BINARY STARS IN GLOBULAR AND OPEN CLUSTERS

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In erecting the edifice we call science, it is given to some to draw the plans by which the entire effort will be guided, to others to lay the foundation stones on which the rest is built, to another group to place the windows that let in light upon the whole, and to still others to cover the result with the paint that will make it acceptable to the populace and the sponsoring agencies. In this review, it is, I fear, my task to run around the construction site, pick up odd bricks and pieces of brick, and ask whether they do not perhaps belong somewhere in the building. After the customary bit of folk history, this will be done in the order globular clusters, open clusters, with observations and theory inextricably mingled, as indeed they really are.

Mizar, whose duplicity was discovered by Jean Baptiste Riccoli in 1650, is a member of the Ursa Majoris cluster. It may even be the massive central binary that should, theory says, eventually end up with most of the binding energy of an evolved open cluster (Wielan 1975). Thus the subject of binaries in clusters is as old as our knowledge of double stars themselves (at least in the sense that the expansion of the universe was discovered by the first Zinjanthropan who noticed that it gets dark at night!). A.D.S. 3264, one of the binary Hyads traditionally used to attack the cluster parallax (Heintz 1969) is $\lesssim$ 554, meaning that Wilhelm Struve found it to be double sometime before 1827.

Mizar also has the distinction of being the first known spectroscopic binary, the splitting of its K line having been noticed by Antonia C. Maury and announced by E.C. Pickering in 1889 (Pannekoek 1961). Algol, whose variability was seen by Montanari in 1670 and attributed to eclipses by Goodricke in 1783, was discovered as an X-ray source (Schnopper et al. 1976) because it is in the general direction of the Perseus cluster (of galaxies). No one has claimed it as a member thereof.

Kuiper (1937) was among the pioneers in using binaries in clusters to extract information not available from binaries or clusters separately. His interpretation of the mass-luminosity relationship he found

James E. Hesser (ed.), Star Clusters, 259–279.
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https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

from visual binaries was that Hyades stars have a hydrogen abundance by mass X = 0.13 (thereby making them brighter than stars on the "Sun-Sirius" mass-luminosity relation via the dependence of luminosity on mean molecular weight). This uncomfortable result has gradually gone away with a larger distance for the cluster and longer periods for some of the binaries than he used.

I. GLOBULAR CLUSTERS

A. The Importance

The dynamical evolution of globular clusters (and other similar systems of many point masses) never reaches equilibrium (though the configuration begins to look relaxed and symmetric after a few crossing times) but tends inexorably to concentrating part of the mass into a more and more tightly bound core (core collapse) while distributing the rest very far out in a halo or expelling it completely from the system (evaporation). The rate at which these processes occur and the proportions of the total mass that collapse and evaporate can depend critically on the initial binary population and the way energy is transferred back and forth between single star motions and binary orbits. The details matter because the more centrally condensed clusters should be approaching or experiencing core collapse at just about their present ages.

Heggie (1975a,b; 1978; Aarseth & Heggie 1976) has reviewed work done on the subject (much of it his own). Some of the interesting results include: (1) Starting with only single stars, an equilibrium population of wide binaries (those with binding energies $\lesssim$ the kinetic energies of individual stars) builds up quickly, systems forming and being disrupted many times in the age of the cluster. (2) No hard binaries (those with BE greater than the mean KE) will form during collapse to the present globular cluster configurations, but some may form during core collapse. (3) Only a few hard binaries can form before the cluster is disrupted by the energy thereby liberated, which matters for some models of the cluster X-ray sources. (4) A primordial binary population evolves in the sense that the wide systems are disrupted quickly and the close ones become more tightly bound; the dividing line occurs at semi-major axes of order 10-100 AU for most clusters. (5) A large initial binary population can significantly retard core collapse, discouraging the formation of a massive central black hole, which matters for other models of the cluster X-ray sources. The general context of gravitational n-body calculations within which these results were obtained is reviewed by Aarseth and Lecar (1975).

Binaries and mass transfer therein have been suggested as solutions, models, or explanations of a variety of phenomena. It would, therefore, be nice if there were some. The phenomena include: (1) The cluster X-ray sources, whose bursting properties are most naturally explained by something the size of a neutron star accreting gas from a companion

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

(van Paradijs 1978), (2) V19, the anomalous Cepheid, in NGC 5461 (Zinn & Dahn 1976) whose light curve is conveniently modeled by a star with twice the turn-off mass ($\sim$1.5 $M_\odot$) and the low-Z cluster composition. This star is apparently similar to the anomalous Cepheids found in dwarf spheroidal galaxies and the SMC (Zinn & Searle 1976), (3) Blue stragglers in general, and (4) Novae and dwarf novae in the directions of several clusters.

Let us anticipate the results of the next section by noting that it may be possible to "save the phenomena" even if there are no binaries at all in globular clusters. Fabian (1979) has concluded that the observed number of cluster X-ray sources could be explained by single neutron stars temporarily in regions of high gas density (like, but not limited to, the winds of red giants). One would also account thereby for their not showing eclipses or other duplicity indicators. Concerning blue stragglers, it is not improbable (B. Paczyński, private communication) that two-body encounters may more often lead to stellar coalescence than to binary formation. Much of the binding energy is then dissipated in the stars as heat and radiated away (rather than tending to disrupt the cluster), and the products should show rapid rotation velocities rather than variable radial velocities. There are no relevant data for the globular cluster stragglers, but the galactic cluster stragglers may in fact have only a normal field incidence of duplicity (Wheeler 1979) and high rotation velocities (Deutsch 1966). Alternatively, Renzini et al. (1977) have suggested that binary systems able to build up the companion to almost twice the turn-off mass may only survive in low-density systems like dwarf spheroidals and the low-concentration cluster NGC 5461. Even single-star novae and dwarf novae are, in principle, possible, if (as suggested by Paczyński and Jaroszyński 1978) massive accretion discs can last for the Hubble time.

Finally, good orbital parameters for spectroscopic, eclipsing binaries in globular clusters, by giving masses and luminosities independent of cluster properties, could help resolve long-standing controversies about cluster ages, distances, helium abundances, and so forth (Niss et al. 1978; Alexander & Budding 1979), while the relative frequency of bifurcation (close) double stars in clusters of different heavy element abundances could test how the collapse of star-forming gas clouds and outward transport of angular momentum depend on cooling of the clouds by metals (Abt 1979). The truth of these remarks is not diminished by the fact that they are of the same general form as "if the sky falls, we'll all catch larks," though their utility may be somewhat reduced thereby.

B. The Search

We are inclined to think we have found a binary system when we see (1) two stars close together in the sky, (2) line doubling or periodic radial velocity variations not associated with pulsational light variation, (3) eclipses, or (4) some phenomenon believed on the basis of previous data to occur only in binaries. Looking for visual doubles in globulars is hopeless. Not only are many of the stars crowded into fields

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

where individual images cannot be resolved, but the widest systems that could survive for the age of the clusters (a $\sim$30 AU) fail by more than an order of magnitude in even the closest clusters to be separable into two dots of light. Neither Space Telescope nor currently envisaged interferometric techniques will change this much.

Gunn and Griffin (1978, 1979) have carried out the most thorough search for radial velocity variations in globular cluster stars. Their radial velocity spectrometer technique, though both faster and of higher precision than standard spectroscopic methods, still reaches only the giants in relatively nearby clusters, but they can work all the way into cluster cores, where binaries (because they are more massive than the single stars) are liking to be hiding. They have examined 111 stars in M3 and some dozens more in M5, 10, 15, 22, and 92. None (apart from known pulsational variables) shows radial velocity variations of more than about 1 km/sec on a time scale of several years. The range of variability probed includes the velocities of stars with the cluster turn-off mass in orbits with a = 0.3 - 30 AU, that is, larger than the star sizes, but small enough to survive over the cluster ages. About 30% of field and open cluster giants studied in the same way show velocity variability. The conclusion that the giant populations in at least some globular clusters are grossly deficient in binaries relative to the field is apparently inescapable. I am not aware of any explanation for this other than the obvious one that binaries with that range of separations simply never formed among stars now leaving the main sequence. No amount of juggling with tidal disruption, mass loss from the component stars, and processes within the systems suffices to remove most systems from the detectable range.

Deliberate searches for variables in globular clusters have largely focussed on the horizontal branch stars and giants among which one expects to find the pulsational variables of large amplitude. Eclipsing stars revealed in such searches will necessarily be of rather rare types. Ordinary Algols, for instance, will have undetectably shallow eclipses, because of the large ratio of giant to main sequence luminosity. Eclipsing binaries to be seen need two stars well above the main sequence. Systems like this are by no means unknown in the field, but nearly all those for which mass estimates are available (Batten et al. 1978, eg stars 116, 305, 351, 530, 657, 761) are far too massive to be globular cluster members. At last count (Webbink 1980, and private communication) there were 47 probable or certain eclipsing variables in the directions of globular clusters. None has been shown via radial velocities (or proper motion or luminosity) to be a likely member, and some of the most promising (eg V65 in NGC 3201, V78 in 5139, V3 in 6868) are known (M.H. Liller, private communication) definitely not to belong to their clusters. A recent search among stars above the main sequence in Omega Cen (Niss et al. 1978) found numerous variables, including six possible and one certain eclipser, this last from the radius and luminosity implied by tis light curve, almost certainly a foreground object (Liller 1978). Because of the rarity of 'double giant' eclipsing systems of low mass in the field, the authors do not regard their results as necessarily

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

inconsistent with normal binary incidence in the cluster.

Down on the main sequence, eclipsing binaries with masses (though not necessarily ages) appropriate to globular clusters are common, many of them being of the contact (W UMa) type. Even with the field incidence (one per 2000 main sequence stars or so) of W UMa's, the number expected with respectable ($\sim 0^{m}.5$) light amplitudes is not absolutely enormous. Your guess is probably as good as mine, which was (Trimble 1977) about 10-100 per rich cluster, most hiding in the core. Baade searched deep plates of M3 without finding any likely candidates (Payne Gaposchkin 1979). Trimble (1976) had similar success with M55 (which has the advantage that main sequence stars are resolved almost all the way to the center). Budding and Kaskambas(1978, and work in progress) have found several variables in the field of NGC 6397 with brightnesses appropriate to W UMa stars at the cluster distance, but cannot say from the available data that any particular one of them is either definitely eclipsing or likely to be a cluster member. Liller (1980) is in the process of searching M55 and several other southern clusters on the basis of new plate material. It is not clear how much significance or discomfort should be attached to these results. M3 is strongly centrally condensed, and all the binaries may well be in the core where individual main sequence stars are not resolved. The M55 search was done by blinking the plates, which is probably not nearly as efficient as the Niss et al. (1978) "sandwich" method. In addition, Webbink's (1978, 1979, 1980, and private communication) grand canonical ensemble of close binary evolution calculations suggests that W UMa stars with large light amplitudes should be quite rare in very old populations. He finds that the incidence of cataclysmic binaries, on the other hand, should be enhanced over that in the field.

Finally, we come to objects-thought-to-be-binaries. Blue stragglers will turn up again among the open clusters. There doesn't seem to be much more to be got out of the cluster X-ray sources, which were nearly impossible to interpret as primordial binaries and not very easy as capture or exchange binaries in concert with everything else we thought we knew about the clusters (Trimble 1977) even before the radial velocity data (Gunn & Griffin 1979) was taken into account. There is, however, perhaps still something to be learned from the cataclysmic variables. Of the three old novae and four dwarf novae (or perhaps two and five) in cluster fields, M.H. Liller (private communication) regards only T Sco (in NGC 6093) as a probable member. It was inside the core radius and reached a maximum luminosity in good accord with the cluster distance (if you allow for its having been an unusually fast, therefore bright, nova). Webbink (1980) also accords probable membership to the old nova in NGC 6402 (which is in the cluster core, but its light maximum was not seen, so nothing can be said about suitability of distance) and to the dwarf nova in NGC 5904, which, though rather far from the cluster core is at least the right brightness. He notes in addition that, if the objects in 6522, 6712, 7099, and 6637 are at the cluster distances, then they are all brighter than field DNe by about the same amount ($\sim 2^{m}.5$). Even I would prefer not to do statistics on the basis

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of one cataclysmic variable in a cluster, but two or more members is already considerably more than the globular's fair share of the galactic total. It is possible to interpret them as either capture (Trimble 1977) or surviving primordial (R.F. Webbink, private communication) binaries, provided one is allowed to ignore the radial velocity evidence for the giants in M3.

C. Binaries in Related Populations

It is not quite the case that there are no binaries in any old (low metal, high velocity, Population II) group of stars. V80 in the Ursa Minor dwarf spheroidal galaxy is an eclipsing system (Webbink 1980); HD 137569 is advertised as "A Population II Remnant of Mass Transfer" (Bolton & Thomson 1980); the spectroscopic binary μ Cas is Pop II on both velocity and compositional grounds; and Nos. 407, 461, and 580 in the Seventh Catalogue (Batten et al. 1978) are at any rate high velocity objects ($\gtrsim$ 100 km/sec relative to the sun) of late spectral type. It does, however, seem to be the case that binary incidence declines monotonically as one goes to higher velocity or lower metallicity groups among field stars (Barry 1977). The effect shows in the data collected by Barry for each variable separately. Abt (1979) interprets the observations of velocity amplitude vs. mean velocity as implying that population II field stars have a deficiency of close (bifurcation) companions compared to population I stars, but a normal incidence of wide (separate condensation) companions.

The nearest I can come to making a coherent picture out of all this is to say (1) that the globular clusters, as one of the more extreme examples of population II available to us, genuinely had an initial binary frequency considerably lower than that among field stars (perhaps because of metallicity effects on cooling, perhaps for some other entirely different reason), but that, of the primordial binaries present, those leading to cataclysmic systems are much more likely to have survived than those leading to other kinds of observable eclipsing systems; (2) that two- and three-body captures have resulted in the production of no binaries among the giants (at least in M3), but may have made a few pairs whose components are some assortment of main sequence, white dwarf, and neutron stars (this requires some juggling of numbers of stars of the various types and optimistic guesses on how capture rate depends on star size; naive considerations favor the giants rather heavily); (3) that such captures (and any primordial very close binaries) must have resulted in stellar coalescence more frequently than in binary formation; and (4) that some of the phenomena we normally associate with binary systems and mass transfer may, in the globular clusters, result from other processes - stragglers from coalescence or mixing in the stars (Wheeler 1979a,b); X-ray sources from accretion of ambient gas; and cataclysmic variables from long-lived discs around single stars. There is nothing absolutely impossible in any of this, but it smells of the lamp.

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

II. OPEN CLUSTERS

A. The Data

1. Visual Binaries. The Pleiades contain about two dozen and the Hyades about four dozen I.D.S. stars. Some of these (eg of Luyten's common proper motion Hyads) may not actually be bound relative to the total cluster potential (R.S. Harrington, private communication), but most are probably real members. Of these, two Pleiads have orbits, one with $P \sim 1000$ yr, the other with $a \sim 0''.4$! This leaves only the Hyad orbits (eight of them are catalogued) to provide constraints on mass-luminosity relations and the like. No other reasonably rich clusters are close enough for orbits with periods less than 150 yr to correspond to resolvable separations.

2. Spectroscopic Binaries. About twenty clusters and associations contain stars with orbits catalogued by Batten et al. (1978). There are also half a dozen or so systems in cluster directions that are known not to be members. The groups in which orbits have been systematically determined are the Pleiades, Ceph OB3, and NGC 6231, 4655, and 6475 (references in Batten et al. 1978), resulting in about half a dozen good orbits per group; additional groups searched systematically for radial velocity variations include Alpha Persei and NGC 2516 (references in Abt 1979), the Hyades, M67, and M11 (R. Griffin, private communication). Within the last three clusters, four or five of about 20 M67 giants show variable radial velocity (by more than 1-2 km/sec over a few years) so far; for M11, 24 giants have yielded one large and four small velocity variations plus some discordant velocities; and in the Hyades, two of the four giants are definitely SB's, and of 46 main sequence stars, at least twenty show velocity variations, with amplitudes ranging from a few to about 200 km/sec and periods from less than two days to at least 16 years; a few additional stars show evidence of double lines during at least one observation. All these are lower limits to binary incidence, as some stars have been looked at only once or twice. The stars are not noticeably different from a field population of the same spectral types in regard to incidence, size, or time scales of radial velocity variations.

Abt (1979) has reviewed the incidence of SB's in the clusters for which data exist. He concludes that there are real variations, high binary incidence being associated with low mean rotational velocities (Ori OBI, IC 4665, NGC 2516 and 6475) and conversely (Pleiades and α Per). The variations are not correlated with cluster age, richness, or density. In addition, he finds that open clusters in general are binary-poor relative to the field at about the 1σ level. Of two competing effects - the field consists of cluster escapers, and single stars get out more readily than the more massive doubles; but binaries are more easily disrupted in clusters - evidently the latter wins.

The distribution of mass ratios and separations for the 60 or so cluster SB's shows little trace of the population having small separation

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

and mass ratio near unity found in the field by Lucy and Ricco (1979) and less cleanly by Abt and Levy (1976, 1978) and Trimble and Cheung (1976). That population can now fairly clearly be attributed to formation from a single gas cloud which, when followed with a finite-size particle gas dynamical code, evolves into a ring that in turn breaks into two or three very nearly equal pieces (L. Lucy, private communication). It is not conspicuous among the cluster SB's largely because many of them were found by people working very hard to identify small velocity variations, who therefore collected lots of examples of small mass ratios and large separations. About a dozen of the cluster SB's are either spectroscopic triples or have one or more faint companions or both. The poor statistics do not warrant a stronger statement than that the incidence of multiple systems is not obviously different from that in the field.

The Seventh Catalogue stars known to show orbital light variations that seem most ripe for further attention are No. 783 in NGC 6871 (which is doubled-lined and eclipsing but has only a visual light curve published) and the (probably) ellipsoidal variables Nos. 597 and 929 in NGC 6231 and 7380 respectively. Results obtained making use of individual systems in clusters will be discussed in section II.B.6.

3. Eclipsing Binaries. Kraft and Landolt (1959) compared positions of variable stars labled 'eclipsing' by Kukarkin et al. (1959) with those of clusters and associations. Of their 26 'cluster' stars, only two have good spectroscopic orbits (Nos. 157 and 929 in Batten et al. 1978). Of these, one is ellipsoidal, and the other has been rather thoroughly dealt with by Budding (1975). Of the remainder, RY Cnc is probably not a member of Praesepe (E. Budding, private communication) but most of the rest probably belong to their clusters on statistical grounds (Kraft & Landolt 1959). About half a dozen of them are brighter than 11th magnitude at minimum light and would seem to be a promising field of investigation. The search could probably also be redone profitably, using more recent editions of the variable star and cluster catalogues.

4. HR Diagrams. Hertzsprung first suggested that one could identify binaries in clusters because they would fall above the normal main sequence in a colour-magnitude diagram (Atkinson 1937). Improbable as it may seem, the results of applying this seemingly straightforward idea are somewhat controversial. The latest published position (Trimble & Ostriker 1978) is that, for the clusters and spectral types that have been studied (typically A stars in young clusters, to avoid effects of evolution) binaries and rotating stars cannot be distinguished from the HR diagrams alone, so that we cannot conclude from the available information that open clusters do or do not differ from the field or each other in binary frequency or distribution of mass ratios. Strömgren four-colour data ought in principle to distinguish rotation from duplicity. An attempt to do this (Trimble & Ostriker 1984) by superimposing the dereddened C_0 vs. b-y diagrams for four clusters (Coma, Praesepe, α

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Per, and the Pleiades) revealed that the differences among cluster averages are about as large as those between stars within each cluster, so we do not know how to interpret the diagram to learn anything about binaries. This is, perhaps, a special case of the phenomenon uncovered by Abt et al. (1979) that ubvy colors are very good at picking out peculiar stars, but not very good at distinguishing one abnormality from another (evolutionary effects, composition oddities, duplicity, etc.). Still further afield, but possibly also part of the same problem, C.H. Payne Gaposchkin and S. Kleinmann (private communication) have found the infrared colors of some binaries difficult to understand on the basis of the supposed nature of the companions.

5. Interesting Types of Stars. Recognized or recognizable (if we were close enough to them) clusters and associations must contain at least 10^{-4} of the stars in the galactic disc (some tens of thousands of groups with a couple of hundred stars each on average). Thus, if there is any type of star of which we know more than a few hundred within the distance to which clusters are well surveyed and none of them occurs in a cluster, or if any type of star is grossly over-represented in the clusters, we need to ask why. I am not aware of any sort of binary system for which either problem is obviously severe in the way that it is for globular cluster giants.

The W UMa stars are duly represented with at least four in NGC 188, and one each in M67 and Praesepe (Whelan et al. 1979). There is a sort of marginal RS CVn star (emission only sometimes) in Coma (Barry 1979). Cataclysmic binaries are represented by the dwarf novae BX Pup in NGC 2482 (Moffat & Vogt 1975) and SS Aur in the Hyades moving group (Eggen 1969). Although both groups have rather early (A) main sequence turnoffs, we do not learn anything about single star masses that give rise to white dwarfs vs. supernovae, as cataclysmic systems have surely undergone considerable mass transfer. Warner (1976) notes, however, that BX Pup and SS Aur at their cluster distances have absolute visual magnitudes at minimum light of 6.5 and 6.3 respectively, rather brighter than the average of +7.5 found by Kraft and Luyten (1965) from statistical parallaxes, and much brighter than the +10.3 found for U Gem (Wade 1979) from spectroscopic parallax of the cool star. There is no obvious relationship of this to the high average brightness of the globular cluster DNe if they are at their cluster distances.

The sixty or so cluster SB's catalogued by Batten et al. (1978) span the same range of spectral types as the non-cluster SB's, apart from a lack of late-type giants and supergiants, but the Eighth Catalogue will presumably contain Gunn and Griffin's (1977) Hyades giants and perhaps some from M67 and M11. There are a couple of Wolf-Rayet stars, a shell star, two Am stars, a white dwarf, and even a tentative identification of an X-ray binary (V861 Sco = OAO 1657-40, a possible black hole candidate, the visible star being otherwise a perfectly reasonable member of the Sco OBI association). More than one of these would count as over-representation (like cataclysmic binaries in globular clusters).

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There are no cluster Algols catalogued, but at least a few must be sitting around waiting to be found (among the Kraft & Landolt 1959 stars?). Masses for even one such in comparison with the main-sequence turn-off mass would be enormously interesting in connection with the question of how much mass is transferred and how much lost completely to the system during evolution to the semi-detached configuration.

B. Applications and Implications

1. Blue Stragglers. McCrea (1964) originally suggested that stars above a cluster main-sequence turn-off might be the products of mass transfer in close binary systems, the initial secondary having been raised to nearly twice the turn-off mass. Wheeler (1979a,b) has analyzed 103 blue stragglers in the 18 open clusters in which they can be clearly identified on the HR diagrams given by Hagen (1970). He concludes that the stragglers cannot be explained by binary mass transfer because (a) their incidence of variable radial velocity is no higher than that for field stars in general, (b) some of them apparently have masses greater than twice the turn-off for their clusters, and (c) their distribution of masses (as deduced from luminosities assuming core hydrogen burning) is not what one would expect from binary mass transfer. He suggests as alternatives either stellar coalescence (as mentioned above for globular clusters) or extended main sequence lifetimes caused by mixing within the stars. I am inclined to regard the former as less unlikely. Blue straggler formation in binaries is recalculated and discussed by Meyer and Meyer-Hofmeister (1980).

The blue straggler problem is not, of course, unique to clusters. It exists in the LMC (Robertson 1974, who favors the binary explanation) and wherever there are field stars of low metal abundance whose masses can be deduced (eg from pulsation properties for dwarf Cepheids, δ Scu stars, and the like) to be significantly above one solar mass (Breger 1979; McNamara & Feltz 1978). The advantage of the cluster stragglers is that the main sequence turn-off tells us precisely what mass is 'allowed.'

2. White Dwarfs in the Hyades. An important and rather poorly known number that enters into all models of galactic chemical evolution is the main sequence, single star mass that divides stars that become white dwarfs from stars that become supernovae (Tinsley 1975, 1980). One of the few constraints on this number comes from comparing the number of known WD's in the Hyades (11 to 14) with the number of stars in various mass ranges above the present turn-off (about 2 $M_\odot$) for some assumed initial distribution of star masses. Van den Heuvel (1975) found a mass cut at 3-4 $M_\odot$ in this way, assuming that all the stars were single. But at least two of the Hyades white dwarfs are close binaries, the eclipser V471 Tau (Nelson & Young 1974) and the emission line star HZ9 (WD + dMe; H. Lanning, private communication). The latter shows light variations, but no eclipses, implying (given K_1 = 130 km/sec from the M star and P = $0^d.56$, reasonable assumptions about the mass and radius of the M dwarf, etc.) a minimum mass for the WD of about 0.46 $M_\odot$. Why does all

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this matter? In the absence of eclipses or emission lines, detecting a faint main sequence companion to a white dwarf is exceedingly difficult; thus our knowing that two of the 11 (14) are binaries means that many of the others may well be too. And when mass transfer and mass loss from a system is possible, any star up to about 7 $M_\odot$ will give rise to a white dwarf, no matter what single stars do (R.F. Webbink, private communication). Thus we can probably no longer say anything very useful about the mass cut from the Hyades white dwarfs.

3. Dynamical Evolution of Clusters. As in the case of globular clusters, transfer of kinetic energy between single star motions and binary orbits can have important effects on the cluster dynamics. Existing calculations are not entirely in agreement. On the one hand, Aarseth (1971) finds that most of the binding energy of a rather poor cluster is likely to end up in a central tight binary (or triple) made of the most massive stars available. Mizar and Alcor in the Ursa Major group may be an example of this (Wielan 1975). And in Heggie's (1975a,b) model open clusters, binaries with separations greater than a few thousand AU are normally disrupted before the cluster falls apart (we would see them at most only as common proper motion pairs of course). Tutukov (1978), on the other hand, finds that an open cluster is likely to put 30-40% of its stars into very wide binaries (separations around 10,000 AU) and liberate them that way (private communication). In addition, these pairs tend to have very small mass ratios, M_2/M_1 near unity being deficient even relative to a van Rhijn luminosity function. The field seems actually to contain many pairs like this (Abt & Levy 1976, 1978), but it is not very obvious that the two sets of calculations are dealing with the same situation!

4. The Distance Scale. The distance to the Hyades is neither precisely known nor quite as important for cosmology (van den Bergh 1977) as is sometimes thought. Since the time when Kuiper (1937) deduced X = 0.13 for Hyades main sequence stars by constructing a mass-luminosity relation based on the visual binaries and the convergent-point distance (37 pc in those days), fashions have changed considerably. Heintz (1969) remarks that, if the error bars on the binary masses are reliable, no choice of cluster distance can simultaneously put all the stars on a single mass-luminosity relation (though he prefers a distance not greater than 40 pc). But the recent trend has been to adopt a distance modulus near $3^m\!.3$ from a variety of considerations (Hanson 1978) and show that the binary star masses and luminosities are then consistent with normal evolutionary calculations (Anthony-Twarog & Demarque 1977) The change is not pure bandwagon; several of the binary orbits have been redetermined in the interim.

5. Runaway Stars. Folklore has long ascribed runaway OB stars to the disruption by supernova explosions of close binary systems in young clusters and associations. This is in some sense impossible, in that mass transfer in close binaries guarantees that it is the less massive star that explodes, so it cannot possibly get rid of enough mass in an isotropic explosion to unbind the system. And if the expulsion is not

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isotropic, one should expect to end up with runaway binaries (J.P. Ostriker, private communication) consisting of OB stars plus neutron star remnant. The massive X-ray binaries are typically examples of this. In addition, it may be significant that all the OB stars in Batten et al. (1978) with systemic velocities greater than 60 km/sec (absolute value) can be divided among X-ray sources and cataclysmic binaries, stars with Wolf Rayet companions or similar stars with gas streams that can badly distort the systemic velocity (eg the two components of the Wolf Rayet No. 782 yield V_O's of +88 and -2 km/sec), and stars with rather small mass functions that may indeed have neutron star companions.

6. Well-Studied Systems. This section deals with those cases where someone has noticed that, because a star is both double and in a cluster, something can be said about either the star or the cluster that could not be deduced from either separately. Thanks in large measure to references supplied by H.S. Hogg (private communication), I have succeeded in chasing down nine of these (which are discussed in chronological and non-judgemental order below) and undoubtedly failed to locate some others.

Lloyd Evans (1973) derived a spectroscopic orbit for HD 90707 in IC 2581 and concluded that the stars (somewhat evolved) are rather more massive and the cluster somewhat younger than had previously been thought. The system light curve shows continuous variations that have apparently not been analyzed. The same year, Whelan et al. (1973) obtained radial velocity, light, and polarization curves for the W UMa variable TX Cnc in Preasepe. They concluded that the system was unevolved and best fit by a contact model of the Lucy (1968) type, having unequal adiabatic constants and a high helium abundance ($Y \sim 0.4$ for the cluster stars).

Cohen (1974) and Wachmann (1974) concluded that V453 Cyg in NGC 6871 though still detached contains two slightly evolved stars, thereby closely locating the cluster turn-off mass at 17 $M_\odot$. By forcing the binary orbit and the cluster distance to give the same properties for the component stars of CW Ceph in Ceph OB3, Nha (1975)learned that the absorbing material connected with the association obeys the normal reddening law ($A_V/E(B-V) = 3$) rather than some anomalous cluster law. The stars came out a bit funny, though, having nearly identical masses of 11.7 and 11.0 $M_\odot$ but rather different bolometric magnitudes of -5.6 and -4.7. Budding (1975) also used SZ Cam as a probe of the gas and dust associated with the cluster NGC 1502 and found no conspicuous anomalies. The latter two systems also provided valuable new points on the main-sequence mass-luminosity relation for very massive stars. Leung and Schneider (1975) found the component stars of HD 162724 in M7 (NGC 6475) to be near the end of core hydrogen burning. The masses from radial velocity curves are 3.15 and 2.49 $M_\odot$ but the spectral types are both given as B9V, which seems vaguely unlikely. The component separations derived from the photometry (via temperatures, fractional radii, and cluster-distance luminosities) and spectroscopy (via period and velocity amplitudes) are in extraordinarily good agreement at 14.6 and

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14.7 $R_\odot$ respectively. More could surely be done with this sytem, both observationally (it is 6th magnitude) and theoretically.

Bohannan and Conti (1976) used V729 in Ceph OB2 to show that Of stars can indeed evolve into Wolf Rayet stars via mass loss and transfer. The star in question is a transition object. Worden et al. (1978) tackled ER Ceph, one of the four W UMa stars in NGC 188, but reached no very firm conclusions for lack of spectroscopically derived masses. All four of that cluster's W UMa's would probably repay the effort needed to get radial velocity curves, but particularly ER and ES Ceph which lie just below and just above the gap in the HR diagram. Finally, a similar study of AN Cnc in M67, for which Whelan et al. (1979) obtained both light and radial velocity curves, yielded two interesting pieces of information. The component properties combined with the cluster HR diagram constrain the cluster metal abundance to solar or less, confirming the work of Griffin (1975, 1979), who found that the cluster giants are definitely not supermetal rich. In addition, the positions of the component stars relative to the gap in the HR diagram near main sequence turn-off can be understood in terms of the evolution tracks of Morgan and Eggleton (1978) but not in terms of those of Aizenman et al. (1969).

III. CONCLUSIONS

As far as the globular clusters go, the main puzzle is clearly the total absence of giant spectroscopic binaries in M3 etc. in combination with the presence of X-ray sources, cataclysmic variables, and blue stragglers normally associated with binary systems and mass transfer therein. The open clusters do not seem to present any comparable puzzles (though I would like to see at least one Algol somewhere!). Careful study of spectroscopic, eclipsing binaries in them does however clearly present a fertile field for further cultivation. A few promising candidates and approaches were noted above.

ACKNOWLEDGEMENTS

Nineteen people responded to my panic-stricken appeals for help with this review. They generously supplied annoted guides to the literature, re- and pre-prints, information on work in progress, advice, encouragement, and moral support. My sincere (and alphabetical) thanks, then, to Helmut A. Abt, Alan Batten, Don C. Barry, Edwin Budding, A.C. Fabian, Cecilia H. Payne Gaposchkin, Roger Griffin, Robert S. Harrington, Helen Sawyer Hogg, Howard H. Lanning, Martha H. Liller, Leon Lucy, Bohdan Paczyński, A.V. Tutukov, Brian Warner, Ronald F. Webbink, J. Craig Wheeler, John Whelan, and Sidney C. Wolff. My gratitude also to Daniel M. Popper for originally interesting me in binary stars, to Joe Weber for his usual patient tolerance of the domestic chaos that invariably accompanies review writing, and to all the astronomers over the past 330 years who have contributed to making the subject of binaries in clusters so interesting.

https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

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https://doi.org/10.1017/S0074180900092020 Published online by Cambridge University Press

DISCUSSION

LILLER: Just to give credit where credit is due, the one eclipsing binary you mention, V65 in NGC 3201, was the one I have not worked on. It was Geyer that proved that that was not a member of the cluster.

TRIMBLE: O.K., but I wouldn't have known about it if you hadn't told me!

KING: I have three . . .

TRIMBLE: Yes, I saw you scribbling there.

KING: I normally don't take notes on something that I hope will be completely different a year from now, but I wanted to write down some things to comment on. Soft binaries in globular clusters. I believe that the formation and dissolution time is short enough that we should not have them all broken up, but that we should have an equilibrium number.

TRIMBLE: Well, that's what I said. They come and go many times in the age of the cluster.

KING: Yes, but I believe that at any given number there should be an appreciable number of soft binaries at the present time. With regard to cataclysmic binaries in the globular clusters, if you believe even one nova, and I'd like to hear comments on the one in 6402 . . .

TRIMBLE: I think that's the one they didn't catch at maximum light, so you don't know whether it's the right brightness for the distance or not.

KING: If you accept the sample of one in a hundred years, that's one nova per $10^9 L_\odot y^{-1}$ and M31 has one nova per $10^{10} L_\odot y^{-1}$, so already we're doing better than Population I.

TRIMBLE: Yes, but perhaps globular clusters are a little easier to spot.

KING: M31 was searched systematically. Arp had the 60-inch every . . .

TRIMBLE: No, I don't mean than M 31, but than the rest of our galaxy.

KING: They're very hard to find because they're not photographed that often and usually at very poor scales.

TRIMBLE: Yes, I've made that argument, too, but I'm not convinced that it is statistically significant unless you have several.

KING: The final comment, which ends with a question - that 0.4 arcsec binary in the Pleiades is a very easy candidate for Speckle interferometry. There ought to be a good orbit. It might marginally be a candidate for radial velocity work. What do you expect the period and velocity to be?

TRIMBLE: I don't know; I haven't done the sum.

KING: What's the apparent magnitude?

TRIMBLE: It's not one of the brighter stars. It's not one of

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the Seven Sisters. It's somewhere down around F, but that's the best I can do.

KING: It still looks pretty good.

TRIMBLE: Yes, I agree. It can and should be studied, but the orbit as it presently exists doesn't tell us anything.

CARNEY: I have three comments, too. One is regarding the Wolf-Rayet stars. Recently Conti and Massey suggested that not all, but perhaps less than half are, in fact, binaries.

TRIMBLE: But the ones with orbits in that catalogue are, I'm sure, binaries.

CARNEY: Second, your use of μ Cas as a halo star probably isn't quite right, because it . . .

TRIMBLE: I didn't say it was a halo star. I merely said it was metal poor and high velocity.

CARNEY: It's not that high velocity and it's not very poor. The more important thing is blue stragglers. Ruth Peterson and I have been doing some work on blue stragglers in the field Population II. And we find that they're probably explicable in terms of rotation, not necessarily binaries.

TRIMBLE: What does rotation do?

CARNEY: It mixes the stars.

TRIMBLE: O.K. - enough to keep something alive at twice or more the cluster turnoff?

CARNEY: Something like that, perhaps. I'm not a theoretician, so I can't say.

TRIMBLE: Well, Craig Wheeler is, and he didn't try to do it. He just said that would work, if you could mix the stars. That's something I forgot to mention. Many, many years ago, Cal Tech graduate students had a thing called "take an astronomer to lunch" and we took Armin Deutsch to lunch one day. I imagine the very idea of graduate students paying for a professor's lunch was sufficiently revolutionary that we never had a professor turn us down. (Laughter). Those were the days when Dicke's Sun was a viable idea. Deutsch brought in as support of the idea of a rapidly rotating core to the Sun the fact that he thought virtually all blue stragglers in clusters were rapid rotators. That would certainly be relevant if you can use that to mix them. I don't know about field objects. These were cluster ones.

MAEDER: You mentioned that from the color-magnitude diagram and from the c_0,b-y diagram you cannot distinguish rapidly rotating stars from binaries, but indeed the simultaneous discussion of both of these diagrams allows the separation. The binaries are above the main sequence in the color magnitude diagram, and not in the c_0,b-y diagram.

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TRIMBLE: Yes, yes, I absolutely agree with you. It's only when you plot the data that you realize it's not going to work.

MAEDER: But you should not plot the data from clusters of different ages. If you take only Praesepe or the α Persei cluster, or another one, you might make the separation.

TRIMBLE: I'm not convinced. I mean, we are sticking with stars that are farther down the main sequence where there's no evolution, so I don't think the age of the cluster matters. It's just that the clusters are so different from one another that I think there must be something important that affects the position of the star in that diagram which is neither rotation nor binarism. And since I don't know what it is, I don't know how to allow for it. From a theoretical point of view, yes, certainly one should be able to tell the difference, but there is some other effect in there which I don't understand and which I think is dominating the whole picture.

RAJAMOHAN: I have a few comments. If you take the rotational velocities of cluster members and only single stars and take the age effects into account, there is no difference between the rotational velocities of various cluster members.

TRIMBLE: I believe you. But the reason for the effect that Abt finds is precisely because the binaries rotate more slowly, so if you ignore the binaries, of course, the effect goes away.

RAJAMOHAN: The mean rotational velocities is different because the frequency of binaries and peculiar stars might be different in different clusters.

TRIMBLE: Yes. That I agree with.

RAJAMOHAN: Now about the blue stragglers; a large number of blue stragglers are being found by Seggewiss to be peculiar stars - a larger faction than in the field. Now if you associate magnetic fields with chemical peculiarity, some of the blue stragglers or most of them in their interiors, could be highly magnetic stars, in which they could live longer in the main sequence.

TRIMBLE: Does that also give you mixing, is that the point?

RAJAMOHAN: No, it's because of magnetic pressures.

TRIMBLE: The central temperature is lower; O.K. I would be surprised if that could double the mass of the turnoff but maybe.

RAJAMOHAN: The third comment is that the runaway stars probably come from binaries which have been completely disrupted, because now we know that few associations have supernova remnants. Also, there are many stars that are associated with those associations so its not true that a binary can never be disrupted - at least observational evidence shows that is not the case at all.

TRIMBLE: Well, it cannot be disrupted by an istropic explosion of a less-massive star. It is also, however, the case that there are runaway binaries. And since a triple system doesn't give you at least runaway velocity, it must also be the case that not all supernovae disrupt.

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SAWYER-HOGG: I don't quite understand why the existence of the nova in M 14 is in doubt because it was not caught at maximum. This star was found by Amelia Wehlau on half a dozen plates that I took in one week in 1938. It was very close to the cluster center and hasn't been seen since. So what do you call it if you don't call it a nova in a globular cluster?

TRIMBLE: Martha? . . . (Laughter).

LILLER: It is possible, although highly unlikely, that it is a foreground or background object. I mean, it could happen and the fact that the maximum magnitude is not known makes it impossible to say absolutely certainly that it is in the cluster, itself.

TRIMBLE: You can't guess the distance without. . .

WHELAU: Well, it has not an unlikely magnitude for it to be a couple of magnitudes below the maximum, which would put it at the right distance for the cluster if it did not change magnitude very much during the week in which we can see it.

TRIMBLE: Let's say we caught it very close to peak time.

COHEN: What about the nova that was found about two months ago in the direction of M3? Is that a member?

LILLER: I know about that one. That one was, as Helen Hogg pointed out to me, not the first rediscovery of a bright Cepheid in a globular cluster. (Laughter).

TRIMBLE: I'm kind of grateful we don't get the IAU postcards at Irvine!

CAYREL: Perhaps abundance differences from cluster to cluster can act in opposite ways on the position of the binaries, and therefore prevent them from going out . . .

TRIMBLE: You mean on the colour-colour diagrams. Yes, the metal abundance doesn't matter very much to that particular diagram. The helium abundance does. And, of course, I have the prejudice that all the young objects have the same helium abundance. It's possible, of course, that I'm wrong.

FEAST: I seem to remember that a few years ago a number of doubles were claimed in the Pleiades on the basis of lunar occultations. I don't know if you've got any comment for that. I mean, if that is so, it shows that we are missing doubles in other ways.

TRIMBLE: O.K., these are things with separations in the fraction of a second of arc. I don't know. It's certainly possible.

KEENAN: In connection with the possible binary nature of burster x-ray sources in globulars, is there any evidence at all that any of the burster sources, whether in clusters or out of clusters, is a binary?

TRIMBLE: I think not. I think it's true that none of the galactic bulge sources show any kind of orbit. I know that none of the globular cluster ones do. But I think it's true that none of the globular cluster ones do, and I think it's true that none of the galactic bulge sources do. If I'm wrong, please correct me.

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FAULKNER: I think that's right and that it was reported at Cambridge last year.

TRIMBLE: Yes, I know that was true a year ago, but things come and go.

ALCAINO: How many of the 26 candidates of eclipsing binaries have proved to be binaries in globular clusters?

COHEN: I can't hear.

TRIMBLE: He says of the 26 Kraft and Landolt candidates, how many are known to be binaries in open clusters? Only the two that have orbits, I suggest. I said that it was a field ripe for exploitation. Some of them certainly have very characteristic eclipsing light curves. Some of them have very little information.

SCHOMMER: If blue stragglers in globulars would be binaries, has anyone ever looked for eclipses?

TRIMBLE: No. Statistically, you wouldn't expect them. Even with W Ursa Majoris stars, which are incredibly common - one star in 2000 is a W Ursae - by the time you go through the numbers you find that you expect 5 or 10 that you can actually detect in globulars.

CANNON: I think you mentioned at one stage you might come back to blue stragglers in globulars, and never really did, in fact.

TRIMBLE: Well, I came back in connection with open clusters.

CANNON: Right, well, my question really is directed to anyone in the audience who knows of any globular that really does have blue stragglers, other than M3 and possibly NGC 6171 which has a rather messy few stars hanging around it?

TRIMBLE: I count the one that has the anomalous Cepheid.

CANNON: O.K., that's different.

TRIMBLE: But that's a particular kind of blue straggler, I think; it's a star that is more massive than it ought to be.

CANNON: Right, but my point is that either M3 is a very peculiar globular in this way or there's something wrong with those M3 observations.

TRIMBLE: Oh, the fewer blue stragglers there are the happier we will all be, I think. (Laughter). If there aren't very many, so much the better.

CANNON: Well, they're certainly nothing like the frequency in several other well observed globular clusters that they are in M3.

GREEN: M71 has a blue star, doesn't it? Cohen would know.

COHEN: I'm not sure. There's only one star, and it's the star Dennis Butler did, and I'm not sure it's a member.

HARRIS: Of about a dozen or so globular clusters that do have photometry down to the main sequence, which is what you need to find the blue stragglers, M3 has by far the most obvious sequence of blue stragglers. I think you can name two or three others that have some indication of stars scattered just above the turnoff, about 0.5 mag or so, but M3 is, by far, the most obvious.

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