1956PASP...68....5B

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THE PERIOD-LUMINOSITY RELATION OF THE CEPHEIDS*

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Around the turn of the century two investigations were started at the Harvard Observatory that had a far-reaching influence on the further development of astronomy: Henrietta S. Leavitt's investigation of the variable stars in the two Magellanic Clouds and Solon I. Bailey's investigation of the variable stars in globular clusters. The Magellanic Clouds turned out to be veritable mines of cepheids with periods longer than one day. In contrast, the overwhelming majority of the variables in globular clusters were cepheids with periods shorter than one day; they were so characteristic of globular clusters that Bailey proposed for them the name "cluster-type variables." Further investigations of these variables led to two very remarkable results. The most striking was Miss Leavitt's discovery that the brightness of the cepheids in the Magellanic Clouds is a function of the period of the light-variation (the observed brightness increases with the period). Since there was every reason to believe that the objects in each Cloud are at practically the same distance from us, the observed period-brightness relation clearly implied a period-luminosity relation for the cepheids with periods longer than one day. Once established, this period-luminosity relation obviously would provide a simple and very powerful tool for determining the distance of any cepheid of known apparent brightness and period.

* This lecture was given at a meeting of the Astronomical Society of the Pacific on June 22, 1955, in Pasadena at which Dr. O. C. Wilson presented Dr. Baade with the Catherine Wolfe Bruce Gold Medal. (See *Pub. A.S.P.*, 67, 323, 1955.)

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1956PASP...68....5B

With regard to the cluster-type variables, the situation seemed to be even simpler. Although their periods range from about 0.2 to 1.0 day, Bailey found little or no dependence of luminosity upon period. His observations justified the assumption that all cluster-type variables have about the same absolute magnitude, the dispersion around the mean not exceeding 0.1 magnitude.

Miss Leavitt's and Bailey's results thus made it clear that both cepheids and cluster-type variables could be used as accurate and powerful photometric distance indicators, if their absolute magnitudes could be determined accurately enough. The first one to use Miss Leavitt's observed period–apparent magnitude relation of the cepheids in the Small Magellanic Cloud for the determination of stellar distances was E. Hertzsprung,[1] who had already shown that the cepheids are stars of high luminosity. From the proper motions of 13 cepheids in the Boss *Preliminary General Catalogue* he obtained $M_{\mathrm{vis}} = -2.3 \pm 0.3$ for a cepheid with $P = 6.6$ days. The resulting value for the distance of the Small Magellanic Cloud was 33,000 light-years.

It may be a surprise to the younger astronomers that in 1913 this figure represented by far the largest distance ever determined for an individual object, the next largest being the distance of the Hyades, 130 light-years, if I remember correctly. Of course, for those who were able to enjoy them, there were also such insipid data as the mean distance of the stars of the tenth magnitude. The rapid development in the measuring of large cosmic distances after 1913 is almost solely due to the application of the period-luminosity relation of the cepheids.

The first to make full use of the new tool was H. Shapley, who had become intrigued by the globular clusters of our galaxy. Shapley saw clearly that the determination of the distances of the globular clusters would be a trivial matter if one could determine the absolute magnitude of the cluster-type variables. However, there was no chance at that time to derive the absolute magnitude of the cluster-type variables from their motions because proper motions and radial velocities were known for only two or three cluster-type variables. In this dilemma Shapley proceeded[2] as follows: the period-luminosity relation for cepheids with periods from 1.3 to 66 days was well established through the work of Miss

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1956PASP...68....5B

Leavitt and the standardization of Hertzsprung. Now Bailey's investigations had shown that besides the cluster-type variables, long-period cepheids occasionally occur in globular clusters; the best example is ω Centauri in which Bailey discovered five cepheids with periods longer than one day, in addition to the more than a hundred cluster-type variables. By fitting the long-period cepheids in clusters like ω Centauri to the period-luminosity relation from the Small Magellanic Cloud, Shapley was able to extend the period-luminosity curve to the cluster-type variables. Their visual absolute magnitude turned out to be $\overline{M} = -0.3$. Thus a period-luminosity relation was established which covered the whole range of the cepheid variation and which was accepted as the period-luminosity relation for the next 30 years. We know today that the procedure by which Shapley connected the cluster-type variables with the cepheids of the Small Magellanic Cloud is open to criticism because the so-called cepheids in globular clusters are objects quite different from the cepheids of the Magellanic Clouds. But this is knowledge gained only in recent years. In 1918, Shapley's procedure appeared perfectly straightforward and nobody protested it.

Shapley's first period-luminosity relation was given in terms of visual magnitudes. Later he derived a photographic period-luminosity relation, the final form of which was published in his book *Star Clusters*. Early in his work Shapley had made a new determination of the zero point of the period-luminosity relation.[2] He used the same proper motion data as Hertzsprung but omitted κ Pavonis and l Carinae because of peculiarities in their behavior. As was to be expected, he obtained practically the same result as Hertzsprung, namely: $M_{\text{vis}} = -2.35 \pm 0.19$ for a cepheid with $P = 5.96$ days. With one exception which will be discussed later, subsequent investigations closely confirmed the zero point derived by Hertzsprung and Shapley. Two of these investigations should be mentioned especially. Mrs. P. F. Bok and Miss C. D. Boyd[3] determined the mean absolute photographic magnitude of 58 cluster-type variables from their proper motions, obtaining $\overline{M}_{\text{pg}} = +0.08 \pm 0.15$, in close agreement with Shapley's period-luminosity relation. In his book, *Star Clusters*, Shapley therefore adopted 0.0 for the photographic absolute magnitude of cluster-

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1956PASP...68....5B

type variables. R. E. Wilson's new discussion[4] in 1939 of the zero point of the period-luminosity relation, based on the proper motions of 157 cepheids in the Boss *General Catalogue*. Included is a rediscussion of the parallactic motions of 55 cluster-type variables for which A. H. Joy meanwhile had measured the radial velocities. From these data Wilson derived the following corrections to Shapley's adopted zero point of the period-luminosity relation:

from 55 cluster-type variables: $\Delta M = 0.0 \pm 0.2$
from 157 cepheids : $\Delta M = -0.14 \pm 0.2$.

It is not surprising that such confirmations greatly strengthened the faith in the accepted period-luminosity relation and led to the belief that no further troubles were to be expected.

In the background, however, there remained a discrepancy which so far had found no satisfactory explanation. When Hubble in 1931 investigated the globular clusters of the Andromeda nebula, he noted that their upper limit of luminosity was about 1.5 magnitudes fainter than the upper limit of the globular clusters of our own galaxy. At first this discrepancy did not cause much concern since the integrated magnitudes of the globular clusters of our galaxy rested on rather uncertain data. But when the integrated magnitudes obtained by W. H. Christie[5] with a Schraffier-kassette confirmed the discrepancy, it became necessary to face the facts. I still remember the numerous discussions which followed, especially on cloudy winter nights on Mount Wilson. While I argued that a real difference in the upper limits would be hard to understand in view of the near equality of the two samples—both galaxies contain about the same number of globular clusters—and that the discrepancy must have entered through some loophole in one of the distance determinations, Hubble took the more cautious line that one should not overwork the principle of uniformity and that there might be a real difference between the richest globular clusters of the Andromeda nebula and those of our own galaxy. What had impressed him was the fact that the brightest globular clusters in Messier 33 were still fainter than those of the Andromeda nebula! The discussions finally stopped because neither side had a really convincing explanation for the discrepancy. I have mentioned these discussions because some

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1956PASP...68....5B

recent reviewers of the problem have rather glibly stated that the discrepancy in the luminosities of the globular clusters implied already a change in the zero point of the period-luminosity relation. It is obvious that no change in the zero point could remove the discrepancy as long as the accepted form of the period-luminosity relation was retained.

It was only after the recognition of the two stellar populations that the first serious doubts arose concerning the accepted form of the period-luminosity relation. The arguments were as follows. Miss Leavitt's cepheids in the Magellanic Clouds and the classical cepheids in our galaxy are clearly members of population I, while the cluster-type variables and the long-period cepheids of the globular clusters are members of population II. Since the color-magnitude diagrams of the two populations leave no doubt that in the two cases we are dealing with stars in different physical states, there was no a priori reason to expect that two cepheids of the same period, the one a member of population I, the other of population II, should have the same luminosity. Moreover, a few well-known facts supported the view that the so-called cepheids of population II are objects different from their counterparts in population I. I mention only the prevalence of stars of the W Virginis type among the population II cepheids with periods between 12 days and 30 days, and the appearance of emission lines in the spectra of these same variables. Altogether there were good reasons to suspect that unknowingly Shapley had made a fatal step when he linked the cluster-type variables to the type I cepheids through the type II cepheids in globular clusters and that in reality we are dealing with two different period-luminosity relations, the one valid for the type I cepheids, the other for the type II cepheids. From this new viewpoint the discrepancy between the luminosities of the globular clusters in the Andromeda nebula and those in our own galaxy was easily explained. The distance of the Andromeda nebula—and hence the luminosities of its globular clusters—had been determined by type I cepheids whereas distances and luminosities of the globular clusters in our own galaxy were based on type II cepheids (the cluster-type variables). Under these circumstances any error in the adopted luminosities of the two kinds of cepheids would show up as a

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1956PASP...68....5B

discrepancy such as that noted by Hubble in the globular clusters. To remove this discrepancy, it was necessary to shift the period-luminosity relation of the type I cepheids upward by about 1.5 magnitudes relative to the cluster-type variables.

This was the situation when the 200-inch telescope was nearing completion and we were discussing the first observing programs for the new instrument. Naturally I was very eager to settle these disturbing questions which had arisen regarding the accepted period-luminosity relation. It was also perfectly clear how to proceed. One would have to select a near-by galaxy which contained both stellar populations in order to study in properly selected fields the two kinds of cepheids side by side, so to speak. The results of such an investigation would show whether or not the accepted period-luminosity relation represents the true state of affairs. There was no doubt that the Andromeda nebula was the most suitable object for such an investigation and that the 200-inch could answer the questions in which I was interested.

The observations of three selected variable-star fields in the Andromeda nebula started in the early fall of 1950. Already the very first plates indicated that the accepted form of the period-luminosity relation did not represent the true situation. If it had, the cluster-type variables of the Andromeda nebula should have appeared at the limiting magnitude of the plates. Instead, the brightest stars of the population II appeared at about this magnitude. Since they are photographically 1.5 magnitudes brighter than the cluster-type variables, the conclusion was unavoidable that the accepted period-luminosity relation made the cluster-type variables, and with them all type II cepheids, about 1.5 magnitudes too bright relative to the type I cepheids from which the distance modulus of the Andromeda nebula had been derived. This situation also fully explained why Hubble encountered the discrepancy in the luminosities when he compared the globular clusters of the Andromeda nebula with those of our own galaxy.

At first I had no intention of following this particular line of attack which had thus opened up, because I felt that in the end the results from the cepheid program would be more convincing. I changed my mind, however, after I had become better ac-

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1956PASP...68....5B

quainted with the population II of the Andromeda nebula through observations at the 200-inch telescope. Although the earlier observations at the 100-inch had revealed the main features of the two populations, in particular their distribution within the nebula, the whole undertaking had remained a tour de force in so far as the population II was concerned, because the 100-inch was just able to reveal the brightest stars of population II under the best atmospheric conditions. With the greater aperture and the well-corrected field of the 200-inch it was now possible to study the population II of the Andromeda nebula and of near-by spheroidal galaxies, like NGC 185 and NGC 205, in more detail, and I used this opportunity as far as the variable-star program permitted. For obvious reasons I used mostly photovisual and red-sensitive plates for this special program. These revealed a very striking fact. Whenever the exposure time for a given field of the Andromeda nebula was sufficient to bring out the brightest stars of population II, the outer parts of any globular clusters which happened to be in the field showed resolution into stars. This was a very direct proof that the brightest stars of population II in the Andromeda nebula have indeed the same absolute magnitude, $\overline{M}_{pg} = -1.5$, as the brightest stars in globular clusters.

It was now only necessary to determine their apparent magnitude in order to find the apparent magnitude of the cluster-type variables of the Andromeda nebula. Since W. A. Baum's accurate faint standards in S.A. 68 were not yet available, I had to use the provisional system of magnitudes which I had set up in the Andromeda nebula. In this system the brightest stars of population II in the Andromeda nebula are of the apparent photographic magnitude 22.4, hence the cluster-type variables which are 1.5 magnitudes fainter are of photographic magnitude 23.9.

But according to the distance modulus of M 31, which is based on the accepted period-luminosity relation and type I cepheid data, they were expected to be of photographic magnitude 22.4. It is therefore clear that the accepted period-luminosity relation makes the cluster-type variables, and with them the cepheids of population II, 1.5 magnitudes too bright relative to the type I cepheids. Or to put it differently: instead of one period-luminosity relation there are actually two, one for type I cepheids, the other

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1956PASP...68....5B

for type II. On the average a type I cepheid is 1.5 magnitudes brighter than a type II cepheid of the same period.

As mentioned earlier, the absolute magnitudes of both cluster-type variables and classical cepheids had been determined from their motions. The question arose now which of the two was the more trustworthy. Since both had been concordant with the assumption that there was a single period-luminosity relation, it was clear that one or both were seriously in error. There was every reason to suspect that the more uncertain of the two values was the absolute magnitude of the classical cepheids. The proper motions of these cepheids are so small that even the best modern values are hardly outside the range where observational errors begin to mask the motions. Moreover, these cepheids are so strongly concentrated toward the plane of the galaxy that the interstellar absorption has to be taken into account. This had to be done in roundabout ways, since it is only recently that the absorption for an individual cepheid can be inferred with confidence from its color excess. Both of these difficulties are absent in the case of the cluster-type variables. Their proper motions are large compared with those of the type I cepheids, and since they show little, if any, concentration toward the plane of the galaxy, larger absorption effects are to be expected only in a few exceptional cases. Since, moreover, for all cluster-type variables of known proper motion the radial velocities also are available, the absolute magnitude derived from the parallactic motions should be fairly reliable and certainly not be off by a large amount. This seemed to be confirmed by A. R. Sandage's color-magnitude diagram of Messier 3 which reaches down to $M_{pv} = +5$. The best fit of the subgiant sequence in Messier 3 with the subgiant sequence in the color-magnitude diagram of near-by stars led to an absolute magnitude of the cluster-type variables of $M_{pv} = +0.11 \pm 0.2$.[6] I felt therefore that for the time being the absolute magnitude of the cluster-type variables ($M_{pg} = 0.0$) was the best choice for the zero point of the period-luminosity relations and that the determinations of the absolute magnitudes of the type I cepheids should be disregarded entirely. The proposed new zero point leaves unchanged all former distance determinations based on cluster-type variables. But the distances derived

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1956PASP...68....5B

previously from type I cepheids have to be multiplied by the factor 2 because these cepheids are 1.5 magnitudes brighter than we had previously thought.

The foregoing results were presented at the session of Commission 28 on extragalactic nebulae at the Rome meeting of the International Astronomical Union in September 1952.[7] Now a few words about the later developments.

Immediately after my talk in Rome Dr. A. D. Thackeray rose to announce that data obtained at the Radcliffe Observatory thoroughly confirmed the large shift of the cluster-type variables relative to the type I cepheids. Thackeray and Wesselink had just discovered the first cluster-type variables in one of the globular clusters (NGC 121) of the Small Magellanic Cloud, but instead of being of apparent magnitude 17.3, as expected according to the old period-luminosity relation, these variables had apparent magnitudes close to 19. This was a most direct confirmation of the findings in the Andromeda nebula. Soon afterward, in 1953, Thackeray and Wesselink[8] announced the discovery of cluster-type variables in two globular clusters, NGC 1466 and NGC 1978, of the Large Magellanic Cloud. From their data for the three globular clusters one obtains, for the shift of the cluster-type variables relative to the type I cepheids, $\Delta M = 1.4$ magnitudes. This figure should be considered provisional since in 1953 no accurate magnitude standards extending to the 19th magnitude were available in the southern sky. In fact Thackeray and Wesselink believe that their figure is too small. However, it is certain that the Magellanic Clouds offer the best opportunity to determine this quantity with high accuracy as soon as photoelectrically established magnitude scales in the Clouds are available. Until then the value $\Delta M = 1.5$ should furnish a sufficiently close approximation. It is confirmed by new cepheid data for the Andromeda nebula and accurate, photoelectrically determined magnitude scales. These gave as the apparent distance modulus of M 31, if the old zero point for the type I cepheids is used, $m - M = 22.75$. A new determination of the photographic magnitude of the brightest population II stars of M 31 gave $\overline{m}_{pg} = 22.7$, hence for the cluster-type variables $\overline{m}_{pg} = 22.7 + 1.5 = 24.2$ and therefore $\Delta M = 1.5$. The same value results if one uses

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1956PASP...68....5B

Baum's[9] photoelectrically determined photovisual magnitude of the brightest population II stars of NGC 205 (the elliptical companion of M 31), $\overline{m}_{pv} = 21.2$ and $\overline{M}_{pv} = -3.0$. Finally H. Shapley and V. McKibben Nail[10] obtained $\Delta M = 1.6 \pm 0.1$ by applying essentially the same methods to the brightest stars in 10 globular clusters of the Magellanic Clouds.

Soon after the Rome meeting I received a letter from the late Dr. Henri Mineur in which he stated that my results were not new but were already contained in his paper on the "Zéro de la relation période-luminosité et absorption de la lumière dans l'espace interstellaire," in the *Annales d'Astrophysique*, 7, 160, 1945. He mentioned also in his letter that he had derived the absolute magnitudes $M_0 = -0.32$ for the cluster-type variables and $M_0 = -1.54$ for the classical cepheids of one-day period.[11] Naturally I was puzzled until I reread Mineur's paper. It then turned out that in his original paper Mineur had derived separately the correction to the zero points for the cepheids and the cluster-type variables, but, sharing the general belief in a single period-luminosity relation, had adopted the mean of the two determinations, $M = -0.73$, as the correction to the zero point. Not until after the Rome meeting had he attributed significance to the fact that the zero points for the cluster-type variables and for the type I cepheids were different and, with some different weighting, derived the values mentioned in his letter. Since Mineur used the same observational data as R. E. Wilson, the question arises why he obtained such a different result for the luminosities of the classical cepheids (Wilson and Mineur are in practical agreement regarding the absolute magnitudes of the cluster-type variables). The answer is that they handled the absorption of the cepheids in different ways. Both had to use statistical corrections, applied to different distance groups. But Mineur realized that because of the very strong concentration of type I cepheids toward the plane of the galaxy the computed corrections would be quite sensitive to the adopted pole of the galaxy. He therefore redetermined the position of the galactic pole from the cepheids themselves. Moreover as a check of the computed absorptions he used a criterion which had been proposed by Bottlinger and Schneller, i.e., that the distribution of the cepheids

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1956PASP...68....5B

perpendicular to the galactic plane should be independent of their distance from the sun. There can be no doubt that Mineur handled the important absorption problem much better than his predecessors. It is another question whether or not the new zero point, $M_0 = -1.54$, which he obtained for the type I cepheids should be taken at its face value. A closer examination of Mineur's results shows that he obtained from the radial velocities the rather large value of $S_0 = 30.2$ km/sec for the motion of the sun relative to the cepheids. This value obviously affects the absolute magnitude derived from the proper motions. If one substitutes the much more probable value $S_0 = 20$ km/sec, Mineur's value for the zero point of the cepheids drops from $M_0 = -1.54$ to $M_0 = -0.92$. The close agreement of Mineur's zero point of the cepheids with that suggested at the Rome meeting is therefore almost certainly accidental. Undoubtedly the best recent determination of the zero point of the type I cepheids is that of A. Blaauw and H. R. Morgan,[12] based on the parallactic motions of 18 cepheids brighter than magnitude 8 at maximum. Blaauw and Morgan used only stars with very accurately determined proper motions (average probable error $\pm$ 0″002) and obtained, as the correction to the zero point of the period-luminosity relation, $\Delta M = -1.4 \pm 0.3$. This value can be further improved when the absorptions for the individual variables, derived from color excesses, become available.

It is obvious from the preceding discussion that the determination of accurate absolute magnitudes of both cluster-type variables and type I cepheids remains one of the most urgent problems. In one respect the situation has become simpler. Since we know the difference in zero points of the two groups from observations in the Andromeda nebula and the Magellanic Clouds, the absolute magnitude of one group also gives that of the other. For this reason G. van Herk's new determination of the absolute magnitude of the cluster-type variables, from proper motions obtained at the Cassegrain focus of the Mount Wilson 60-inch, is awaited with the greatest interest. Besides these classical methods of determining the zero points of cluster-type variables and cepheids, other methods undoubtedly will come into their own as time goes on. I will mention only the possibilities offered

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1956PASP...68....5B

by "pulsation" parallaxes; by the color-magnitude diagrams of globular clusters, once it has been settled whether the observed main branches represent the ordinary dwarf or some subdwarf sequence; and, last but not least, the possibility of connecting in the Magellanic Clouds cluster-type variables and cepheids with the A-stars of the main sequence.

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[11] Mineur gave the same figures in a later note in *C. R. Acad. d. Sc.,* **235,** 1607, 1952.
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[13] See J. Stebbins, *Pub. A.S.P.,* **65,** 118, 1953.

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