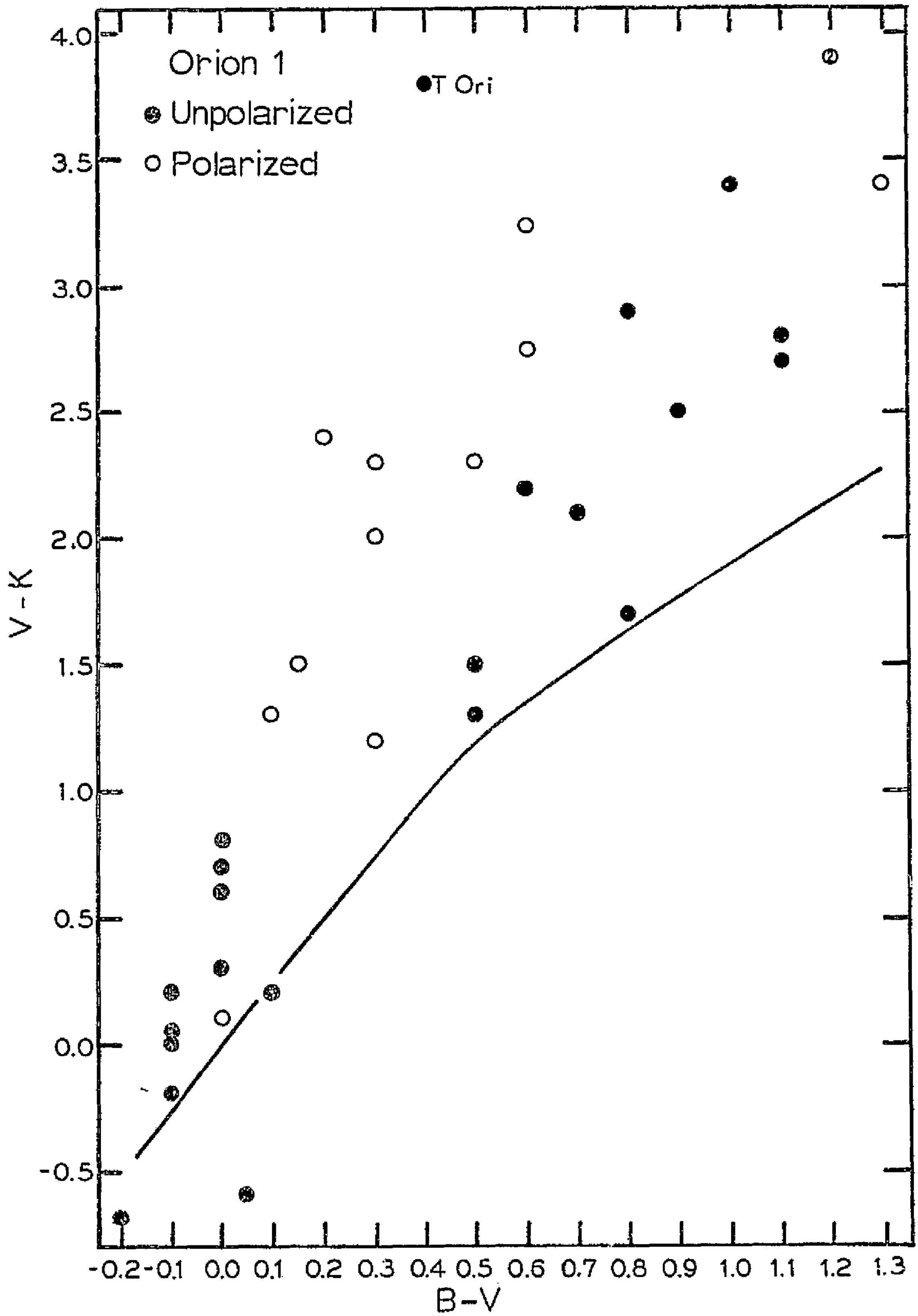

Orion 1
Unpolarized
Polarized
Known or suspected variable
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
b-y
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
B-V


Orion 1
Unpolarized
Polarized
Known or suspected variable
u-b
U-B
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-1.0 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5


-4° 10'
20
30
40
50
5°00'
10
20
30
40
50
-6°00'
10
δ(1900)
5h 33m
5 32
5 31
5 30
5 29
5 28
5h 27m
α(1900)
PX
LZ
KX
V359
42
45
IN
TV
EZ
V569
V360
MX
AZ
V566
NQ
NU
MU
LT
MR
θ1
V361
θ2
KS
LP
T
V358
NV
V372
OR
V381
IU
IY
ι
YY
XX
V586



Orion 1
P (%)
E(b-y)
0
1
2
3
4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7



Orion 1
Unpolarized
Polarized
T Ori
V-K
B-V
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3