N 69 39359

CASE FILE COPY

NASA CR 106229

POSSIBLE VARIATIONS OF HELIUM CONTENT WITH POSITION IN THE GALAXY

H. L. Shipman and S. E. Strom

September 1969

NGR-22-024-001

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

908-154

POSSIBLE VARIATIONS OF HELIUM CONTENT WITH POSITION IN THE GALAXY

ABSTRACT

The helium abundances for 94 Population I B stars have been determined from observations of He I λ4471 line strengths. The mean helium abundance of this sample of stars is 0.115 ± 0.003 (p. e.) by number fraction or 0.331 by mass fraction. The data also suggest that the helium abundance varies from one OB association to another by as much as 0.02 in number fraction. Furthermore, the Perseus arm of the galaxy seems to be overabundant in helium by 0.013 in number fraction. The helium overabundance in this arm suggested from the B-star data is further supported by the observed increase in high-amplitude, short-period Cepheids in the Perseus arm, which can be interpreted in terms of enhanced initial helium content.

INTRODUCTION

To date, determinations of Population I helium-abundance values in our galaxy have been based on small numbers of objects — individual stars or clusters of stars and a few H II regions. However, uncertainties in the methods of helium-abundance determination from B-star spectra have precluded surveys of Population I helium content based on the extensive data available for these stars.

Recent investigations (Johnson and Poland 1968; Shipman and Strom 1970; Norris 1969; Poland 1970) have shown that the strong, well-observed He I diffuse lines are formed in LTE. In the last three of these papers it is also shown that the so-called singlet-triplet anomaly in the He I spectrum of B stars can be explained within the context of LTE line-formation theory. Furthermore, improved broadening theories for the strong He I λ4471 (Griem 1968; Barnard, Cooper, and Shamey 1969) have enabled us to compute theoretical profiles for diffuse series lines for B stars. The work of Shipman and Strom (1970) demonstrates that helium-abundance values based on the line strengths computed from these broadening theories and the assumption of LTE are quite reliable. They conclude that accurate values of helium abundance can be obtained from observations of strong helium lines even at moderate dispersions.

Consequently, it now seems possible to examine published observations of B-star spectra and to determine the helium abundance for large numbers of stars. The survey of Walker and Hodge (1966) is ideal for this purpose since it contains measurements of λ4471 line strength for a significant sample of O and B stars. Moreover, because their survey encompasses a selection of faint B stars, it is possible to study the large-scale behavior of helium content with galactic position.

In order to derive abundances for these B stars, we must first determine their atmospheric parameters, $\theta_{eff} = (5040/T_{eff})$ and log g. We chose to determine these parameters from, respectively, the observables Q [$Q = (U-B) - 0.71\ (B-V)$] and W(Hγ), the equivalent width of Hγ. We computed the reddening-independent parameter Q from the colors extracted from the U.S. Naval Observatory compilation of UBV observations (Blanco, Demers, Douglass, and Fitzgerald 1968). Most of these colors were in fact measured in Hiltner's (1956) survey. We found no systematic differences between Hiltner's measurements and the measurements of other observers whose colors we used. The observations of W(Hγ) were taken from the survey of Petrie and Lee (1966).

Hydrogen-line-blanketed models were used to compute UBV colors, from which a relation between Q, θ_{eff}, and log g was obtained. The temperature scale for stars of near main-sequence surface gravities derived in this way is in excellent agreement with the temperature scales of Morton and Adams (1968), Wolff, Kuhi, and Hayes (1968), and Hanbury Brown, Davis, Allen, and Rome (1967). We also computed equivalent widths for Hγ, using the Edmonds, Schlüter, and Wells (1967) broadening theory, for models covering the appropriate θ_{eff} and log g range. This allowed choice of log g from the observed values of W(Hγ) and Q. Values of He I λ4471 equivalent widths, W(4471), were computed from our models; the Barnard et al. (1969) broadening theory (cf. Shipman and Strom 1970) was adopted for these calculations. The observed value of W(4471) was then used to choose a value for the helium abundance, N(He), from the appropriate model calculation.

Because the Walker and Hodge (1966) survey includes many stars of luminosities higher than those appropriate to class V, we had to determine the range over which LTE line-formation theory is applicable. We note that the derived helium content in our survey should be independent of θ_{eff} and log g if LTE holds. Plots of our derived helium-abundance values against θ_{eff} and log g showed that departures from LTE are unimportant for log g > 3.5 since we found no systematic variation of N(He) with either of these parameters in this range. This confirms and strengthens the conclusions already reached by Shipman and Strom (1970). However, non-LTE effects become quite important for log g < 3.5, especially in the temperature regions (T_{eff} > 25,000°K and T_{eff} < 18,000°K) where a significant fraction of the equivalent width of the line is contributed by the line core; we excluded such stars from our survey. For log g < 3.5 and 18,000°K < T_{eff} < 25,000°K, there is a small dependence of abundance on log g; we chose to include stars in this range in our survey since the effects were small (< 2% in N(He)). It is interesting to note that we found remarkably close agreement between the plots of deduced abundance against log g and a theoretical prediction based on a crude extrapolation of the Johnson and Poland (1968) estimates of the effects of departures from LTE in the line core.

RESULTS

The mean abundance we obtain for the 94 B stars remaining in the sample is N(He) = 0.115 ± 0.003 (p. e.) by number fraction. As a guide to the influence of errors in the observables on the derived mean helium abundance, we note that a systematic error of 0.02 in N(He) will result from either a systematic error of $0\overset{m}{.}04$ in Q or a systematic error of 10% in either the $H\gamma$ or the He I λ4471 equivalent widths. We do not expect the errors to exceed these values. The possibility of any significant error in N(He) introduced by changes in the mean slope of the reddening line, which would enter as an error in the Q value, appears to be ruled out by the absence of any correlation of abundance with color excess.

A histogram of the abundances is presented in Figure 1. The dashed line represents a Gaussian distribution having the value of the standard error of 0.037 found for the sample. On the basis of quoted errors in the equivalent widths measured by Walker and Hodge (1966) and an estimate of a standard error of $0\overset{m}{.}03$ in Q, we expect a standard error of 0.025 in N(He). The possibility of local, intrinsic variation in the helium abundance is suggested both by the width and by the non-Gaussian nature of the histogram.

In order to examine this possibility we assigned to each star a value for ΔN, the difference between the abundance of the star and the mean abundance of the sample at the appropriate value of surface gravity; a least-squares line was used to define a mean relation between N(He) and log g. We used this method in order to avoid introducing the spurious scatter in our abundance survey, which might arise from the (small) dependence of abundance on surface gravity. Also, because of the homogeneity of the color and line-strength data, we expect high <u>internal</u> accuracies in N(He). While systematic errors in the <u>absolute</u> values of N(He) may exist, the ΔN should be significant.

The plots of these abundance deviations, ΔN, as a function of galactic position are shown in Figures 2 and 3. In Figure 2 we plot only the stars with the highest ΔN, while in Figure 3 we plot the entire sample. The distances were obtained from the absolute magnitudes of Petrie and Lee (1966) and the assumption that $A_V = 3.0\ E_{B-V}$. The apparent abundance excesses and deficiences in these plots seem to congregate in groups, some of which correspond to well-known OB associations. Not only do these groups differ in helium abundance from the sample mean, but the internal consistency of the abundance determinations within a group is greater than that found for the complete sample.

The group of apparently helium-deficient stars at $\underline{l}^{II} = 200°$ includes the OB association I Mon. The mean abundance deficiency ΔN is -0.012 ± 0.005 (p. e) and the standard error is 0.024 for the seven stars in the association. This difference between group and complete sample mean values is significant at the 90% confidence level, and the difference in standard deviations is significant at the 95% confidence level.

Another group of stars with negative ΔN is found in the direction of the constellation Perseus. This group falls between the Cygnus and Perseus arms with $130° < \underline{l}^{II} < 150°$ and with heliocentric distances between 1.0 and 1.8 kps. For this group, $\Delta N = -0.029 \pm 0.004$ (p. e). The difference between ΔN and its standard deviation from the values for the complete sample is significant at the 99.99% confidence level.

It is noteworthy that the average ΔN is $+0.013 \pm 0.006$ for all the stars in the Perseus arm. This excess is significant at the 92% confidence level. In addition, the three stars in our sample from the association I Lac are highly overabundant ($\Delta N = +0.027$, $+0.072$, and $+0.048$).

The above results seem to suggest that the helium abundance of B stars varies from one part of the galaxy to another. Because of the small number of observations involved, however, we cannot regard these results as conclusive. Consequently, we searched for an independent check on these apparent abundance variations.

In the context of the theory of Cepheid pulsation, Christy (1969) has remarked on the behavior of stellar evolutionary tracks in the vicinity of the

Cepheid instability strip. He notes that the evolutionary tracks of Iben (1967) and Hoffmeister, Kippenhahn, and Weigert (1964) indicate that stars after reaching the red-giant tip will loop back farther to the left in the H-R diagram the higher their initial helium abundance. Consequently, with higher initial N(He), more stars of low mass will reach the instability strip, thus increasing the number of low-luminosity, short-period variables. Furthermore, more short-period Cepheids will reach the <u>center</u> of the instability strip with resulting increase in their amplitudes. Thus the behavior of the period-amplitude and period-frequency relations can act as a diagnostic for the initial stellar helium content. Because this diagnostic depends on a statistical treatment of Cepheid data, the consequent averaging over large sections of the galaxy tends to obscure the cluster-to-cluster variations mentioned above, although galactic arm-to-arm variations can be detected. Another difficulty is that an increase in initial helium content is mimicked by a decrease in metal content.

An increase in the frequency of short-period Cepheids in the distant northern Milky Way, roughly corresponding to the Perseus arm, was first noticed by Bahner, Hiltner, and Kraft (1962). This behavior in the period-frequency relation <u>could</u> indicate an increase in the helium abundance of that region, in agreement with the spectroscopic results for B stars. In order to rule out the possibility of selection effects in the period-frequency relation due primarily to patchy interstellar obscuration, we have examined the period-amplitude relations for Cepheids in various parts of the galaxy. Plots of the period-amplitude relations for various galactic arms are shown in Figures 4 and 5. The limits of the arms were derived from the 21-cm data of Oort, Kerr, and Westerhout (1958).

It is evident that the number of high-amplitude, short-period Cepheids definitely increases in the Perseus arm and possibly in the Carina arm and decreases in the Cygnus and Sagittarius arms. According to Christy's (1969) interpretation, where high-amplitude, short-period Cepheids are correlated with high helium content, these results indicate a higher helium abundance in the Perseus and Carina arms. Unfortunately, no reliable data are available for B stars in the Carina arm; the Cepheid data for the Perseus arm support the B-star results. From the tracks of Hoffmeister <u>et al</u>. (1964) we guess that the scale of the helium-abundance variations must be 0.02-0.03 in N(He), or roughly the same scale as implied by the B-star data; a more accurate determination of the scale of these variations must await more detailed calculations of evolutionary tracks. The likelihood that changes in the metal abundance might influence this conclusion is diminished by the determination of normal metal content for the Cepheid variable TV Cam by Abt, Osmer, and Kraft (1966). TV Cam is an extreme representative of the large-amplitude, short-period Cepheids in the Perseus arm; no data are yet available for analogous Cepheids in the Carina arm.

Radio observations of recombination lines in H II regions give a helium abundance of N(He) = 0.077 (by number fraction) while optical determinations have varied, with a mean of N(He) $\approx$ 0.11 (cf. Palmer, Zuckerman, Penfield, Lilley, and Mezger 1969). We do not regard the difference between our value of N(He) and values obtained by other methods as significant, for systematic errors may exist in all methods of deriving the helium abundance. The possible sources of systematic error in our method are described above. In the optical analysis of nebular spectra, uncertainties in the corrections for interstellar reddening as well as uncertainties in the line-transfer problem and ionization equilibrium can affect the results. In the radio determinations, the assumption that the H II and He II regions coincide is the most crucial to the accurate determination of N(He). The calculations that test this assumption (Rubin 1968) indicate a strong dependence of the ionization structure of the H II region on the ultraviolet radiation field from the central star. This radiation field cannot be regarded as well known. The models of Mihalas (1965), which Rubin used in his calculations, are unblanketed and do not include the important far-ultraviolet opacity arising from C, N, O, or Ne. Consequently, we must consider the validity of the assumption of coincident H II and He II regions as provisional. It should be emphasized, finally, that our results on abundance variations will be unaffected by any possible systematic error in our absolute value of N(He).

While either the Cepheid results or the B-star spectroscopic results might alone be regarded as merely tentative, we feel that the combination of these two independent methods of determining helium abundances provides strong evidence in favor of a variation of helium abundance with galactic position. Any firm conclusions, however, must await a more detailed investigation of the abundance variations from one OB association to another. In such cases, much more accurate estimates can be made for errors arising from reddening-law variations and stellar rotation. In particular, reddening-law variations in the vicinity of nearby associations can be important, thereby introducing errors into our determination of θ_{eff}. We are examining data for the OB associations, I Lac, I Ori, I Per, and the Pleiades, using plate material generously supplied by Dr. Helmut A. Abt, which should allow rigorous study of all possible sources of error. However, if our suggestions of variations in helium content with galactic position are confirmed, they will present interesting problems in describing the chemical history of the galaxy.

We acknowledge with gratitude the help of K. M. Strom in assembling and analyzing the Cepheid data. One of us (HLS) would like to thank Professor W. A. Fowler for an inspirational comment. This work was supported in part by NASA grant NGR 22-024-001.

H. L. SHIPMAN

Harvard College Observatory and Smithsonian Astrophysical Observatory*

S. E. STROM

State University of New York at Stony Brook and Smithsonian Astrophysical Observatory.

*Now at the California Institute of Technology, Pasadena, California.

REFERENCES

Abt, H. A., Osmer, P. S., and Kraft, R. P. 1966, Ap. J. **145**, 479.

Bahner, K., Hiltner, W. A., and Kraft, R. P. 1962, Ap. J. Suppl. **6**, 319.

Barnard, A. J., Cooper, J., and Shamey, L. J. 1969, Astron. and Astrophys. **1**, 28.

Blanco, V. M., Demers, S., Douglass, G. G., and Fitzgerald, M. P. 1968, Magnitudes and Colors of Stars in the U, B, V, and U_C, B, V Systems. (United States Naval Observatory Publications, vol. $\overline{21}$).

Christy, R. F. 1969, Lecture notes from Summer Institute for Astronomy and Astrophysics, State University of New York at Stony Brook.

Edmonds, F. N., Jr., Schlüter, H., and Wells, D. C., III. 1967, Mem. R.A.S. **71**, 271.

Griem, H. R. 1968, Ap. J. **154**, 1111.

Hanbury Brown, R., Davis, J., Allen, L. R., and Rome, J. M. 1967, M.N.R.A.S. **137**, 393.

Hoffmeister, E., Kippenhahn, R., and Weigert, A. 1964, Z. Ap. **60**, 57.

Hiltner, W. A. 1956, Ap. J. Supp. **2**, 389.

Iben, I., Jr. 1967, Ann. Rev. Astron. Astrophys. **5**, 571.

Johnson, H. R., and Poland, A. I. 1968, in Resonance Lines in Astrophysics. (Boulder, Colorado: National Center for Atmospheric Research), pp. 413-430.

Mihalas, D. 1965, Ap. J. Suppl. **9**, 321.

Mitchell, R. I., Iriarte, B., Steinmetz, D., and Johnson, H. L. 1964, Photoelectric photometry of Cepheid variable stars. Boletin de los Observatorios Tonanzintla y Tacubaya 3, pp. 153-304.

Morton, D. C., and Adams, T. F. 1968, Ap. J. **151**, 611.

Norris, J. E. 1969, Ap. J., in press.

Oort, J. H., Kerr, F. J., and Westerhout, G. 1958, M.N.R.A.S. **118**, 379.

Palmer, P., Zuckerman, B., Penfield, H., Lilley, A. E., and Mezger, P. G. 1969, Ap. J. **156**, 887.

Petrie, R. M., and Lee, E. K. 1966, Pub. Dom. Ap. Obs. 12, 435.
Poland, A. I. 1970, Ap. J., in press.
Rubin, R. H. 1968, Ap. J. 153, 761.
Shipman, H. L., and Strom, S. E. 1970, Ap. J., in press.
Walker, G. A. H., and Hodge, S. M. 1966, Pub. Dom. Ap. Obs. 12, 401.
Wolff, S. C., Kuhi, L. V., and Hayes, D. S. 1968, Ap. J. 152, 871.

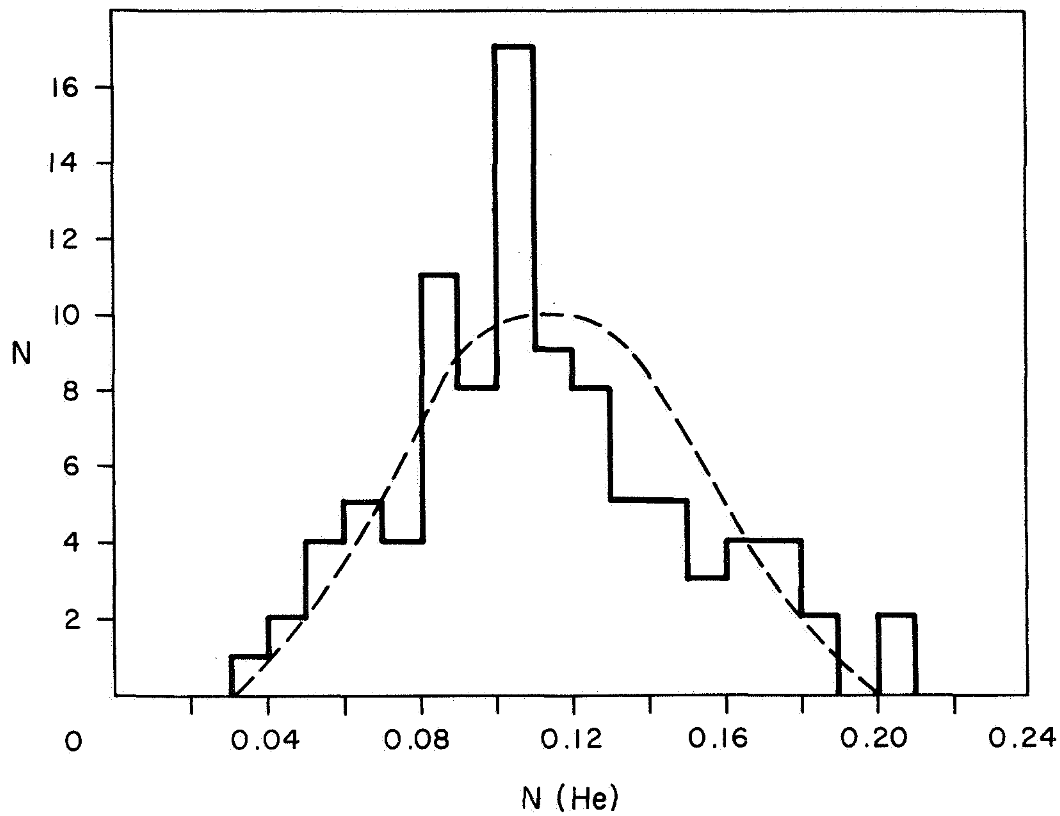

Fig. 1. Histogram of the deduced helium abundances.

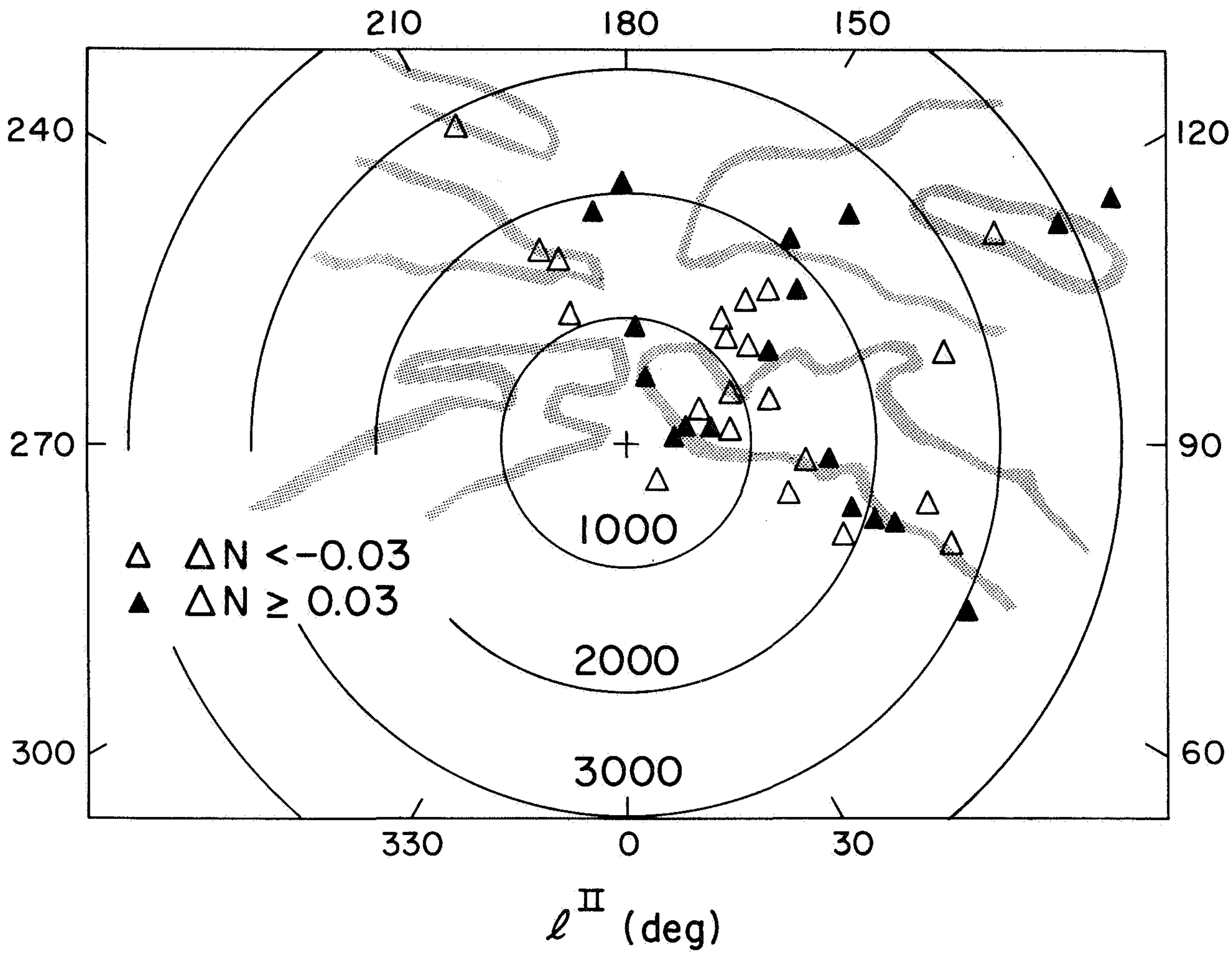

Fig. 2. The galactic locations of the extreme overabundant and underabundant stars. Heliocentric distances are in parsecs; the shaded outlines represent the outlines of the galactic arms as determined by the 21-cm data (Oort <u>et al</u>. 1958).

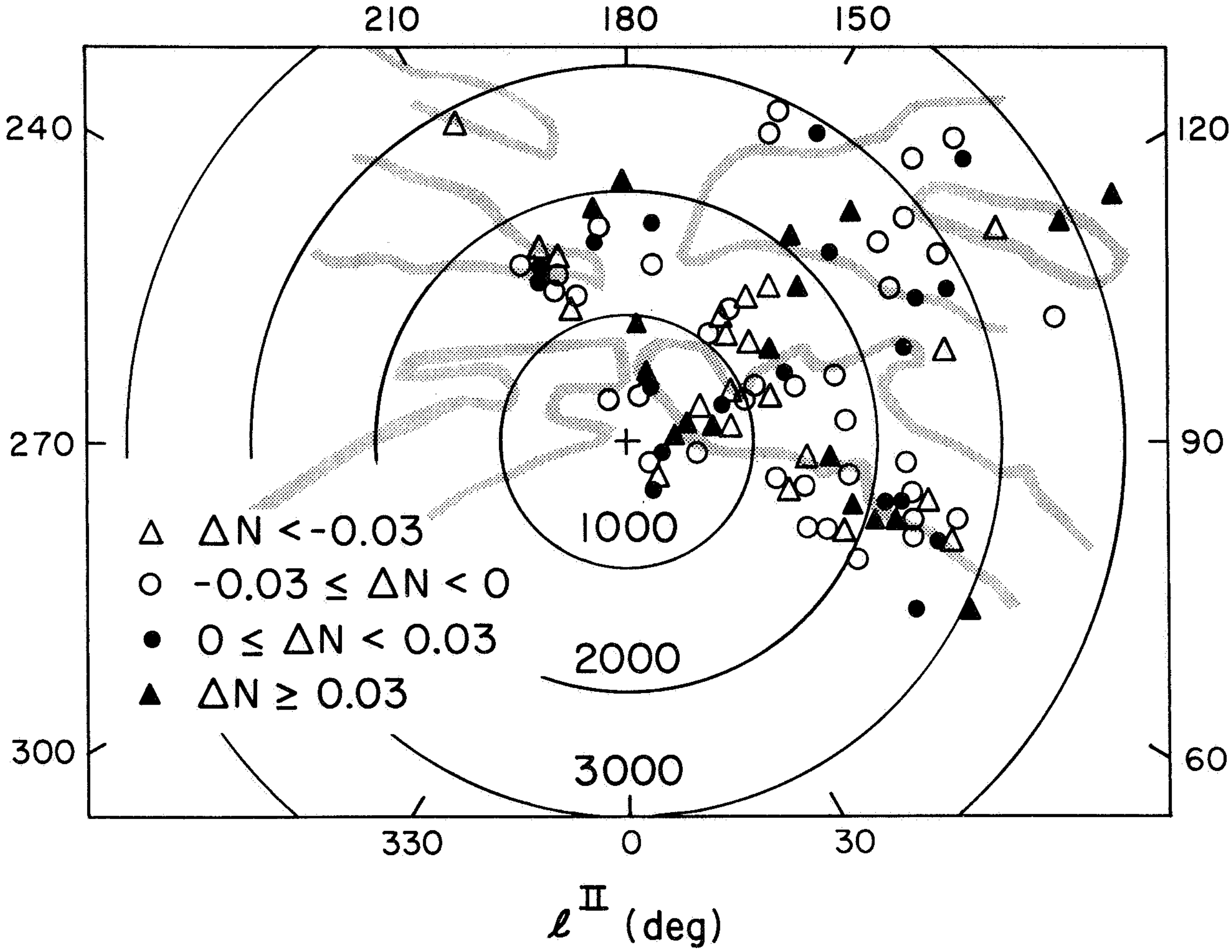

Fig. 3. The galactic locations and abundance deviations of all the stars in the sample. Notation as in Fig. 2.

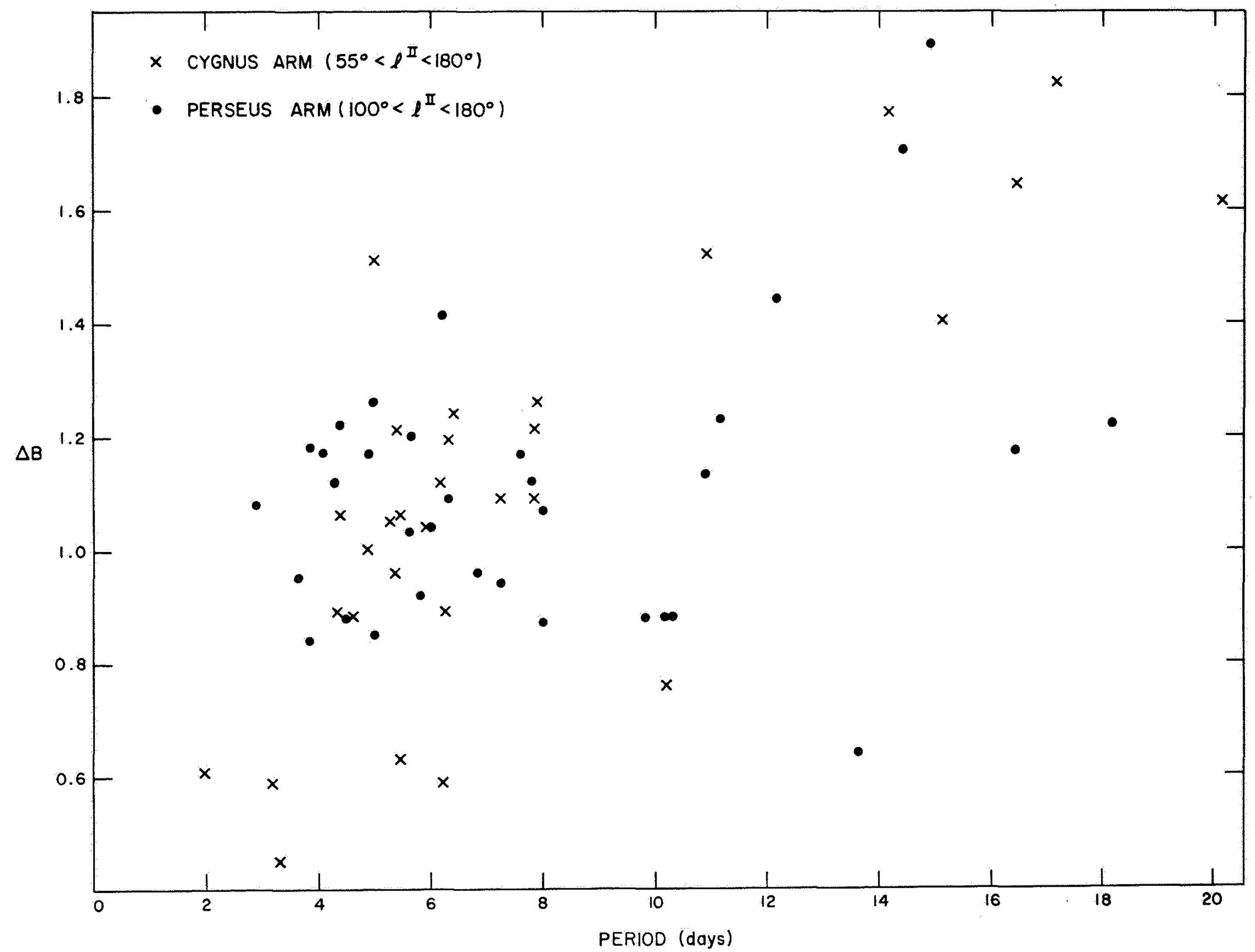

Fig. 4. Period-amplitude diagram for the stars in the Perseus and the Cygnus arms. ΔB is the amplitude in the B magnitude for a given Cepheid variable. The data are taken from Mitchell, Iriarte, Steinmetz, and Johnson (1964).

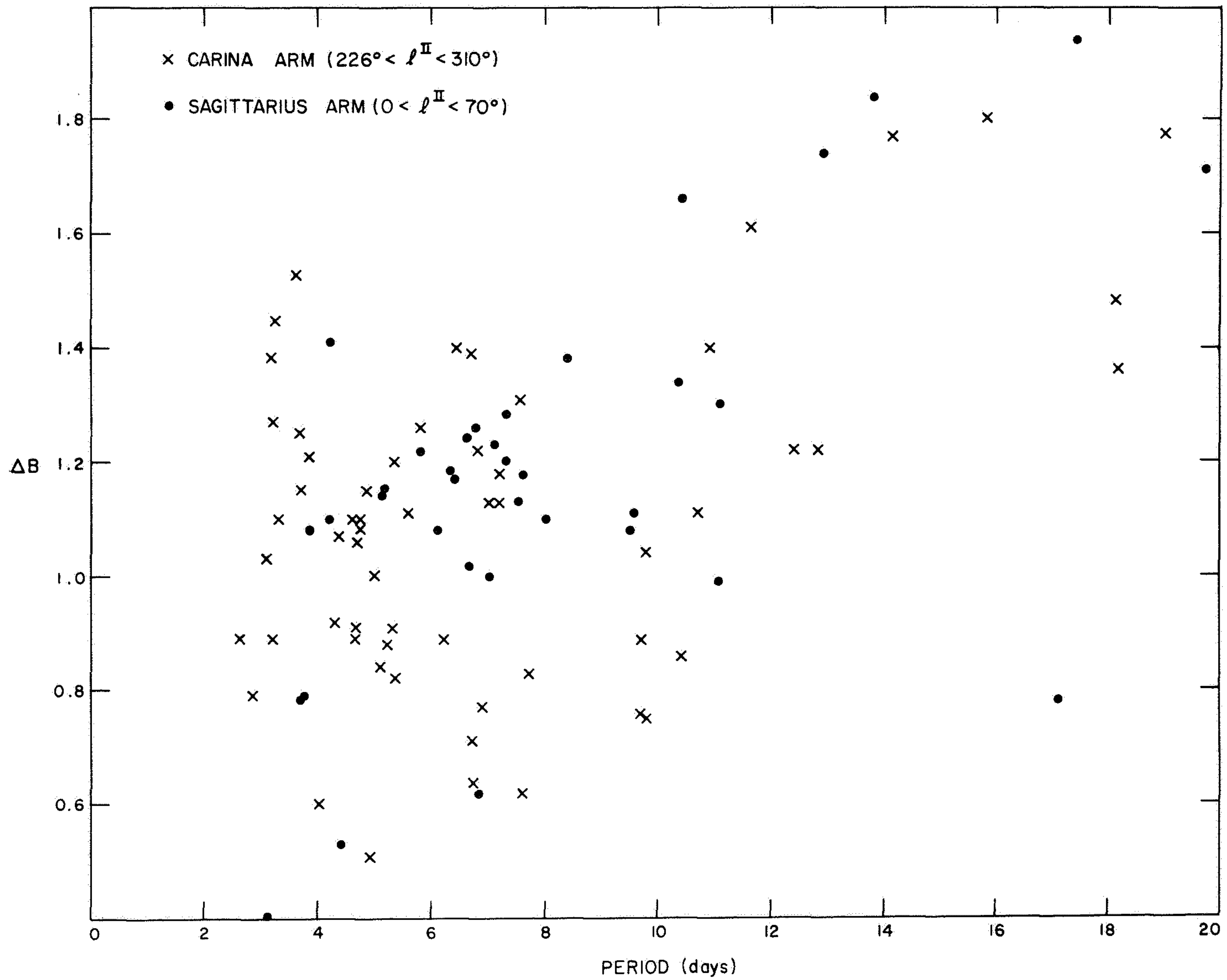

Fig. 5. Period-amplitude diagram for the stars in the Carina and the Sagittarius arms. Notation as in Fig. 4.