THREE PROPOSED B-ASSOCIATIONS IN THE VICINITY OF ZETA PUPPIS

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It has recently been suggested by Brandt et al. (1971) that some of the bright B stars within 4° of γ Velorum may comprise a physical association. This suggestion coincides with the conclusions of Robert Altizer and myself from an unpublished study of the distribution of B stars in this part of the Milky Way. Our study tends to confirm the reality of the association around γ Vel. It also indicates the existence of one or two additional associations of B stars in neighboring regions, and gives some indication of the ages of all three groups.

We were interested not so much in stars associated with γ Vel or the pulsar PSR 0833-45, as in those which might be associated with ζ Puppis. An O5 star so close to the Sun (about 400 parsecs if $M_v = -6$), and without any obvious cluster or association as its place of origin, presents a strong challenge to the idea that all stars are formed in clusters or associations. The magnitude of the challenge was not entirely clear to begin with, for although no nearby OB-associations had been recognized in the Vela-Puppis area, it was by no means evident that no such association existed. A map of B stars in this area (e.g.: Becvar's Atlas Australis) shows plenty of candidates for any number of associations. The problem is to separate out those with distances near 400 parsecs, and to locate the high-density regions at that distance.

With a very low interstellar absorption such as is found in the Vela-Puppis area, the members of an association at a distance of 400 to 500 parsecs and of spectral type B2.5 and earlier will be within the magnitude limit of the Bright Star Catalog. The stars of later spectral types will be mostly below the limit of that Catalog, except that close binaries and evolved stars (luminosity classes III and IV) will still be included to B4 or B5. These considerations indicate that any associations of the type postulated should be discoverable from a study of the distribution of O - B5 stars in the Bright Star Catalog. Fortunately, Hiltner et al. (1969) have included precisely these stars in a new and complete list of revised MK types on a uniform system. These spectrum and luminosity classifications, together with UBV or U_cBV photometry of the same stars from various sources, are the basis for our present results on the location of B-associations in Vela and Puppis. Some data on fainter stars have also been included in our studies, but this material is so incomplete that it will not be discussed here.

A 40° X 30° area with limits ℓ = 235° to 275°, b = +10° to -20°, contains 151 HR stars of spectral types B5 and hotter. (This area is centered approximately on ζ Puppis, and it includes most of the Gum Nebula.) Distance moduli for all 151 stars have been estimated on the basis of their revised MK types, with suitable allowance for interstellar absorption (small in most cases) derived from 3-color photometry, or from 2-color photometry and spectral types in a few cases. The distance moduli also include some rough corrections, in the case of known visual or spectroscopic binaries, for the excess luminosity of the system over that of a single star. The absolute magnitudes adopted for each MK class are those of Mrs. Lesh (1968).

The stars have been divided into a number of groups, according to the estimated distance moduli, and maps of the apparent distribution in the sky have been made for each group. The most interesting results are obtained for the group with $7.6 < (m - M)_0 < 8.6$ (Figure 1). This map shows apparent clustering in the four regions labelled A, B, C, D. Region A coincides approximately with the association proposed by Brandt et al.

Before accepting the reality of these clusterings, it is well to check whether the same areas stand out on maps of the more distant stars. If they do, they would be more plausibly explained as holes or clear lanes in a nearby dust cloud, than as real clusters. The map of the more distant stars does in fact show a concentration in region D. Furthermore, the distant stars in region D have very small color excesses. Region D is therefore probably a hole in the dust, and not a real cluster. But regions A, B, and C are practically empty on the map of stars with $(m - M)_0 > 8.6$. Therefore they appear to be regions where the B-star density at 400 parsecs is really higher than normal.

It is also of interest to see whether the apparent clusterings A, B, and C show up on maps of stars with smaller estimated distance moduli. Clusters B and C are not seen at all for any distance moduli less than 7.6. Cluster A persists for $(m - M)_0$ as low as 7.0, but not for lower values of the modulus, with a shift of the apparent cluster center toward the bottom of the region outlined in Fig. 1 as the stars with smaller $(m - M)_0$ are included. All of this suggests that the groups are real, that the accidental errors in the assumed distance moduli do not exceed 0.5 magnitude and that group A is somewhat elongated along the line of sight. Since none of these regions contain any O stars, with the possible exception of the spectroscopic companion to γ^2 Vel, it seems appropriate to call them B-associations.

The color-magnitude diagrams for the three proposed B-associations are shown in Figures 2 and 3. These diagrams include stars with estimated distance moduli 7.0 to 7.5, as well as those in the range 7.6 to 8.6 shown in Fig. 1. Symbols refer to luminosity classes and (in class V only) to a star's status as

single, resolved binary, or unresolved binary. (A number of visual binaries are counted as "resolved", in the sense that photometry of the combined pair has been reduced to the light of the primary alone, on the basis of visual estimates of ΔV and the assumption that both stars lie on the main sequence.) The zero-age main-sequence curve in each diagram is that of Blaauw (1963), fitted to the single stars and resolved binaries of luminosity class V.

The color-magnitude diagram for association C shows a well-defined main sequence turnoff at B3, corresponding to an age of about 50 million years. The main sequence itself appears to be barely reached at apparent magnitude 6.5. The distance of this group cannot be accurately deduced from the stars shown in Figure 2, but it appears to be more nearly 300 parsecs than 400. A similar result is found for associations A and B as well. All three groups appear to have mean distance moduli much closer to 7 than to 8, on the basis of the color-magnitude diagrams. The original estimates of distance modulus appear to have been systematically too large. In part this is due to the fact that Lesh's M_v values for luminosity class V are systematically brighter than the Blaauw values for the zero-age main sequence.

It should also be remarked that the interpretation just given for the color-magnitude diagram of association C implies that the MK luminosity classes do not mean very much, at least not in the range IV to V. Alternatively, if these classifications do correspond closely to luminosity, then this group of stars must have a substantial spread in depth, corresponding to $0^m.8$ or more in $(m - M)_0$. The angular size of region C would lead one to expect a total spread of about $0^m.3$ in $(m - M)_0$.

Concerning association B, little can be said beyond the fact that its distance is approximately the same as that of C, but its age is evidently considerably smaller.

Association A, which contains both γ Vel and PSR 0833-45 within its limits, is situated in the larger bright area of the Gum Nebula. It may be the place of origin of ζ Puppis, a question to which I shall return in a moment. Its color-magnitude diagram (Figure 3, left) does not show any well-defined turnoff, but the diagram is not easy to interpret because of the apparent spread in distance moduli of the stars. I have tried to obtain a clearer diagram by excluding all stars which lie outside the main distribution in radial velocity, proper motion, or color excess. The results of this elimination appear in Figure 3, right. This reduced list of high-probability association members is the basis for the main-sequence curves drawn in both halves of the figure. As in groups B and C, the color-magnitude diagram indicates a smaller mean distance than the original estimates based on luminosity classes. If we assume that most of the stars in Figure 3 are on the zero-age main sequence, their range in distance modulus is about 6.5 to 7.6.

The question whether any of the stars in association A have significantly evolved off the zero-age main sequence is important in connection with the origin of ζ Puppis. The proper motion of ζ Pup, relative to the mean value for association A, is shown projected backward in time in Figure 1. An interpretation of ζ Pup as a "runaway star" of moderate velocity from the northern part of region A is plausible, if the stellar types in this association are compatible with an age of 3×10^6 years or less. This figure is approximately the main-sequence lifetime of a normal O5 star. The age of ζ Pup as a runaway would have to be 1 million years or less, if it originated in region A, but its total age could be as high as 3 million years.

Association A does not contain any stars of spectral class earlier than B1.5, except for γ^1 and γ^2 Vel. But this circumstance by itself does not rule out a very young age compatible with ζ Pup. The proposed cluster is not a rich one, and it might very well have been formed with no more than one or two stars in the range O5-B1. NGC 2264 may be mentioned as a well-established cluster of this kind.

The most serious obstacle to the identification of association A as the birthplace of ζ Puppis is the presence in it of some B1-B5 stars of luminosity classes III and IV. There are seven such stars in the area, when the limits of estimated distance modulus are taken as 7.0 and 8.6. But the one star of class III has an anomalously high color excess, as have two of the six stars of class IV. These stars may be tentatively assigned a larger distance than the main group. The remaining four stars of class IV cannot be eliminated on the basis of velocity or reddening. In order to assign a very young age to the association it is necessary to assume either that the luminosity classifications of Hiltner et al. are sometimes wrong by one class, so that these stars are really all class V; or else that the four stars in question are not true members. At this stage of our knowledge it does not seem difficult to accept one or both of these assumptions, and we therefore consider association A as a likely birthplace of ζ Puppis. But much remains to be learned about association A, especially since its reality as a physical group is not yet entirely established.

To summarize, there appear to be three loose B-associations in the general vicinity of ζ Puppis, all at distances of approximately 300 to 400 parsecs from the Sun. Their diameters perpendicular to the line of sight are 20 to 50 parsecs, and their separations are of similar size. All three of them are situated in bright areas of the Gum Nebula. The proposed associations A and C lie in the two brightest parts of the nebula. The three associations are not all of the same age. Association C is about 50 million years old, whereas A and B are decidedly younger. The ages of A and B cannot be determined from the present data, as their color-magnitude diagrams show no clear signs of turnoff from the main

sequence. Association A may be young enough to qualify as the birthplace of ζ Puppis, but no definite conclusion on this point is yet possible. It can be asserted with confidence that there is no other identifiable association in which ζ Puppis can have originated, unless its age is substantially greater than the 3 million years I have assumed.

Aside from the question of origin of ζ Pup, association A is in any case the locus of a Wolf-Rayet star and, apparently, a pulsar. Further investigations of this region will therefore be of great value. If the pulsar is indeed a member of the association, its original mass must have been at least 15 $M_{\odot}$. An even higher figure can be set if it is established that ζ Pup is also a member.

References

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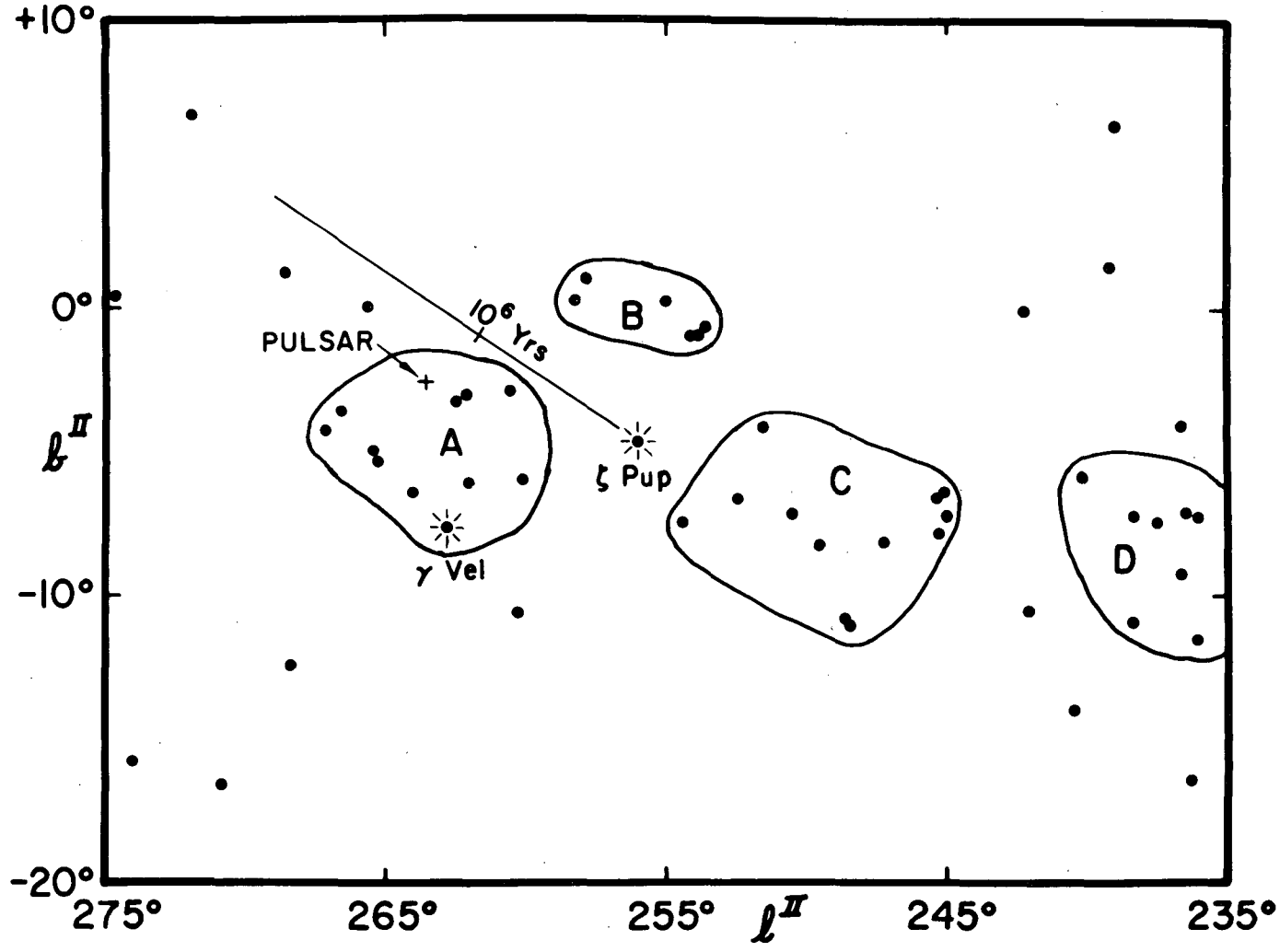

Figure 1. Projection on the sky of O-B5 stars in the Catalogue of Bright Stars with estimated distance moduli 7.6 to 8.6.

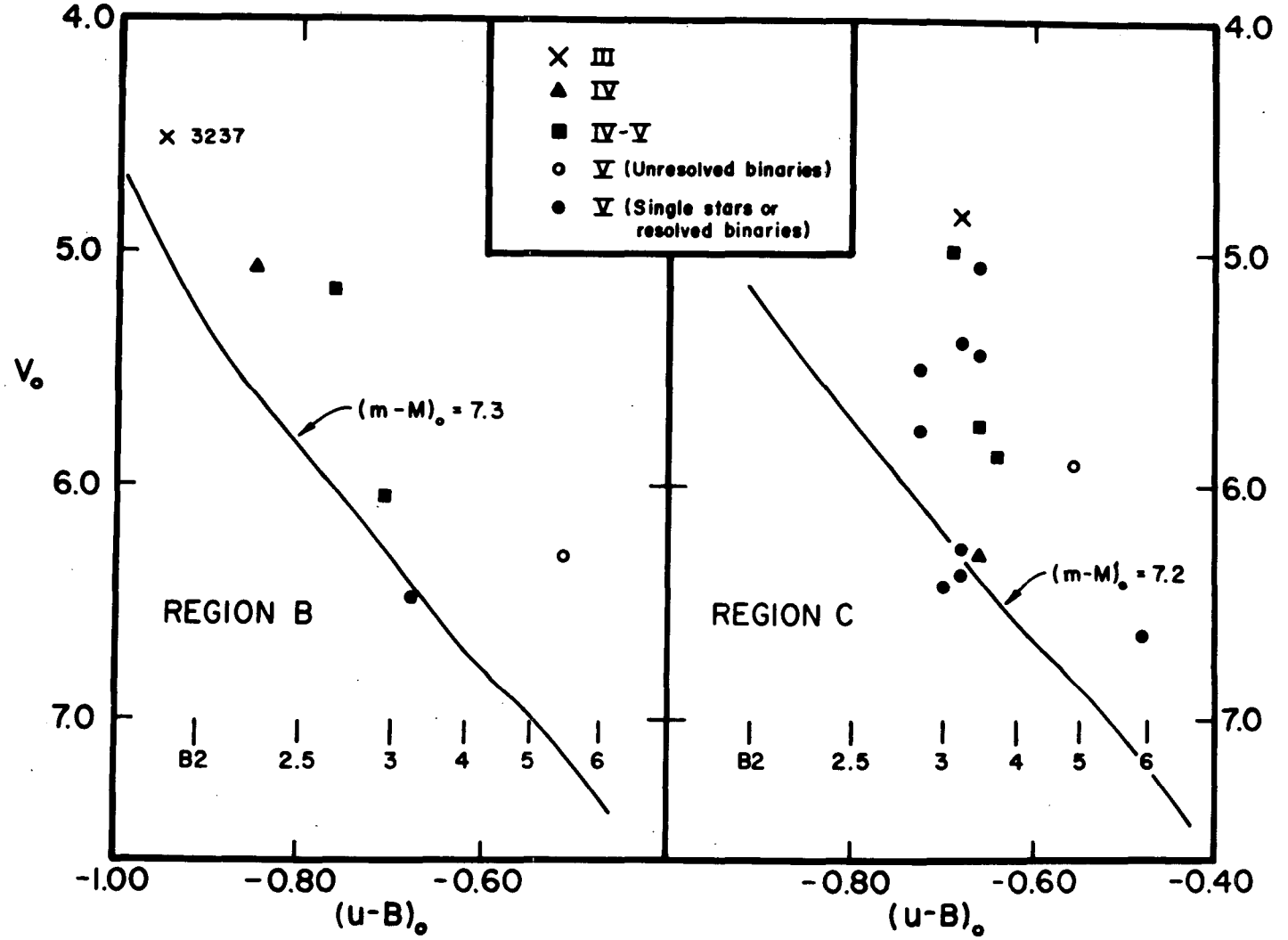

Figure 2. Color-magnitude diagrams for the stars in regions B and C, with estimated distance moduli 7.0 to 8.6.

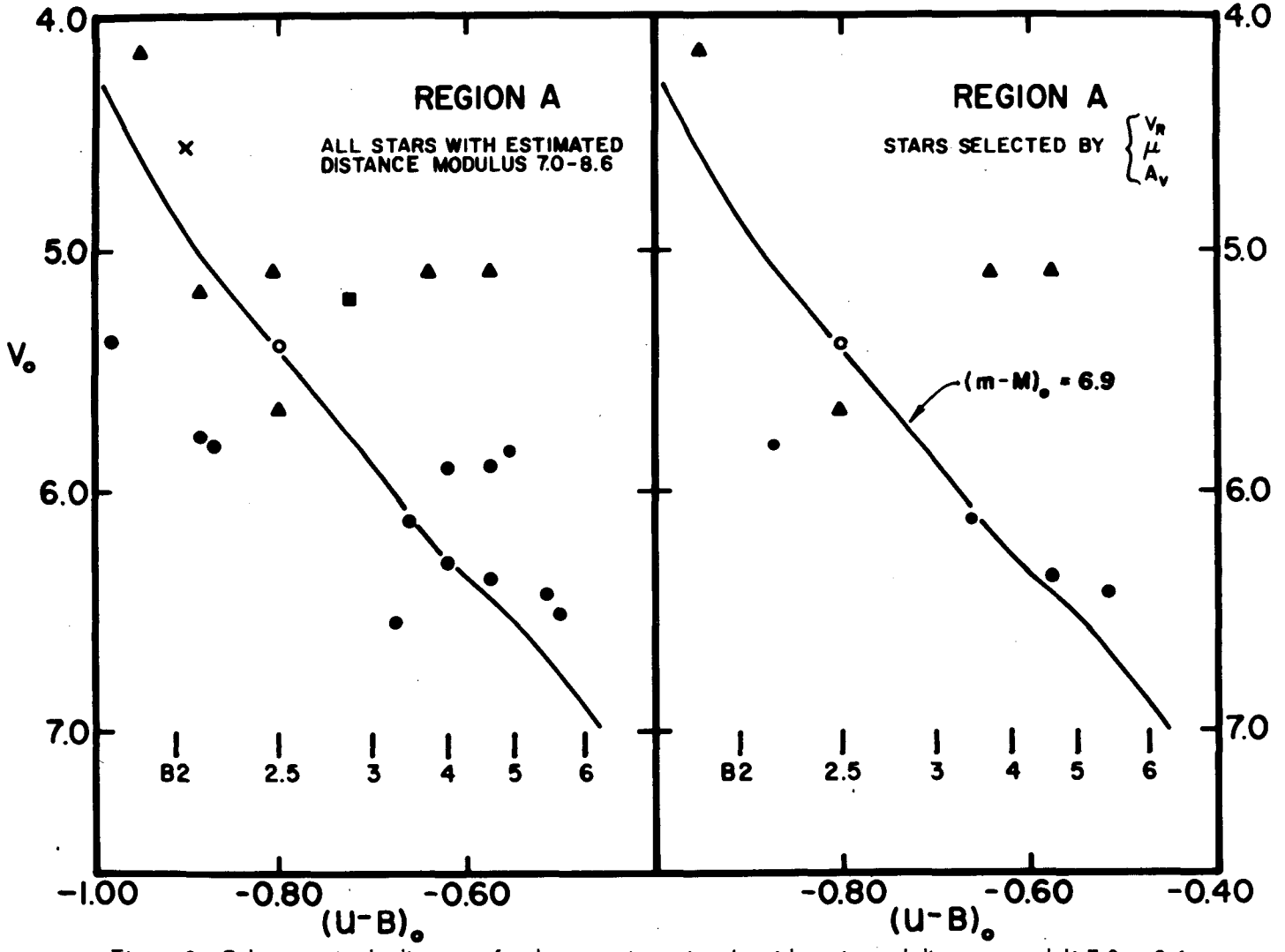

Figure 3. Color-magnitude diagrams for the stars in region A, with estimated distance moduli 7.0 to 8.6. Symbols have the same meaning as in Figure 2.