OPEN CLUSTERS AND STELLAR EVOLUTION

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Several topics relevant to the study of stellar evolution through open clusters are discussed. These include composite color-magnitude diagrams, the need for thorough studies of populous clusters, parameters affecting the core helium burning stage, and the potential importance of initial conditions and dynamical evolution on the cluster color-magnitude diagram.

Clearly the title by itself suggests a topic impossible to cover thoroughly within the space of this paper. Therefore, instead of attempting any comprehensive discussion, I plan to highlight a few problems which have particular interest to me. A main thread running through my discourse will be the need for thorough, careful and many-faceted studies of open clusters at all ages - observations such as UBV, uvby, and DDO photometry, spectral types, radial velocities and proper motions. It is particularly important to complete such work for populous clusters, since it is becoming increasingly clear that the picture of stellar evolution we currently have from open clusters is severely limited and at times confusing or misleading - often because of the sheer small size of the typical open cluster. Such difficulties increase when we attempt to study post-main-sequence evolutionary stages, where the time scales are shorter and the number of stars observed at these stages correspondingly smaller.

1. POPULOUS CLUSTERS AND COMPOSITE COLOR-MAGNITUDE DIAGRAMS

In the oldest open clusters where the evolving stars are $\sim 1 \mathfrak{M}_{\odot}$, the time scales in the core helium burning and other later stages are 10-20% of the core hydrogen burning stage. Thus we can expect to, and do, see color-magnitude diagrams (CMD's) with moderately well populated giant regions. However, in the younger clusters with more massive evolving stars, we see typically only a handful of stars providing the barest outline of the evolutionary pattern. In addition, they just don't make clusters like they used to - at least in this Galaxy! The

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moderately populous older clusters which are the only ones to have survived to the present time are simply not duplicated to any great extent, if at all, in the youngest Galactic clusters.

Attempts to offset the problems of small cluster population by producing composite CMD's of clusters of similar age have been made and do provide useful information. But they also cause confusion due to imprecision in reddening, distance and age determinations of the individual clusters that are used to produce the composite "cluster". Differences in chemical composition, number of binaries, stellar rotation, etc. influence many details of the HR or CM diagram and the simple combination of clusters into one CMD will obscure the characteristics of an individual cluster and in turn conceal the effects of any physical parameter which may make it unusual.

The first few figures illustrate the variations in quality of composite CMD's using composite clusters (Harris 1976) and CMD's for individual clusters in those groups taken from the Catalogue of Open Cluster Colour-Magnitude Diagrams (Hagen 1970). Fig. 1 shows composite Group II with a median age of $\sim 10^7$ yr. Here we see the characteristic clump of M supergiants 1-2 magnitudes fainter than the peak of the B-F supergiant distribution. This is probably the best of the groups, simply because spectral types, proper motion and radial velocity data are available for most of the individual clusters. Fig. 2 is the CMD of NGC 457, one of the clusters included in Group II. The general pattern is very much the same but the definition of the post-main-sequence pattern is much poorer - there are obviously fewer evolved stars in NGC 457 than in Group II. This kind of difference illustrates the primary advantage of composite CMD's - the larger number of evolved stars provides information about later evolutionary stages that is simply not available in the typical sparse open cluster.

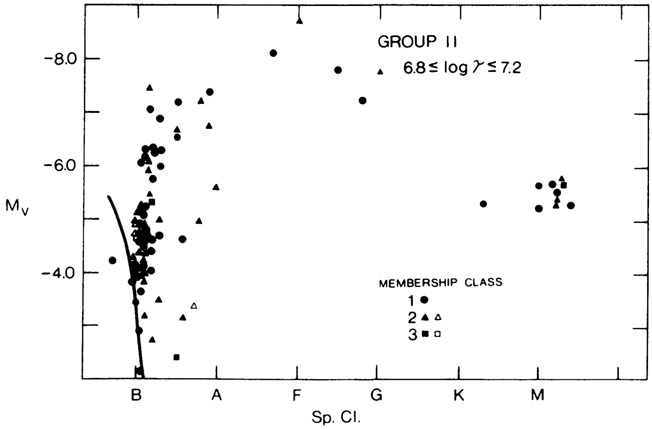

Figure 1. Composite CMD for Harris Group II; age $\sim 10^7$ yr.

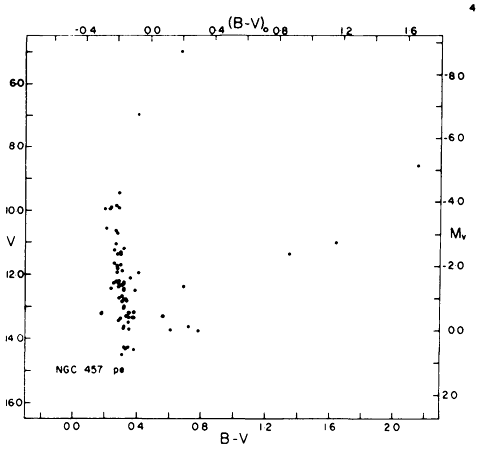

Figure 2. CMD for NGC 457, one of the clusters that makes up Group II.

Conversely, to demonstrate the confusion that can be produced by composite CMD's I now show Group IV (Fig. 3) which has a median age of $\sim$6 x 10^7 yr. In contrast with Group II, this group is based on much sparser, poorer data on spectral types etc. for cluster stars. Here the early stars appear to form a fairly consistent, well-defined pattern while the F-M stars do not. This is likely to be primarily the result of a wide range of cluster ages within the group which substantially weakens the value of the composite CMD. A typical member of Group IV is NGC 2168 (Fig. 4) containing only one giant and showing an extended turnup region. Clearly such a composite, without thorough high quality observations for the individual clusters and hampered by minute giant populations in those clusters, can at best only suggest tantalizing possibilities.

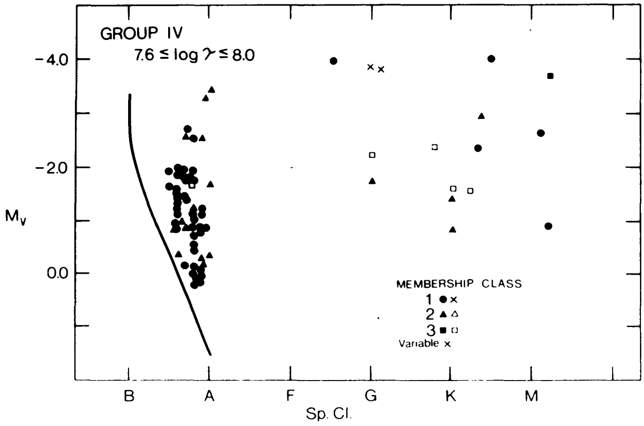

Figure 3. Composite CMD for Harris Group IV; age$\sim$6 x 10^7 yr.

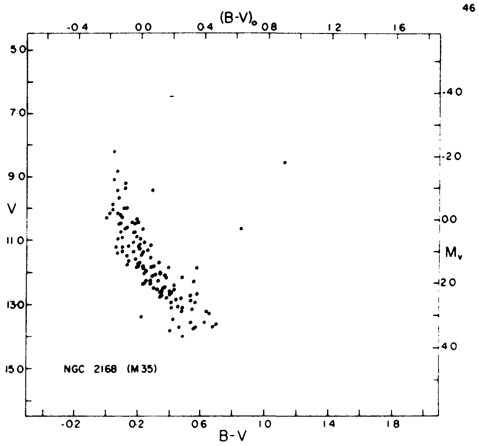

Figure 4. CMD for NGC 2168, one of the clusters that makes up Group IV.

Ultimately, of course, the aim of studying open clusters is not the production of beautiful CMD's, but an understanding of the physical characteristics of stars in our Galaxy and their evolution. It's worth repeating that such information, if firmly based, can be used to probe the structure and evolution of the Galaxy as a whole as well as external systems. The Magellanic Clouds are the most important example of such application, with their many populous globular-like clusters, both young and old.

We will be hearing more about the Magellanic clusters later in this meeting but it is important to remember that we know of no comparable systems in our Galaxy. The most populous open clusters known are of the order of a few x $10^3 \mathfrak{M}_\odot$ (cf. table below) whereas the "blue globulars" in the Magellanic Clouds appear to be an order of magnitude more massive (Freeman 1974, Freeman and Gascoigne 1971). An understanding of these objects will rely heavily on knowledge gained from clusters of similar age in the Galaxy, making it even more important to have high quality observations of the few populous open clusters we can observe. Additional related comments will be made below.

Cluster	log Age	Mass ($\mathfrak{M}/\mathfrak{M}_\odot$)	Source
M 11	7.8	~5600	McNamara and Sanders 1977
M 67	9.6	~1600	McNamara and Sanders 1978
NGC 6067	7.2	~1500	Lohmann 1976
Pleiades	7.8	~700	Jones 1970
Praesepe	8.8	~550	Jones 1971
Hyades	8.8	~300	Pels et al. 1975

2. COMPARISONS OF MODELS AND OBSERVATIONS - CORE HELIUM BURNING GIANTS

The most effective means of comparing stellar model calculations with the real universe is still the use of model isochrones superimposed on cluster CMD's. Ciardullo and Demarque (1977) have produced the most notable recent tabulation of such data, but their models and those of many other authors are for stars of a few solar masses or less and thus have application only to the oldest open clusters. For the younger clusters ($\lesssim 5 \times 10^8$ yr; $\mathcal{M}_T \gtrsim 2\mathcal{M}_\odot$) we do not have such an all encompassing set of models from a single code. This is simply because the internal stellar structure undergoes many significant changes in the 2-20$\mathcal{M}_\odot$ range both on the main sequence and from the ZAMS to more evolved stages.

The general characteristics of evolutionary tracks in the range 0.25-15$\mathcal{M}_\odot$ can be seen in Fig. 5 (Iben 1967). In this mass range major recent concerns in model calculation and comparison with observations have been the effects of rotation, composition and convection on the core hydrogen exhaustion phase and the effects of a variety of factors, such as convective overshooting and composition, on the core helium burning loop. We will concentrate here on the latter problem.

Numerical stellar model calculations in the 2-20$\mathcal{M}_\odot$ range have shown that the position and extent of the blue helium burning loops are

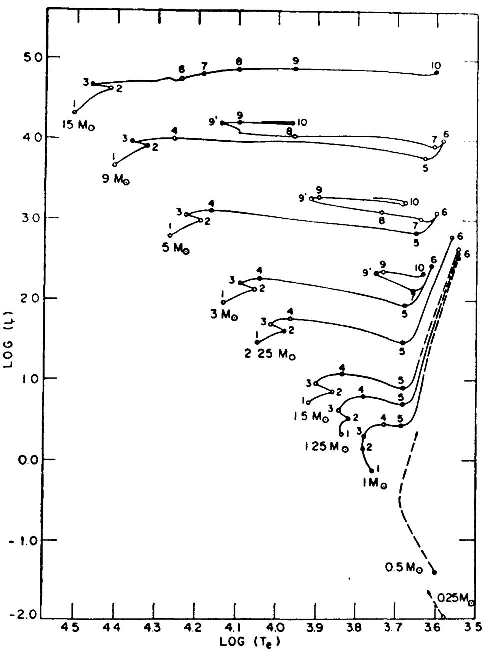

Figure 5. Paths in the theoretical HR diagram for metal rich stars of mass 0.25-15$\mathcal{M}_\odot$ from Iben (1967).

affected by composition (Alcock and Paczynski 1978; Harris and Deupree 1976), rotation (Endal and Sofia 1976; Kippenhahn et al. 1970), convective overshooting and methods of treatment of convection (Schlesinger 1977; Stothers and Chin 1976) and opacity (Stothers and Chin 1977). Although the situation is extraordinarily complex a few general conclusions seem possible:

a) The very complexity of the problem may mean that minor differences in computational technique will produce entirely different results regarding the effects of a given parameter change.

b) For lower values of Z, the core helium burning loops are bluer and brighter and the evolution from blue to red, (or red to blue) is less concentrated at the ends of the loops.

c) Semiconvection and convection tend to produce blue loops and speed the the transition between the ends of the loops.

This means that the position in M_V, B-V as well as the distribution (amount of clumping etc.) depend on the star's internal structure and composition and can provide direct tests of stellar model calculations.

Fig. 6 illustrates the kind of effect these differences might produce. The diagram shows CMD's for synthetic clusters produced by Harris and Deupree (1976) from their model calculations in the range of 3.5-9 $\mathcal{M}_\odot$ with Z=0.01, 0.04. Note that the clumping in the red supergiant region and the emptiness of the Hertzsprung gap are both more pronounced for the higher Z "clusters" as predicted above. However, I

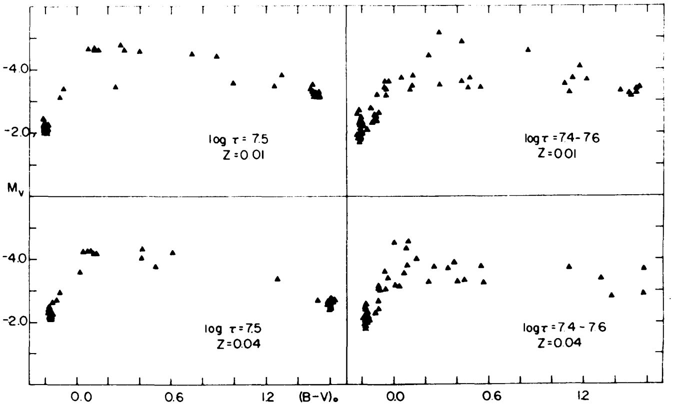

Figure 6. Synthetic clusters for both Z=0.01 and 0.04 at a fixed age of 3.2 x 10^7 yr and an age spread of 2.5-4 x 10^7 yr.

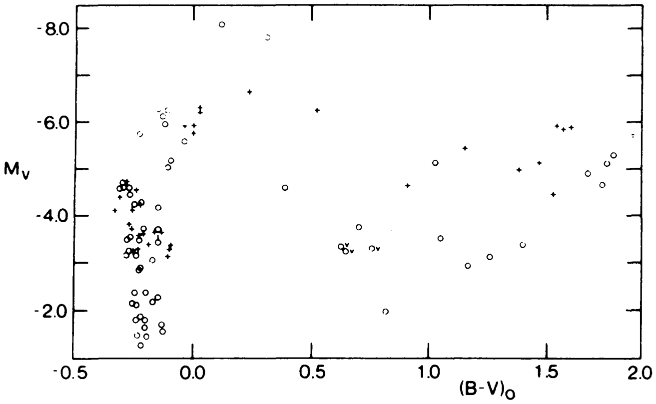

Figure 7. Comparison between the SMC cluster NGC 330 and a composite cluster with median age 1.5 x 10^7 yr. ○; Galaxy; +, NGC 330.

should stress here that a variety of other effects can produce similar changes. For example, as can also be seen in Fig. 6, the differences caused by altering Z are suppressed when a non-zero period of star formation (i.e. an age spread within the cluster) is introduced.

Similar variations in the distributions of evolved stars can be seen when comparing young Galactic open clusters and young clusters in the Magellanic Clouds. Fig. 7 shows the CMD of the Small Cloud cluster NGC 330 superimposed on a composite cluster with an age of ~1.5 x 10^7 yr.

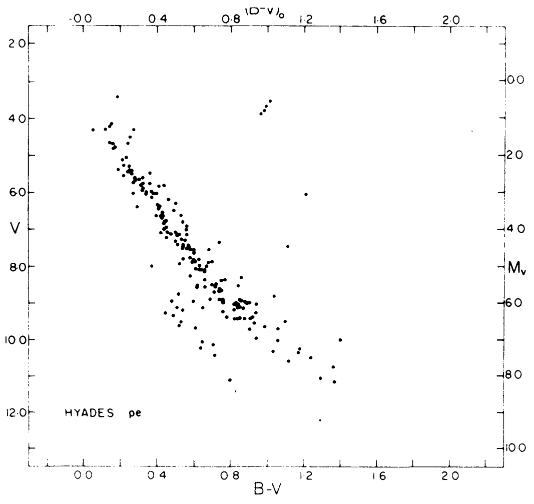

Figure 8. CMD for the Hyades cluster.

The position and distribution of both the blue and red supergiants is significantly different for the two clusters and may well be due to differences in heavy-element abundances (Hagen and van den Bergh 1974, Harris and Deupree 1976).

Older Galactic clusters also display significant differences in the location and distribution of giant (core helium burning) stars. Fig. 8 is the CMD for the Hyades (Hagen 1971). Its features are well known but I draw your attention to the position and distinct clumping of the giants.

In Fig. 9 we see the CMD for NGC 1817 (Harris and Harris 1977), a cluster of similar age to the Hyades but clearly more populous. The NGC 1817 giants show a pronounced clumping as well, but the position of the clump is significantly bluer and brighter than that of the Hyades. The next diagram (Fig. 10) is a superimposition of mean CMD lines for the Hyades, Praesepe and NGC 1817. Even when the NGC 1817 giants are dereddened to correct for the difference between $E_{B-V}(B0)$ and $E_{B-V}(K0)$, the giant distribution in NGC 1817 is still displaced relative to the Hyades and Praesepe giants. It seems probable that the cause is a lower heavy-element abundance in NGC 1817. Its giants also seem slightly less clumped (another possible indication of lower Z) but dynamical membership data (i.e. proper motions and radial velocities) are necessary before this can be confirmed.

Another cluster important for its large population and relative youth ($\lesssim 10^8$ yr) is NGC 6705 (M11). W.E. Harris and I have completed the first phase of a study including UBV photoelectric photometry, DDO photometry and MK classification. Combined with the proper motion data of McNamara et al. (1977) we have been able to eliminate non-members and to produce the "laundered" CMD seen in Fig. 11. Distinctive features

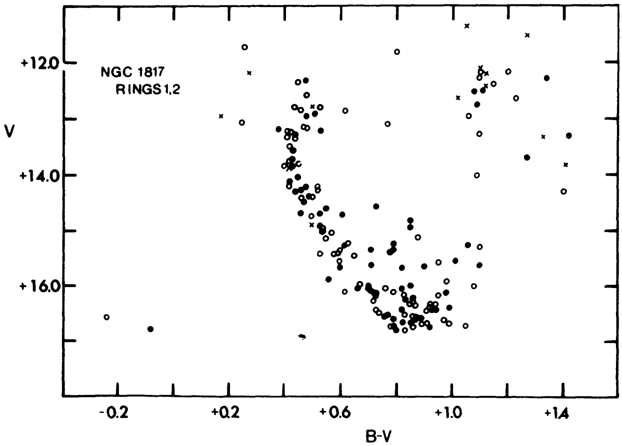

Figure 9. CMD for the open cluster NGC 1817. ●, ring 1; O, ring 2.

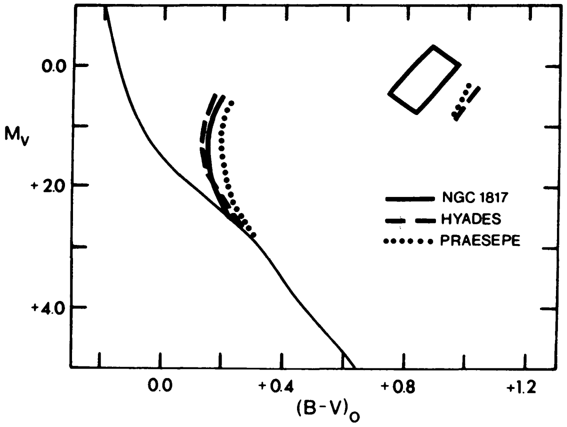

Figure 10. A schematic CMD for NGC 1817 compared with the Hyades and Praesepe. The red giants in NGC 1817 fall within the boxed region at the upper right.

of the M11 diagram are the wide range in B-V occupied by the giants and their somewhat red color. This redness of the giants was noted previously by Burbidge and Burbidge (1959) and more recently by Eggen (1974) who

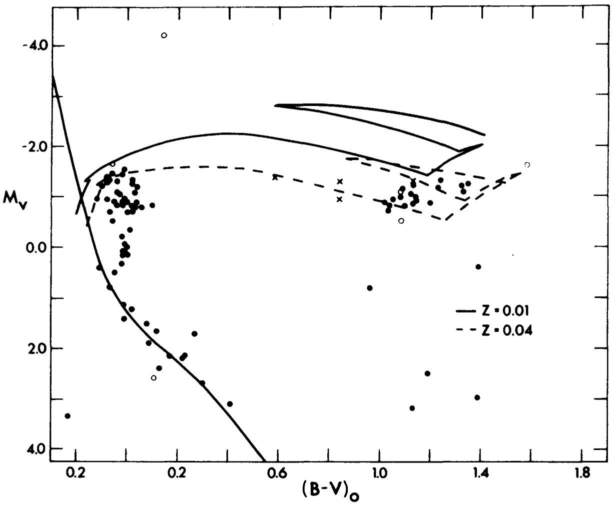

Figure 11. The CMD for the populous open cluster NGC 6705 (M11). Open circles are stars for which the membership determinations based on photometry and spectral types were in conflict with the proper motion results. Crosses are stars which have composite spectra. Superimposed are evolutionary tracks by Harris and Deupree (1976) for stars of 4.5 $\mathcal{M}_\odot$; Z=0,01, 0.04.

suggested a possible similarity to weak Ba II stars and thus slightly enhanced CN absorption as the cause. Our DDO photometry of the giants does indicate a stronger than solar CN, corresponding to $Z = 1.5\ Z_{\odot}$ and a modest Ba II enhancement may be present in their spectra.

Fig. 11 also shows the models of Harris and Deupree (1976) superimposed on the CMD for M11. We can see that the giants, red as they are, do populate the core helium burning region in a location consistent with high metal abundance. Also, their color spread is in moderate agreement with the predicted time scales along the helium burning loop. From our color-color diagram, differential reddening of $\gtrsim 0.04$ can be ruled out, supporting the conclusion that the color spread is intrinsic. Other possible causes of the color spread among the giants are a range of star formation times of the order of a few x 10^7 yr and substantial rotation in some cluster stars - delaying their evolution and producing effects detectable even in the giant region. The rather wide turnup region seen in Fig. 11 may be a hint of rotation effects (cf. Maeder 1971, Hazlehurst and Thomas 1970, Strittmatter and Sargent 1966).

A less populous cluster of age similar to M11 is NGC 2287 (Feinstein et al. 1978) and Fig. 12 shows a schematic comparison of their CMD's. Unlike M11, NGC 2287 is virtually unreddened (0.01-0.05) but its giants nonetheless occupy a similar spread in M_V and B-V - confirming the reality of a wide and rather red giant region for clusters in this age group.

In summary, the few clusters just discussed illustrate several ways in which real objects can put constraints on (or confirm predictions from) evolutionary tracks. From NGC 1817 and the Hyades we see that, for clusters of virtually the same age, the position of the core helium

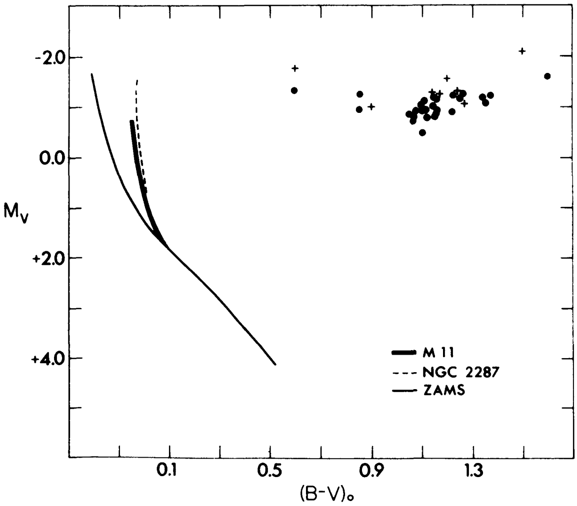

Figure 12. Schematic CMD's for the open clusters M11 and NGC 2287. The giants in both clusters are plotted individually. O, M11; +, NGC 2287.

burning giants can be quite different, possibly a function of such parameters as composition and rotation. M11 and NGC 2287 demonstrate that in some clusters with evolving stars in the intermediate mass range ($\sim 5\mathfrak{M}_\odot$), the clumping at the core helium burning phase is not nearly as pronounced as at both lower and higher masses. It appears that the complexities introduced by large or differential reddening cannot always be invoked to explain broader than expected color distributions.

In addition, our calibration of the intrinsic colors of such luminous giants ($M_V \sim -1$) may well be in error, due to the limited sample available and to too strong a reliance on extrapolation from the data for Hyades-like giants ($M_V \sim +1$). Both examples also underline the dubious merit of relying strongly on the giants themselves when determining cluster reddenings or distances. Finally, it is important that comparisons between young clusters in the Galaxy and the Magellanic Clouds should be made with the awareness that even Galactic open clusters are not similar to each other at any age.

3. POPULATION SEGREGATION WITHIN CLUSTERS

Yet another factor that complicates our understanding of open clusters and stellar evolution is the apparent difference in stellar population (and thus the CMD) for different spatial regions within a cluster. Observations restricted to the central region are common, merely as a means of eliminating the field star contamination that is often a serious problem. This device clearly produces a "cleaner" CMD, but by the elimination of cluster members in the outer regions may also bias the nature of the diagram and produce a mildly (or sometimes significantly) altered picture of the relative proportions of stars of different types.

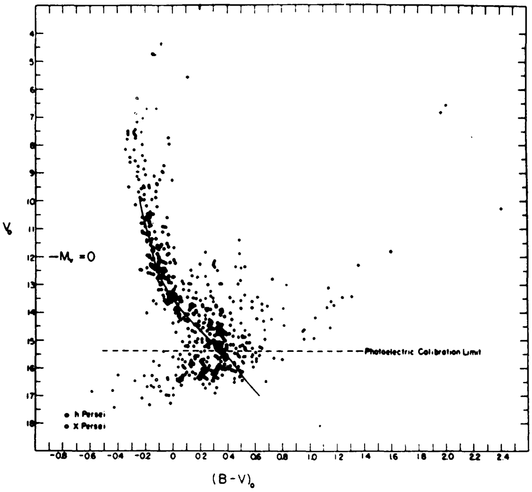

Figure 13. CMD for the young open clusters h and χ Per showing the central core regions only.

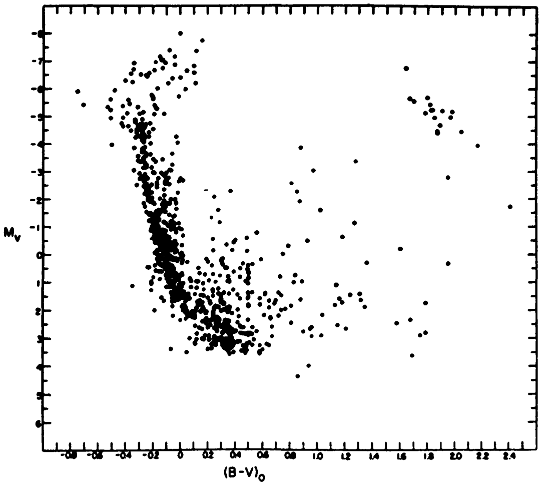

Figure 14. CMD for h and χ Per as above, but including the outer cluster region.

An example of this phenomenon in a very young cluster is h and χ Per, located at the core of a larger association. Fig. 13 shows the CMD for the inner region (Wildey 1964), which contains only two supergiants and a few luminous early-type stars. When the entire region is plotted (Fig. 14) the number of bright stars, both blue and red, increases dramatically. In addition, the regions occupied by the red and blue supergiants are broader in B-V, suggesting a larger age range in the whole region than the core.

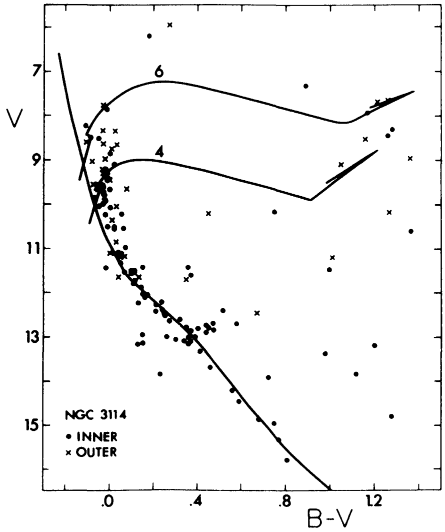

Figure 15. V, B-V diagram for the open cluster NGC 3114. The superimposed evolutionary tracks are for masses of 4 and 6$\mathcal{M}_\odot$ (Flower 1977).

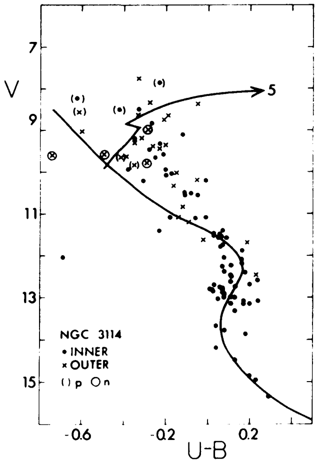

Figure 16. V, U-B diagram for the open cluster NGC 3114. Superimposed is an evolutionary track for $5\mathcal{M}_\odot$ (Flower 1977).

A recent UBV photometric result by W.E. Harris (1979) for the moderately young cluster NGC 3114 ($\sim 8 \times 10^7$ yr) may present a similar picture. Figs. 15 and 16 show the photoelectric (V, B-V); (V, U-B) diagrams he has obtained. For both diagrams it is clear that large numbers of bright (massive) stars are found in the outer regions. As with h and χ Per, the areas occupied by evolved stars in the turnup and giant regions are broader for the whole cluster than for just the core. This phenomenon seen in Figs. 15 and 16 must be intrinsic since the foreground reddening of NGC 3114 is negligible (E_{B-V}=0.08) and the brighter stars have all been measured photoelectrically an average of 6 times each. Also the surrounding field population is such that $\sim$90% of the blue stars should be cluster members. The color spread could again be due to a large range of ages among cluster members ($\gtrsim 10^7$ yr), or possibly a substantial spread in rotation velocities or a high fraction of binaries. Several Bp stars and a few rapid rotators are known to exist in the turnup region (cf. Fig. 16).

Burki (1978, 1977) and Burki and Maeder (1976) studied the distribution of the brightest stars in open clusters younger than $\sim 2 \times 10^7$ yr and concluded that:

a) Massive stars ($\mathcal{M} \gtrsim 20\mathcal{M}_\odot$) are formed with a lesser degree of central concentration than are smaller stars, i.e. the proportion of bright stars increases strongly with increasing cluster diameter.

b) The youngest stars are closest to the original stellar space distribution within the cluster.

c) The stellar mass spectrum may be different for clusters of different size.

Burki also suggests investigations of these effects be extended to $M_V > 0$ (older clusters). One may then postulate that, at least for moderately young clusters, the pattern of stellar evolution deduced from the CMD may be different for inner and outer cluster regions. If the picture of massive stars being initially more dominant in the outer cluster regions has any relevance for clusters 10^8 - 10^{10} yr old, then the distribution of giants in the CMD may not fit the stellar model calculations as well as we might otherwise expect. If the stellar mass spectrum is a function of initial cluster formation conditions, then clusters similar in age and metallicity may exhibit significant differences in their CMD's.

There are indications of similar situations in older clusters ($\sim 10^9$ yr) as well. McClure and Twarog (1977) noted that the giants in NGC 188 form a more dispersed distribution in the sky than main sequence stars while Tinsley and King (1976) discussed the same situation in the case of M67. Most puzzling of all is the cluster Mel 66 which may be the oldest open cluster known at $\sim 5 \times 10^9$ yr (Anthony-Twarog et al. 1979 Hawarden 1976). These authors discuss the preferential population of the blue edge of the giant branch by stars from the outer cluster regions. Recent results by Hawarden (1978) seem to rule out the possibility of differential reddening in the cluster, and the effect remains. In general these distributions in older clusters have been explained as due to either a) mass loss in the later evolutionary stages and a dynamical evolution of the cluster in which these stars tend to move to the outer cluster regions, or b) selective loss of faint, low mass stars from the outer regions resulting in an overpopulation of bright stars. These older clusters are generally assumed to be relaxed and initial conditions are thus not considered.

Thus we see evidence for differences between inner and outer cluster regions at all ages. It is possible, even probable, that such effects are real in some cases, but a word of caution must be added. Van Altena (1966) found that the radial distribution for bright members of the Hyades was much larger than that for faint members, much as has been noted above. However, new proper motion data by Pels et al. (1975) revealed additional faint members, many in the outer parts of the cluster. They concluded that the central concentration of the bright stars is actually much higher than that for the faint stars in the core, and in the outer cluster region the distributions for the two groups are approximately the same. This example underlines the fact that selection effects operate in favor of identifying bright stars and against faint stars as cluster members outside the central cores.

The physical effects of mass loss, rotation, composition, etc. all contribute to the variety of CMD's we now see; but our estimates of their importance may be in error if we do not know about the total membership of a cluster. Proper motion data are important for stars of all masses within a cluster, not just the brightest stars.

4. FINAL REMARKS - GOOD AND POOR COLOR-MAGNITUDE DIAGRAMS

As a final point I would like to remind you of the effects of good

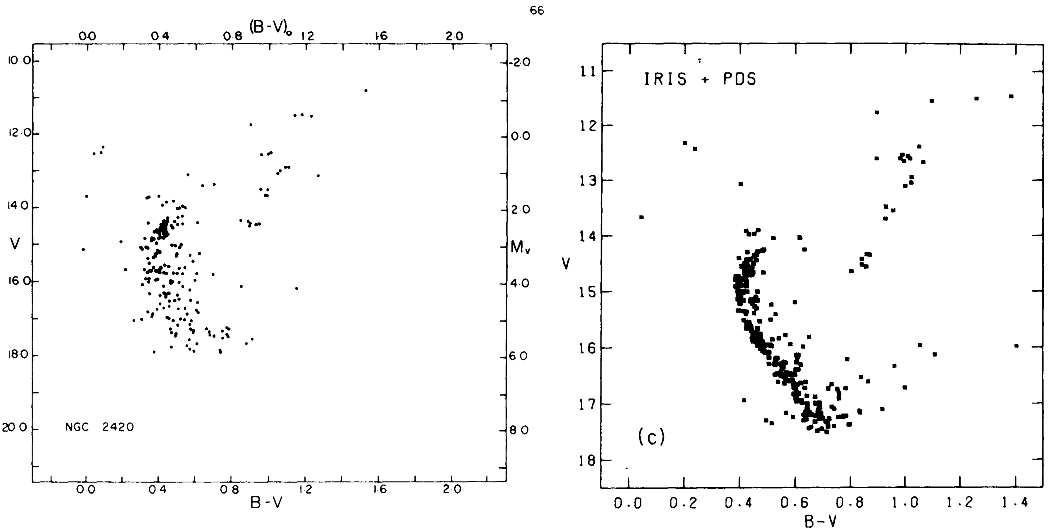

Figure 17. Color-magnitude diagrams for the cluster NGC 2420, from Hagen(1970) on the left and McClure et al.(1978) on the right.

photometric, spectroscopic and astrometric data on the CMD whose nature we are trying so hard to understand. The best example I know of radical improvement in a cluster CMD, simply by careful photometric work, is that of NGC 2420. Fig. 17 shows CMD's for this cluster from the compilation of Hagen (1970) on the left and the recent investigation

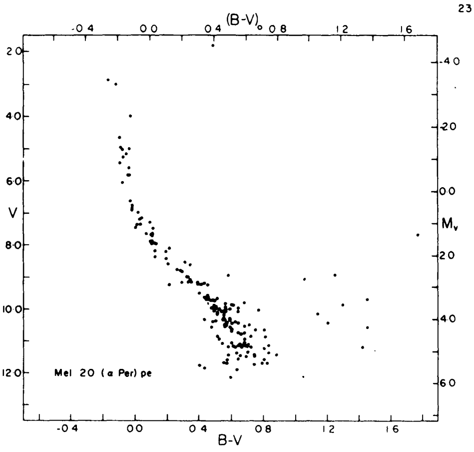

Figure 18. The CMD of α Per (Hagen 1970).

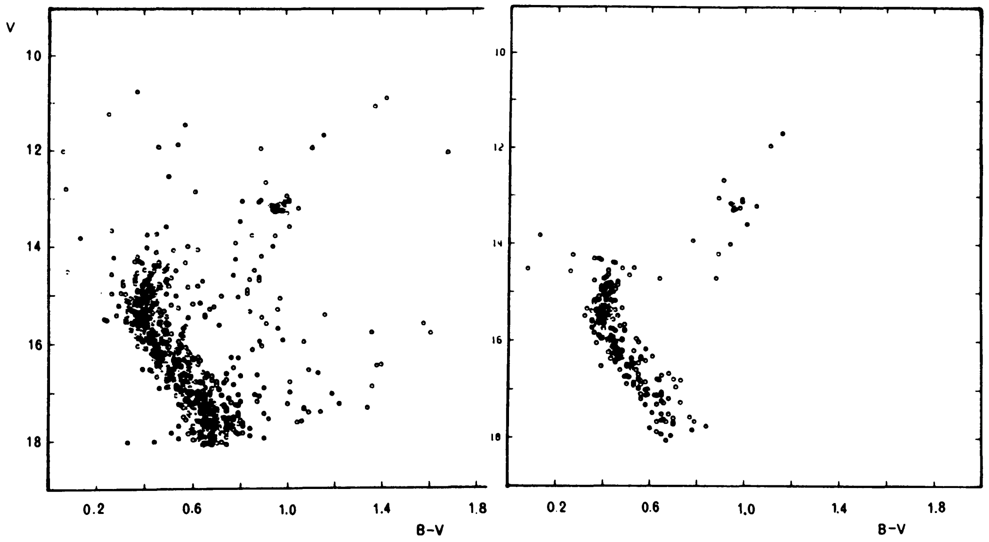

Figure 19. CMD's for NGC 2506; all stars (left-hand diagram); only proper motion members (right-hand diagram).

by McClure et al. on the right. The difference is striking and speaks for itself. The difference in astrophysically valuable content is also striking and NGC 2420 has become an object capable of revealing fundamental knowledge regarding stellar and Galactic evolution - simply from improved photometric data.

α Per is a cluster for which extensive data are available on radial velocities and spectral types as well as UBV photometry. Unfortunately the spectroscopic data extend only to V~9 and the effect on the CMD (from Hagen 1970) can clearly be seen in Fig. 18. The main sequence is clearly broader and less delineated below ninth magnitude.

A final superb example illustrates the potential effect of proper motion membership information on the CMD. Fig. 19 shows recent photometric data obtained by McClure et al. for NGC 2506, an old metal-poor cluster. In the left-hand diagram all observed stars are plotted, while in the right-hand diagram only stars with proper motion membership probability ≥ 90% (from van Altena and Chou) are shown. Since the field is more crowded than that of NGC 2420 the photometry is not as good, but the result is still a well-defined CMD ideal for detailed interpretation.

Unfortunately, it will never be possible to produce such beautiful and informative CMD's as the ones I have just shown for all clusters, even with the most painstaking effort. Discrimination between field and cluster stars is not always clear; differential reddening and large amounts of foreground reddening can be virtually insurmountable, as can crowding. But when we can overcome these problems the results are well worthwhile.

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DISCUSSION

CAYREL: You said that the comparison of your positions of giants in the observational HR diagrams can be made with the theoretical grids of HR diagrams, grids of evolutionary models. I disagree. The funneling effect on this part of the theoretical HR diagram is very heavy and we can say nothing about ages, about chemical composition, and about the true evolution of the star.

HARRIS: I would tend to disagree. At something like $5M_\odot$ we don't really have very much in the way of theoretical models and studies, and the ones that have been done show there is every reason to believe we can expect a range of colors, such as we see.

CAYREL: $5M_\odot$, yes, but not $1M_\odot$.

HARRIS: Oh, no, I'm not talking about $1M_\odot$.

CAYREL: In the Hyades you have $1M_\odot$, not $5M_\odot$

HARRIS: Yes, but in the Hyades there is distinct clumping.

MERMILLIOD: The main problem I see with the composite diagrams is the age determination for the cluster. There have been several attempts to determine the age from the upper main sequence and the few stars at the top of the main sequence; and that introduced confusion because of the peculiarities that are present among these stars. I try to use the entire H-R diagram to have a better age determination than you can produce with the group results, and the composite diagram now shows less dispersion.

HARRIS: I've seen your diagrams and they clearly are an improvement. You have been able to make some better age discrimination than I was able to. However, the point I want to stick with is that in the long run we're obscuring individualities among clusters if we superimpose them. We have to do that in some cases, but it's really vital to take the observing time we have and try to work on the clusters for which we can derive some real information in more detail than we can from composites or individually poor clusters.

MERMILLIOD: Yes, but when you find a peculiar star in one cluster and you find a similar star in another cluster, that provides information that that star perhaps is a real cluster member and not a superimposed field star.

HARRIS: Yes. That's the limitation of restricting yourself to populous clusters, because you have only a few clusters that you can work with and you can't be sure about the peculiarities. So we have to look at both aspects of the problem. I agree.

RENZINI: The first core helium burning phases, the most advanced evolutionary phases, are very exciting, as well. Is there any hope of finding objects like carbon stars, Mira variables etc., in clusters? At least a few? . . . One? (Laughter).

HARRIS: I don't know. I know of only one well-confirmed bright giant variable in an open cluster and that is a bright K2III star in NGC 6405, which is a long period variable. It's not nearly red enough to fit into this category. I suspect the characteristics of Miras are such that our chances are very poor. It would be nice, but I have no information.