upper main sequence and the large vertical extent and redward curvature of the turnoff which distinguish the overshooting isochrone in Figure 1: Overshooting seems definitely present in NGC 3680 also.

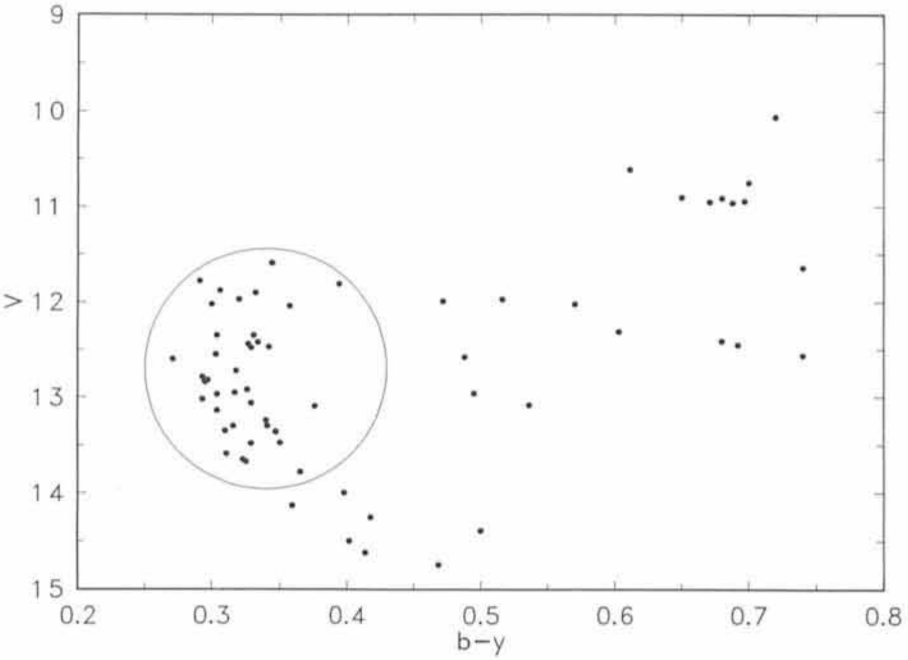

Figure 3: *CM diagram of NGC 3680 from Anthony-Twarog et al. (1989), Nissen (1988), and Eggen (1969, transformed to b-y). Note the apparent bimodality of the main sequence; CORAVEL data for the circled stars show this to be an artifact of binary and non-member contamination.*

Some Lessons

One lesson is immediately obvious: If significant conclusions on stellar models or cluster age depend on the correct interpretation of minor features of a cluster CM diagram, careful star-by-star identification of non-members and binaries is essential. The microscope may reveal that initial, and perhaps biased, impressions are in fact wrong.

Then, together with the binary evidence, the cluster data seem to show that convective overshooting does exist as an observable phenomenon in stars of these masses. Future stellar evolution models will have to take this into account. With their precise photometry and membership data, clusters such as IC 4651 and NGC 3680 will be very valuable in helping to calibrate the model parameters used in the convection prescription. We hope to extend this type of work to clusters of other ages, and subject new generations of stellar models to tests based on both binary and cluster data.

A third significant consequence of accepting the validity of overshooting models is that higher ages (~4 10^9 yr) are estimated for the stars in IC 4651 and NGC 3680 than with standard models, by almost a factor of two (cf. Fig. 1). This result appears to be typical for evolved main-sequence stars (cf. Table 1 in Andersen et al., 1990), and should be of some significance for models of the evolution of the Galactic thin disk population.

Why did Mazzei and Pigatto (1988) derive ages a factor of three *lower* from their overshooting models, when they considered their ages accurate to ~10 %? Their determination of reddening in the isochrone fit itself is a likely reason: Their values of E(B-V) are ~0.15 mag larger than those observed directly, maybe because the C-S opacities lead to their models being too hot. Overcorrecting for reddening by 0.15 mag will, of course, lead to significantly lower age estimates.

Acknowledgements

We thank Drs. B. Anthony-Twarog, M. Mayor, B. Twarog, and D. VandenBerg for helpful conversations and correspondence, and ESO, the Danish Board for Astronomical Research, the Danish Natural Science Research Council, and the Carlsberg Foundation for financial support.

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The Oldest Stars

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Introduction

Traditionally, young stars have been favourite objects for investigations of galactic structure and dynamics. Among the reasons for this preference, the generally high luminosity of hot stars has played a major role. As a result, our knowledge of the young population in the Galaxy is relatively advanced. The same is definitely not true for the oldest populations in the Galaxy. The major reason for our limited insights into the early generation of galactic stars is their low luminosities and generally incon-

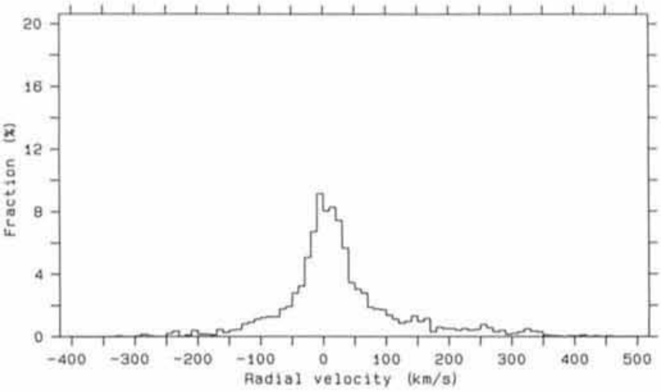

Figure 1: *Fractional histogram of radial velocities obtained for the 1300 objects selected for our present study. Bin size is 10 kilometres per second.*

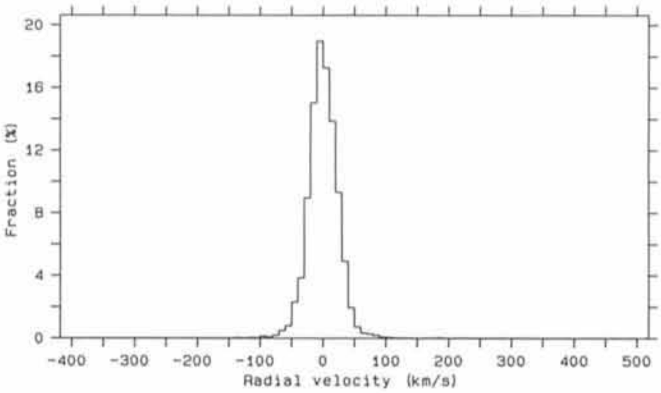

Figure 2: *Fractional histogram of radial velocities for stars included in the Bright Star Catalogue. Bin size is 10 kilometres per second.*

spicuous appearance. Simply speaking, these stars have not been able to raise the same enthusiasm among observers as their hotter and more recent counterparts. Consequently, our knowledge of the first generations of galactic stars has long been rather limited. This is a definite weakness in the understanding of our own galaxy, its structure and evolution. It is also, in a corresponding manner, a limitation to our understanding of the evolution of stars and of the Universe.

Stars of Interest

For a study of the earliest phases of the evolution of the Galaxy, we are interested in stars with lifetimes comparable to, or longer than, that of the system itself. In practice, this means that we are limited to stars of roughly solar temperature and cooler. At the same time, there is a special advantage in studying stars which are reasonably similar to the Sun in their basic properties, as this largely improves our possibilities to interpret observing data through direct comparisons with corresponding solar data. Taking into consideration both the age and the similarity to the Sun, we are limited to stars of spectral types from late F to late K. Among these, those with higher surface gravities are the most interesting ones.

What Do We Want to Know?

Nobody embarking on a project concerned with the earliest generations of galactic stars should have difficulties in identifying interesting topics for studies. Such topics are as numerous as important. Largely depending on our present lack of suitable data, a major problem is to arrive at some basic understanding of early star formation and its governing processes.

In general, we want to obtain a picture of the early Galaxy, its structure and dynamical behaviour. At the same time, the evolution of star-forming processes as a function of time is an important target for our studies. In addition to parameters describing structure and dynamics as a function of time, we are highly interested in the chemical evolution of the Galaxy. This involves the chemical composition of the very young Galaxy and the subsequent composition evolution.

The structure, the dynamics and the chemical composition may be seen as parameters describing the Galaxy as an entity or, in other words, as seen by an outside observer watching our galaxy at low spatial resolution.

In our case, it is natural to include parameters describing the Galaxy more in detail. Such parameters concern star-formation processes. How were the first stars formed? Did first-generation star formation occur mainly in groups or clusters, or did it give preference to individual stars? Are there a number of galactic stellar components well or at least reasonably well distinguishable or is the distribution of such components generally smooth? Is the total history of star formation marked by explosive events or does it present overall continuity? Does star formation present a largely isotropical pattern or is the picture of a more patchy nature? Are early and more recent star formation processes approximately comparable or are the mechanisms significantly different?

From the dynamical point of view, a detailed approach provokes a number of questions. How did the early Galaxy behave dynamically? Can we determine galactic rotation as a function of age of the Galaxy? How are orbital parameters depending on age? Can stars have high space velocities but still not show significant underabundance of heavy elements?

Is there a smooth transition between stars with high space velocities and those with modest and low velocities? Is space velocity a large-scale characteristic only, or can isolated groups of stars break an otherwise smooth velocity distribution? Can we derive a well-defined velocity of escape for the solar neigh-

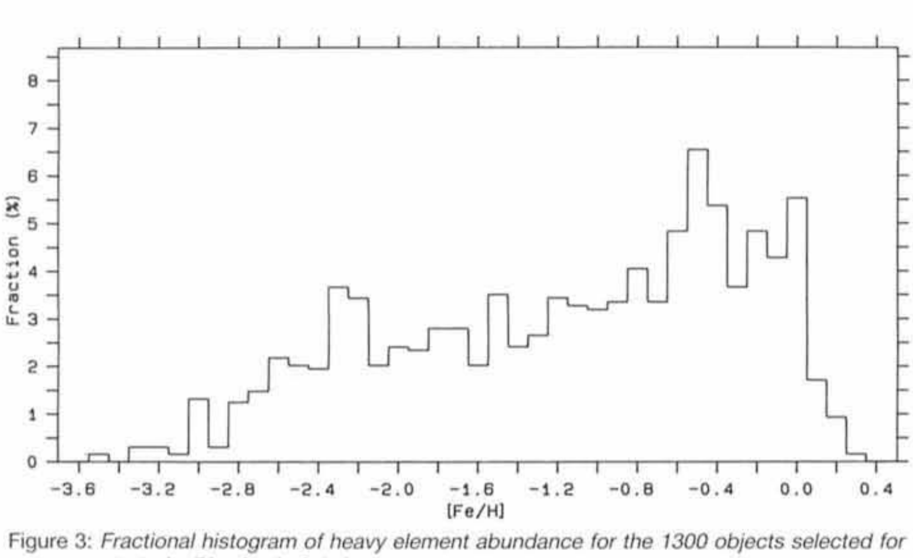

Figure 3: *Fractional histogram of heavy element abundance for the 1300 objects selected for our present study. Bin size is 0.1 dex.*

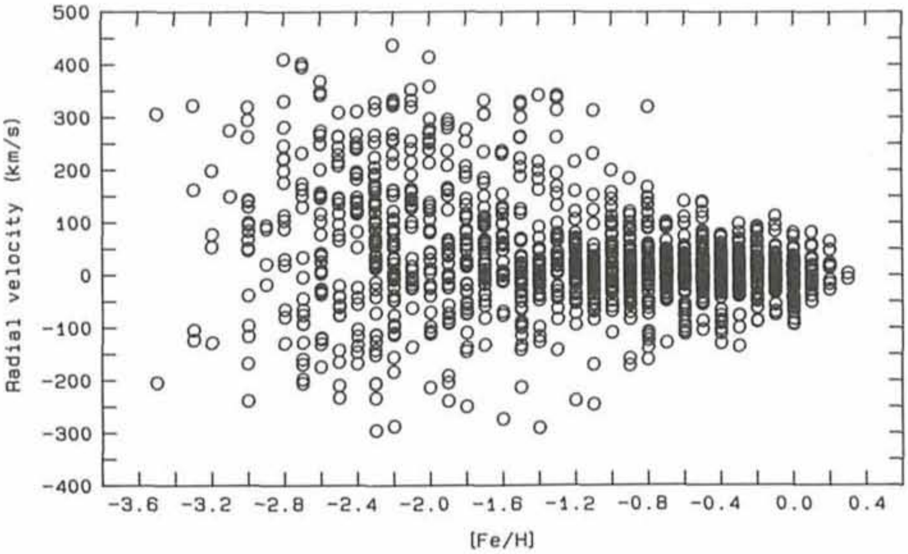

Figure 4: *Radial velocity, expressed in kilometres per second, vs. abundance of heavy elements, expressed in dex, for the 1300 objects selected for our present study. In the right-hand central part of the diagram, plot crowding is substantial.*

bourhood and thereby obtain an estimate of the mass of the Galaxy outside the solar orbit?

In addition to our concerns regarding the chemical evolution of the Galaxy, we are interested in the general chemical picture presented by the early Galaxy as well as by its more recent counterparts. Is there a metallicity gradient in the Galaxy? If so, what is the nature of this gradient? Is metallicity a parameter with smooth variations, or does it present an uneven pattern?

Both for a study of large-scale parameters of the early Galaxy and for investigations of star formation processes, data on binary and multiple stellar systems with high ages are highly valuable. Among other things, such data can contribute to our understanding of early-generation protostellar matter. Further, we are highly interested in the ratios of binary and multiple objects as a function of stellar age. From a sample of old binary systems, the circularization time for short-period systems can be estimated. From data on period cut-off, abundance of heavy elements can be inferred. A study of binary systems permitting mass determinations should provide crucial information concerning the mass-luminosity function for the oldest stars. Such data would significantly improve our possibilities to understand early stellar evolution and also provide an estimate of the production of helium in the first phases of galactic evolution as well as, possibly, an estimate of the primordial abundance of helium. Finally, with a solid material for binary systems, it should be feasible to identify components with very small masses, possibly down to the mass range occupied by brown dwarfs and planets.

Observations

Our weak knowledge of the oldest stars has been and is still emphasized by the fact that observational samples of such stars are normally seriously affected by selection bias. Such bias has been exceedingly hard if not impossible to avoid. Nevertheless, it is a significant limitation concerning almost all our knowledge of the first generations of galactic stars. For this reason, we have endeavoured to obtain an observing material which is, firstly, as free as possible from selection bias and for which we can, secondly, study possible effects of existing unavoidable bias. To this extent, we have chosen to include both a primary observing sample and sub-samples supporting the primary one and our possibilities to study sample bias.

The primary observing sample is based on photometric criteria. It includes stars with spectral types between F5 and M0, observed on the Strömgren uvby system. Our photometric data give us effective temperature, surface gravity and abundance of heavy elements (Crawford, 1978; Nissen and Gustafsson, 1978; Nissen, 1981; Ardeberg and Lindgren, 1981; Ardeberg et al., 1983; Olsen, 1984; Ardeberg and Lindgren, 1985a). In addition to general stellar parameters, this provides us with a sensitive selection criterion regarding metallicity. In this way, we define the sample of stars for which we subsequently obtain radial velocity data. This basic set of programme stars is, in parallel, supported by samples of stars defined entirely from kinematical data (Stock and Wroblewski, 1972; Giclas et al., 1971, 1978).

For the total sample of programme stars selected for radial velocity observations, we have used the photoelectric radial velocity scanner CORAVEL. The major part of this work has been made with the Danish 1.54-metre telescope at La Silla, with a minor part made with the Swiss telescope at the Haute-Provence Observatory in France. Our present report refers exclusively to data obtained at La Silla.

From our photometric data, we have identified around 3000 stars as belonging to Population II. For approximately 2400 of these stars, we have obtained radial velocity data. In addition, we have made spectroscopic studies of some of the most interesting objects. Finally, astrometric data are forthcoming for many of the stars, partly obtained with the Carlsberg Automatic Meridian Circle at La Palma, partly with the HIPPARCOS satellite. These data will furnish both distances and tangential velocities.

Some Tentative Results

As described above, a search for binary and multiple systems among our programme stars is an essential part of our project. For this reason, we have scheduled our observations, of photometric quantities as well as of radial velocities, to cover adequate time intervals. In practice, these intervals depend on the periods of the systems we want to include. At the same time as our observations have to cover relatively large intervals in time, there is a corresponding need for data of high accuracy. This is especially emphasized for radial velocity data, as we want to be able to detect also components with small masses.

From the total of 2400 objects which are classified as belonging to Population II, and for which we have obtained photometric as well as radial-velocity data, we have selected approximately 1300 objects, including also a smaller number of reference stars, mainly belonging to the younger galactic population. For the latter objects, the data now available and reduced are solid enough to permit some tentative conclusions, even if additional data are needed for conclusions of a more definite nature.

In Figure 1, we present a fractional histogram of the radial velocities obtained for the 1300 objects selected. For the systems with variable radial velocity, we have used best available estimates of system radial velocities. As a comparison, Figure 2 shows the corresponding data for stars included in the Bright Star Catalogue. While a difference in the fractional distributions is to be expected, we think that the observed difference clearly indicates the need for systematic surveys, as unbiased as

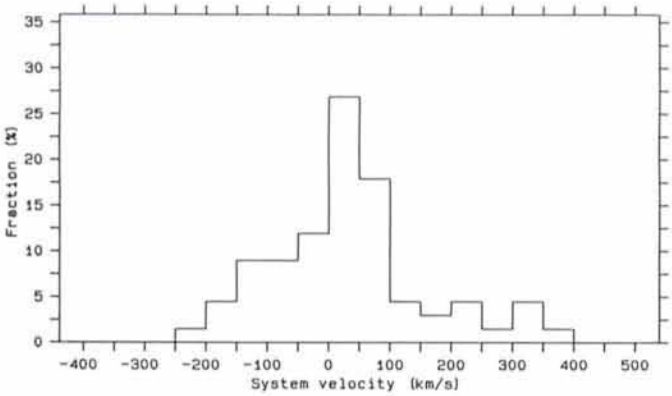

Figure 5: *Fractional histogram of system radial velocities for our sub-sample of binary and multiple systems. Bin size is 50 kilometres per second. About 70 systems are included.*

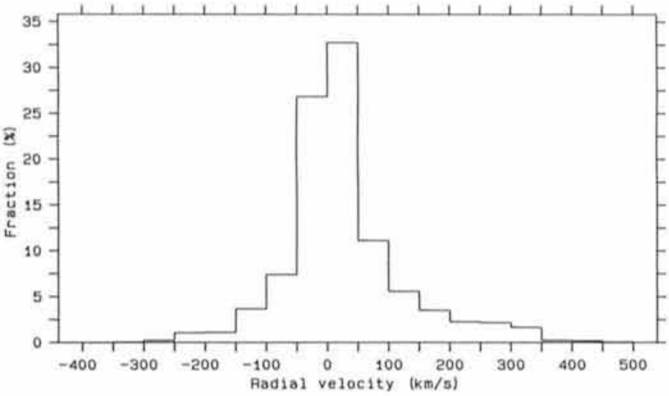

Figure 6: *Same as Figure 1 but with a bin size of 50 kilometres per second for convenient comparison with data shown in Figure 5.*

possible, of stars belonging to the old galactic population.

For the stars studied, the abundance of heavy elements is a key parameter. Formally representing this parameter as [Fe/H], we display, in Figure 3, the fractional distribution of this parameter. The result most immediately obvious from Figure 3 is the large range in [Fe/H], covering an abundance interval including objects typical for populations ranging from that of the solar neighbourhood disk stars to values normally described as indicative of an Extreme Population II or even a Population III.

Some discussion concerning galactic stellar populations has concentrated on the internal relations between these populations. From the distribution of metallicity (Fig. 3), some tentative comments may be made. First of all, an Intermediate Population II seems indicated. The extension of the range of the metallicity for this population has been subjected to extensive debate. We mention the conclusions drawn by Strömgren (1966) and by Eggen et al. (1962). From our data, we find a relatively strong indication of an Intermediate Population II being rather restricted in [Fe/H]. As a matter of fact, our data indicate a range in this parameter even more narrow than that proposed by Strömgren (1966). At the same time, there is some suggestion of a split in metallicity between Intermediate Population II and Population I, although this should be more carefully studied when more data are available.

Whereas it appears possible to delimit tentative ranges in [Fe/H] for Population I and for an Intermediate Population II from our data, stars with more extreme underabundance of heavy elements seem to have a comparatively smooth distribution with respect to [Fe/H]. Whether this fact should be taken as an argument against the existence of a Population III cannot be decided from the present status of our material. At any rate, the substantial range of Extreme Population II seems verified beyond doubt.

Judging from the distribution in Figure 1 only, it is difficult to distinguish between stars belonging to Intermediate Population II and those pertaining to Population I. Rather, these two populations merge in the radial velocity domain. At the same time, the difference between Population I and Intermediate Population II, on the one side, and Extreme Population II, on the other side, seems rather pronounced. This fact, as well as the large width of this Population in radial velocity, tends to confirm the impressions based on the distribution of metallicity. As was the case in the metallicity distribution, it is not clear whether or not separation of a Population III can be made by means of the present radial velocity material.

The data on abundance of heavy elements and on radial velocities have been combined in Figure 4. The separation of stars belonging to Intermediate Population II and to Population I is confirmed, especially when compared to Figure 3. From the distribution of data, both populations show kinematical characteristics defining them as disk populations. At the same time, there is a significant indication of a thick disk (Gilmore and Wyse, 1986). This thick disk is most clearly defined by stars whose metallicities show that they belong to Intermediate Population II. However, the presence of a thick disk seems also well indicated in the range ascribed to Population I.

From the width of the distribution of radial velocities, Extreme Population II is clearly present over a range in [Fe/H] from around −1.0 to beyond −3.0. Over a major part of this metallicity interval, this population appears to be rather homogeneous. However, at its high metallicity end, Extreme Population II

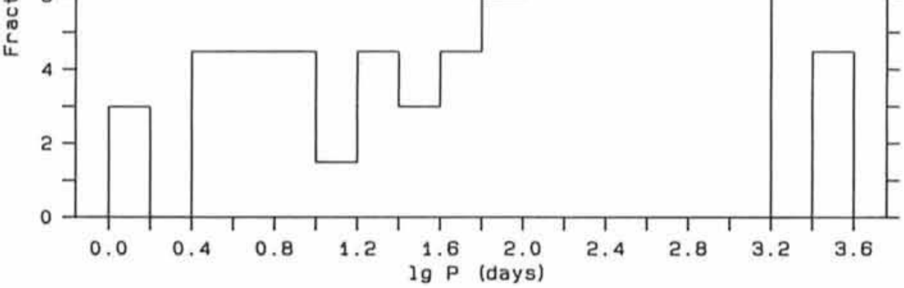

Figure 7: *Fractional histogram of orbital periods, expressed in days, for our sub-sample of binary and multiple systems. No attempt has been made to correct for selection effects, which are probably highly significant. See the text.*

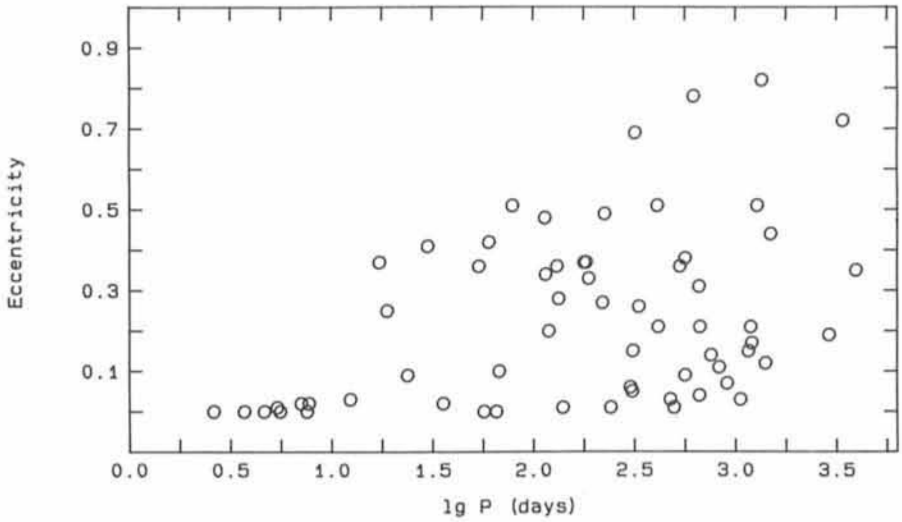

Figure 8: *Orbital eccentricity vs. orbital period, expressed in days, for our sub-sample of binary and multiple systems.*

seems to display considerably smaller radial velocity dispersion than more metal poor stars. Whether this should be interpreted in evolutionary terms is a problem that merits a closer study with more complete data. As judged from Figure 4, the reality of a Population III seems possible, but is not confirmed. More data are necessary, before this question can be addressed in a fully adequate manner. Very tentatively it might be suggested that, if real, Population III is in evolutionary terms rather firmly coupled to Extreme Population II.

From the sample of objects classified as binary and multiple systems (Ardeberg and Lindgren, 1985b, c; Lindgren et al., 1987, 1989; Ardeberg and Lindgren, 1990), we have selected those for which system radial velocities and orbital periods are determined with accuracies which, although not sufficient for definite conclusions, allow some reasonably well-defined statistical conclusions. This gives us a sub-sample of close to 70 binary or multiple systems. In all but a few cases, eccentricities have also been determined to an accuracy that allows tentative statistical conclusions.

For this sub-sample of binary and multiple systems, Figure 5 shows the fractional distribution of system velocity with a bin size of 50 kms^{-1}; a rather wide distribution is noted. In order to compare it to the distribution in radial velocity of the total sample of stars under present study, we have, for the data presented in Figure 1, made a rebinning resulting in the fractional distribution of radial velocities presented in Figure 6.

A comparison of Figures 5 and 6 indicates that the distribution of system radial velocities for binary and multiple systems is as wide as that defined by the distribution of radial velocities for the total sample of stars presently under discussion. This is a result of special interest, in particular with reference to the long-standing controversy about the relative incidence of binary and multiple systems among the oldest stellar generations as compared to the corresponding incidence among younger stars. We refer to studies by Abt and Levy (1969), Crampton and Hartwick (1972), Lucy (1977), Peterson et al. (1980), Griffin (1989), Lucke and Mayor (1982), Mayor and Turon (1982), Lindgren et al. (1987), Carney and Latham (1987) and Latham et al. (1988). The fact that our data, with their low bias, indicate a fractional radial velocity distribution for binary and multiple systems comparable to that of our total sample of stars, speaks clearly in favour of the absence of a significant dependence on galactic age of processes determining stellar multiplicity. At the same time, this is obviously a question that merits a more stringent treatment with a better data base. Given the importance of the topic, we will endeavour to revisit this field as solidly as possible.

In Figure 7, we have displayed the fractional distribution of orbital periods for our sub-sample of binary and multiple systems. In order to interpret such a distribution in an adequate manner, we have to consider effects of selection as well as of other bias. We mention the difficulties to derive non-spurious selections of the systems with the shortest periods, due to the high resolution necessary in the radial velocity data, and, equally, of the systems with longer periods, in this case due to the large time coverage needed for detection and determination of radial velocity variability of systems. Nevertheless, it is of considerable interest to note the presence of systems with very short as well as with rather long periods.

The distribution of orbital eccentricity, versus orbital period has been shown in Figure 8. Except for a general trend of the upper and lower envelopes for periods longer than around 15 days, the existence of a cut-off period seems strongly indicated. This is another topic that needs further study.

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