THE INTEGRATED SPECTRA OF STAR CLUSTERS AND THE HISTORY OF THE MAGELLANIC CLOUDS

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ABSTRACT

This paper reviews the attempts that have been made to derive the ages and compositions of star clusters from studies of their integrated light. It discusses what can be learned by such methods regarding the history of the Magellanic Clouds. Finally, it reviews what is known about the age-spread and abundance-range in the cluster-systems of other galaxies and considers the history of the Magellanic Clouds in this context.

1. THE INTERPRETATION OF INTEGRATED LIGHT

The simplest problem in the study of the integrated light of stellar systems is that of inferring the age and chemical composition of a star cluster from the character of its integrated spectrum. If we can't do that, how can we hope to understand the spectra of galaxies, or interpret their spectral evolution?

The Magellanic Clouds are the ideal laboratory for investigating such problems. They contain many populous clusters of different ages and compositions, and they are sufficiently close that inferences from integrated light can be checked by spectroscopy and photometry of individual stars. What is learned in this way about the interpretation of integrated spectra can be applied to more remote galaxies, making possible the intercomparison of the systematic properties of cluster systems.

It is reasonable to begin with the assumption that the main factors determining the integrated spectrum of a star cluster are its age and its chemical composition. It is not difficult to imagine other factors that may play a role but, with an important exception that I shall discuss in a moment, there is no direct evidence that any other factors actually do modify integrated spectra. If we are mistaken in this assumption we shall find out soon enough! The important exception that

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I referred to is the undoubted importance of stochastic fluctuations in the the populations of rare but luminous stars. Persson and his colleagues (1983) have shown that in a typical intermediate-age Cloud cluster about half the bolometric luminosity is radiated by two or three carbon stars. The infrared spectra of such clusters are inevitably dominated by stochastic effects. Similar effects are likely to be important in the far UV. Stochastic effects will be minimal in those spectral regions dominated by the light of numerous faint stars. For clusters with turnoff effective-temperatures between 5000 and 10000K, the spectral region around 4000Å appears to be optimum. At this wavelength light-profiles of populous clusters are quite smooth, showing that this light comes from large numbers of faint stars.

If two parameters, age and abundance, determine the blue spectra of star clusters, their spectral classification will evidently require a two-dimensional scheme. Older classifications of cluster spectra were one-dimensional, and are therefore quite incapable of describing the relations among clusters that formed in galaxies with essentially different chemical histories. I shall not review in any detail these one-dimensional classification schemes here. For globular clusters the best schemes have beem photometric. Particularly important are those of Zinn (1980) and of Aaronson and his colleagues (1978) for the clusters of the Galaxy, and that of Frogel, Persson, and Cohen (1980) for the clusters of M31; these schemes provide useful abundance rankings. No convincing two-dimensional classification of the spectra of Galactic globular clusters has yet been achieved, although it is clear from the existence of the "second parameter" phenomenon that such a classification is needed. The age classification of the spectra of open clusters is less well studied. Again, the best schemes are photometric and can provide useful age estimates for sufficiently populous clusters [see, for example, Sandage (1963), Searle, Sargent, and Bagnuolo (1973), and Larson and Tinsley 1978)]. Stochastic effects are important for most open clusters and have been explored by Barbaro and Bertelli (1977). No two-dimensional work has been attempted, so far as I know.

The realization that there is a need for a two-dimensional classification scheme for the integrated spectra of star clusters arose from intercomparison of the spectra of old clusters in the Clouds with those of Galactic globulars. Danziger (1973) obtained the first significant quantitative data on the spectra of old Cloud clusters and attempted a first classification. His ordering was essentially one by metal-line strength and it plainly failed to order all the line-indices that he had measured. While puzzling over this data, I luckily happened upon a reference to Gelfand's (1969) thesis: "Seriation of Multivariate Observations through Similarities." Application of Gelfand's algorithms quickly brought out the real order to be found in Danziger's data. This order is not one by metal-line strengths but rather by hydrogen-line strength. Along the sequence of clusters ordered in this way the metal-line strengths smoothly vary, but their behavior is not monotonic. This work was published, along with a supporting photometric classification, in a paper by Althea Wilkinson, Bill Bagnuolo, and myself (SWB 1980).

A brief word about this SWB classification. It is not wedded to the photometric system that I happened to use; it can be reproduced in your favorite system, so long as that generates two independent reddening-free blanketing measures. In the case of the Clouds, where reddening seems to be negligible, even the two-color plane of UBV photometry suffices, as was first realized by Frenk and Fall (1982). As I shall show, the SWB classification is also a spectral classification.

The natural classification plane for the integrated spectra of old star clusters has the strength of the Balmer lines on one axis and the strength of the metal-lines on the other. The globular clusters of the Galaxy and the old clusters of the Clouds lie on sequences in this plane, but the sequences are different. Rabin (1982) termed this classification diagram the Hydrogen-Metals diagnostic diagram, or HMD. In a careful study of the integrated spectra of 16 old star clusters in the Magellanic Clouds, he both confirmed its importance for the classification of integrated spectra, and made clear its physical interpretation. From models based on stellar evolutionary tracks, and on model-atmospheres of a cluster's component stars, Rabin was able to estimate quantitatively the behavior of hydrogen and metal line strengths in the integrated light of star clusters. He convincingly demonstrates that the hydrogen-line strengths in the integrated spectra of a star cluster are, and are expected to be, strongly dependent upon the cluster's age.

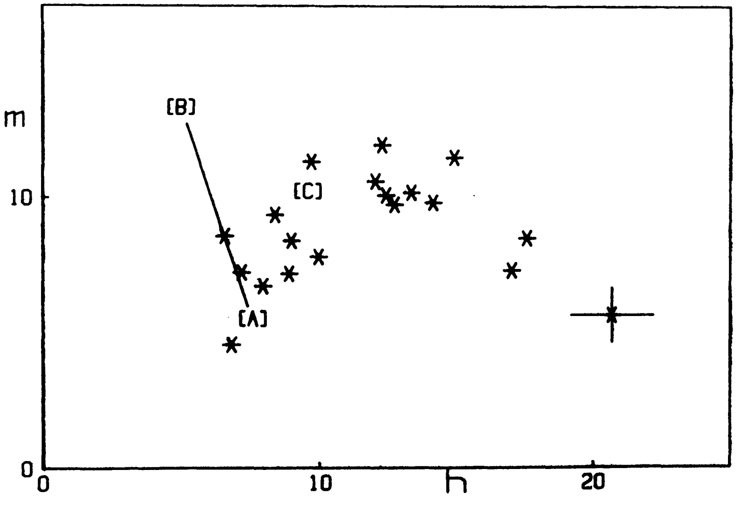

Figure 1. The HMD for integrated spectra of old clusters in the Large Cloud. The straight line is the locus of Galactic globular clusters. The points A, B, and C are for the clusters M15, 47 Tuc, and NGC 2158 respectively.

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In Figure 1, I have plotted the HMD for some star clusters in the Large Cloud, together with the locus of the Galaxy's globulars. The data are taken from observations of integrated spectra obtained with Shectman's (1981) photon-counting spectrograph on the du Pont telescope at Las Campanas. The data are from a study in progress by Horace Smith, Armando Manduca, and myself. The quantity h is proportional to the equivalent widths of the Balmer lines, while m is proportional to the equivalent width of strong metallic features in the spectra. The errors in the determination of these quantities arise not from photon statistics but from stochastic effects in the subtraction of the spectrum of the star field in which the cluster is embedded. It will be difficult to beat these errors down. These new results confirm Rabin's conclusion that, in the HMD, almost all the old cloud clusters lie apart from the sequence of Galactic globular clusters.

In Figure 1 the LMC clusters define a sequence; the scatter about it is no greater than that expected from the precision achieved. In Figure 2, I have drawn zones in the HMD that contain clusters of different SWB type. The point here is that the spectra insist on the same classification as that derived from the SWB photometry. The advantage of a classification in terms of the HMD, rather than in terms of photometric indices, is that the physical interpretation of the classification becomes clear.

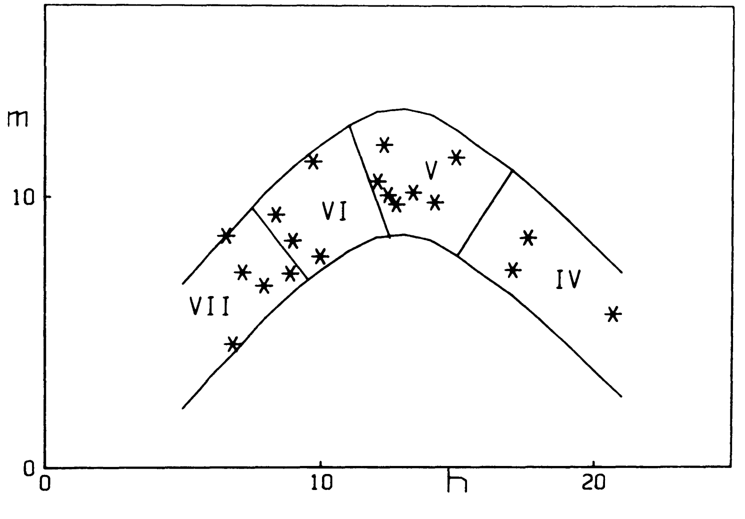

Figure 2. The SWB classification in the HMD.

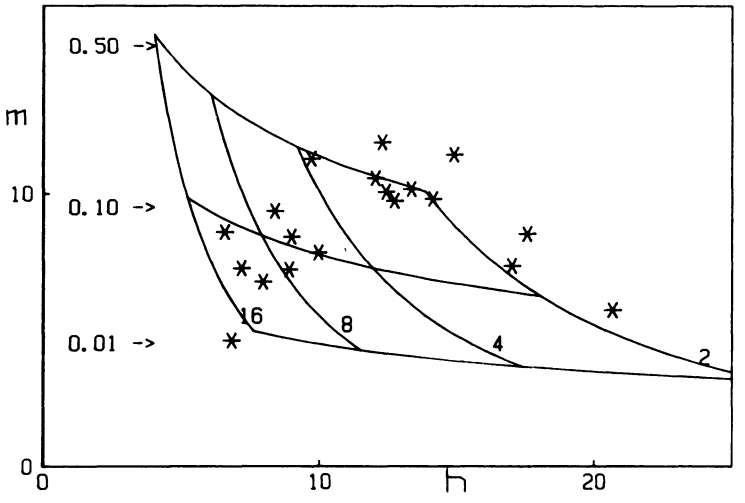

Figure 3. Preliminary classification of the HMD after Manduca. Vertical grid lines are labelled by age in gyr. Horizontal grid lines are labelled by metal-abundance in solar units.

Manduca has recently extended and improved on Rabin's model-making using the synthetic spectra of Bell and Gustafsson. In Figure 3, I show a preliminary version of Manduca's calibration of the HMD. The problem of calibration is difficult and fundamental, and I do not beleive that it can be solved by model-making alone. Clearly, a few reliable ages and abundances for calibrating clusters are necessary before one can have confidence. But, Manduca's work is a big step forward, and I think it is now possible to draw reliable inferences from integrated spectra concerning the relative ages and compositions of clusters.

How do the results compare with those of others? Forming the average of the values of h and m for the clusters of SWB types V, VI, and VII respectively, I obtain ages of 2, 5, and 10 gyr respectively for those types. The corresponding values of log z (in solar units) are -0.3, -0.7, and -1.3. These ages are somewhat lower than those suggested by Rabin for types V and VI and in fair agreement with the median age at a given type in the compilation of ages inferred from color-magnitude diagrams by Hodge (1983). The compositions for a given type are also in fair agreement with the results of Cohen (1982) who derived abundances from spectroscopy of individual cluster giants.

It is comforting to see convergence, but possibly we shall learn more by focussing on disagreements. Let us consider some of these. Some clusters were undoubtedly misclassified in SWB. A good example is NGC 1831. Frenk and Fall (1982) pointed out, and spectroscopy confirms, that this is a type IV, and not a type V as SWB photometry suggested.

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Another type of disagreement arises, I suspect, from misinterpretation of color-magnitude arrays; an example may be NGC 416. In Hodge's (1983) compilation NGC 416 and NGC 419 are assigned the same age of 0.6 gyr. Danziger's work shows that these two clusters have similar metal-line strengths but that their hydrogen-line strengths are very different. Rabin's spectra confirm this; the equivalent widths of the Balmer lines are 2 or 3 times greater in NGC 419 than in NGC 416. Neither cluster has a blue horizontal-branch. How can this difference in hydrogen line strengths arise if not from a big difference in age and in turnoff temperature? Rabin's Figure 5 shows that an age difference of something like 4 gyr is required. The ages assigned to these two clusters by Smith, Manduca, and myself from our new spectroscopy confirm Rabin's conclusions; we find ages of 2 and 6 gyr for NGC 419 and NGC 416 respectively. So here is a nice test case.

2. THE HISTORY OF THE CLOUDS.

When the calibration of the HMD is put on a sound empirical basis it will directly yield the age-abundance relations for both Clouds. Until then, no firm conclusions can be drawn. In the present circumstances, a consideration of what the HMD implies about the history of the Clouds is still useful, however, since it helps to define problems for future work.

Notice, in Figures 2 and 3, the small abundance range that is indicated for the type V clusters. Chemical homogeneity at the present epoch is a feature of Magellanic irregulars, in contrast to spirals (Pagel and Edmunds 1981, Webster and Smith 1983). In this respect, the Large Cloud, 2 gyr ago, appears to have been typical. It would be valuable to set good limits on the abundance range among type V clusters in the Large Cloud by differential study of the spectra of their red giants.

In Figure 4, I show two sequences in the HMD based on the predictions of the simple model of galactic evolution (i.e., homogeneous evolution with constant yield, see e.g., Searle and Sargent 1972). These represent hypothetical histories of the Large Cloud and are based on present-day abundance that is 0.75 solar, a present gas fraction of 12 percent, and an age of 16 gyr for the oldest stars. The upper sequence supposes a uniform rate of star formation. The lower one superposes a Gaussian burst of star formation on a uniform background rate. This burst is supposed to have peaked 3 gyr ago, and to have a dispersion of 2 gyr. In the model illustrated the number of stars formed in the burst is just twice the number formed by the uniform background rate of star formation. Comparing such tracks with the observed location of clusters in the HMD, I tentatively conclude, on the basis of the present calibration, that the rate of star formation in the Large Cloud in the recent past was greater than the past average rate but that the hypothetical recent burst formed fewer than 50 percent of its stars. More important than this shaky inference, Figure 4 emphasizes

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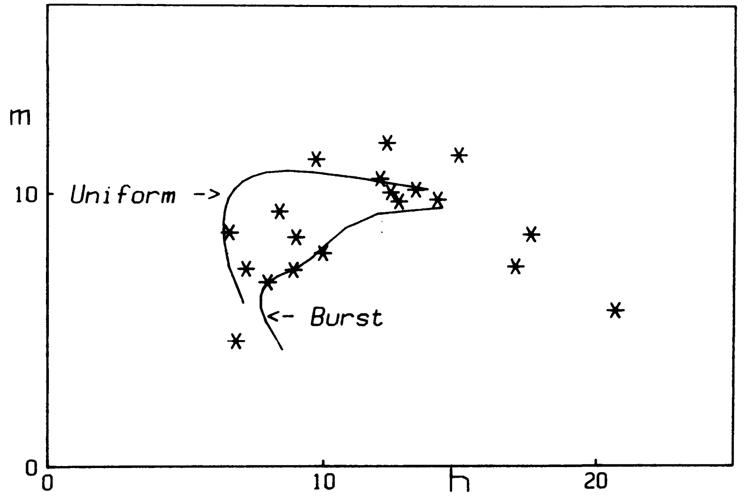

Figure 4. Hypothetical histories in the HMD. See text.

that the only clusters that contain significant information about the chemical history of the Clouds are those of SWB type VI. It would be really important to determine accurately the age and composition of some of these. NGC 1978 is probably the best candiate.

In the HMD the sequence of the Galaxy's globular clusters lies along a line of constant age. The sequence of old Cloud cluster appears to cut right across the age lines, even for cluster of SWB type VII; this is a point made by Rabin. The search for the "true globular clusters" in the Clouds is an old one, and the list of candidates shrinks as knowledge grows. Perhaps the search is futile. The clusters of the Clouds seem to be telling us that the age-abundance relation is different in different galaxies. Whether the age-abundance relations of different galaxies have points of intersection in the remote past seems to me to be a crucial question. We ought not to assume the answer.

Finally, in the HMD the clusters of the Small Cloud show a small displacement from those of the Large. On the basis of the calibration in Figure 3, Small Cloud clusters with ages between 5 and 10 gyr appear to be about twice as metal-rich as Large Cloud clusters of the same age. Since the interstellar medium of the Small Cloud today is metal-poor compared to that of the Large Cloud (Pagel and Edmunds 1981), this apparent reversal is surprising and interesting. It would be important to try to confirm or refute this inference; a differential spectroscopic comparison of red-giant spectra could provide a direct test.

3. CLOUD CLUSTERS IN CONTEXT

Many of the clusters in the Clouds have no obvious counterparts in the Galaxy. It may be that, located in the murk of the Galactic plane, we are poorly placed to make the comparison. The question I want to consider is: Do the types of Cloud clusters that have been recognized, have counterparts in other nearby galaxies?

Certainly populous blue clusters do. These are the Cloud clusters of SWB type II and III. The brightest of these have absolute visual magnitudes between -8 and -9. Christian and Schommer (1982) have discussed their occurrence in M33. Recently, Judy Cohen, Eric Persson, and I have found that in all spectroscopic and photometric characteristics Hiltner's (1960) clusters a and c in M33 closely resemble the type II and III clusters in the Clouds. The absolute magnitudes are also similar using the new distance to M33 derived by Sandage and Carlson (1983). Similar clusters also exist in M31. In his classic study, van den Bergh (1969) recognized a number of Hubble's "globular clusters" as being blue and young. Hubble 5 is one of the brightest; it lies near the boundary of the type II and type III clusters in the Q-Q plane according to my spectrophotometry, just like the clusters a and c of M33. It has an absolute visual magnitude of -8, but is probably somewhat reddened.

Nor are intermediate-age clusters unique to the Clouds. Christian and Schommer (1982) have an interesting discussion of this point. NGC 1783 is one of the more remarkable intermediate-age clusters in the Large Cloud. It is a type V, with an age near 2 gyr according to the HMD, and has an absolute visual magnitude of -7.8. This is less than 2 magnitudes fainter than the brightest younger clusters. If a cluster has a Salpeter mass function it fades about 5 magnitudes as it ages from .01 gyr to 1 gyr. The existence of such a cluster as NGC 1783 might, therefore, be taken to support the notion of a special epoch of star formation in the Large Cloud a few billion years ago. Do clusters like NGC 1783 exist in other nearby galaxies?

I think that they do. In absolute magnitude and location in the Q-Q plane (i.e., in SWB type), Hiltner's cluster f of M33 is a close match to NGC 1783. The same problem exists for it too, it cannot have evolved from clusters like the younger clusters now seen, if the mass-functions are of Salpeter type. Similar clusters, with similar problems appear among the "globular clusters" of M31; numbers 68 and 137 from Vetesnik's list (1960) are the brightest found in my unpublished survey. Whether type VI clusters, like NGC 1978, exist in M31 or M33 is an important unanswered question. Such clusters exist in the peripheral regions of the Galaxy's disk. NGC 2158, whose location in the HMD is illustrated in Figure 1, is a well known example (Arp and Cuffey 1962, Hardy 1981). In any case, the existence of blue and intermediate-age globular clusters in not a privilege unique to the Clouds.

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A real and important difference between the Clouds and the Galaxy is that the latter contains old metal-rich clusters. All systems contain old metal-poor clusters; they differ in the abundance range of old clusters, and in the fraction of old clusters that are metal-rich. As a readily visible signature of such differences among galaxies, we might take the presence or absence of clusters at least as old as 47 Tucanae and at least as metal-rich. Such clusters can easily be recognized photometrically and spectroscopically. The existence of such old, metal-rich clusters is, of course, evidence for rapid enrichment. No such clusters are known in the Clouds. None are known in M33 either, although the study of the clusters in this galaxy is very incomplete. In the Galaxy some 10 percent of the globular clusters are of this type, while in M31 about 30 percent of its clusters meet the requirements. There appears to be a significant trend here, perhaps related to the prominence of the spheroidal population.

The facts that I have reviewed suggest some caution in accepting catastrophist accounts of the evolution of the Clouds. The cluster contents of the Clouds are not so unusual as once was thought, and the undoubted differences between the chemical history of the Large Cloud and that of the Galaxy may find their explanation within the regular systematics of galactic chemical evolution.

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DISCUSSION

McCarthy: Could you illustrate the hydrogen line fluctuations in the ranking of metal-line strengths? What is the magnitude of such fluctuations?

Searle: The answer to your question is contained in Figure 1. Very roughly you may take the quantity to be the equivalent width of Hγ. It ranges from 5 to 20Å with a measurement uncertainty of about 1Å. In the ordering by hydrogen-line strength the metal-line strength behaves regularly but not monotonically.

Graham: How closely do the integrated spectra of the oldest, metal-poor clusters in the Galaxy and the Magellanic Clouds compare?

Searle: I think you can see the answer from Figure 1. I have the impression that most type VII clusters have significantly stronger hydrogen lines than the galactic globulars. Rabin already made this point. It seems likely that the age-metallicity relations of the Clouds and the Galaxy began to disagree very early.

Frogel: Would you comment on D. Burstein's claim that M31 globulars have systematically stronger H-line strengths than Galactic globulars? Do the M31 clusters differ from Milky Way clusters in the same way as LMC clusters do?

Searle: I believe that Rabin (in his thesis) concluded that the phenomenon you refer to existed for Hβ but not for Hγ and Hδ. He attributed it to blending, I believe. In any case, I doubt that it is in any way very connected with the hydrogen line strength-age relation found in the Clouds.

Mould: Your (m,h) diagram suggested a lower dispersion about their mean line for the galactic globular clusters than those of the Clouds. Is that real? Is there a reason for it?

Searle: I think it results from observational techniques. The background subtraction problem is more difficult for the clusters in the Clouds.

Peimbert: Do you think that the positions of the two youngest clusters of the LMC plotted in the (m,h) diagram are significant?

Searle: Menduca's grid (from the work we do as mentioned in the text) refers to clusters older than 2 Gyr - it would be unsafe to extrapolate it to young clusters. In particular, I do not think it would be safe to infer from Figure 3 that the clusters you refer to are metal deficient compared to the type V's. I doubt that very much. More work is needed on the integrated spectra of young clusters.

Flower: Let me point out a potentially serious problem with Rabin's (1982 Ap.J. 261, p 85) cluster age estimate based on Balmer-line strengths from integrated spectra of Magellanic Cloud star clusters. He used integrated light models for star clusters which were constructed from a grid of evolutionary tracks that did not include core-helium-burning giants (no published grid includes these stars). However, color-magnitude diagrams of populous (red or blue) Magellanic Cloud star clusters are dominated by red giant (core-helium-burning) stars. Color-magnitude diagrams of NGC2121 and NGC1978 (both c-m diagrams suggest ages of less than 10 Gyr) show red clump giants ($B-V \approx 1.0$) that are a magnitude or more brighter than the brightest main-sequence stars. These red giants are as bright in the blue as are the brightest main-sequence stars. Thus, the Balmer line strengths from integrated cluster spectra are clearly contaminated by these bright red giants. The brightness of core-helium-burning red giants relative to the brightest main-sequence stars depends on both the chemical composition and the number of giants. Thus chemical composition variations and stochastic effects in the population of red giants from cluster to cluster will tend to invalidate current integrated light ages of Magellanic Cloud star clusters.

Searle: The answer is, of course, that red giants are relatively rare. The smoothness of scans over these clusters shows that their blue light is dominated by contributions of intrinsically faint stars. Stochastic effects are not important here. Danziger's, Rabin's, and our new spectra confirm that the integrated light of NGC1978, for example, closely resembles that from Kron 3, which has an age of 7 Gyr. If NGC1978 has an age an order of magnitude smaller, as you suggest, the value of intergrated spectra as an age indicator would, indeed, be brought into question. But it would take better color-magnitude diagrams than those currently available to cause me to have serious doubts. I suggest the situation may be similar to Hodge 11, for which c-m diagrams gave erroneous conclusions. The great age of Hodge 11, insisted upon from its integrated light, has been confirmed by the better color-magnitude diagrams now available.