loops on Y and Z may be approximated by the linear relations:

$$\Delta \log T_e = 1.31\,\Delta Y - 3.9\,\Delta Z$$

$$\Delta \log L = 3.8\,\Delta Y - 10.4\,\Delta Z$$

These relationships may be compared with those of Hallgren and Cox[6] who have also calculated 5 $M_\odot$ sequences,

$$\Delta \log T_e = -0.25\,\Delta Y - 4.5\,\Delta Z$$

$$\Delta \log L = 4.0\,\Delta Y - 11.9\,\Delta Z$$

The agreement is quite good, except for the dependence of loop length on helium abundance. However, an error has been detected (Robertson[5]) in the main sequence evolution of two of Hallgren and Cox's tracks, which may explain why the effects of helium abundance differ, while the effects of metal abundance agree. The dependence of loop length on Z found here contradicts Schlesinger's[7] results, but Schlesinger's extremely small loops compare with those obtained using the Mount Stromlo evolution program with core overshooting neglected.

The inclusion of core convective overshooting increases the core size and hence the timescale of the helium burning evolutionary stage. The ratio of time spent at the blue end of the loops to time spent on the red giant branch is increased, but not enough to agree with observation. It may be worthwhile to indicate a possible solution to this problem. Robertson[8] and Lauterborn, Refsdal and Weigert[9] have pointed out the extreme sensitivity of the effective temperature at the bluest point of the loop to the hydrogen abundance in the hydrogen burning shell. At the red giant tip, the innermost extent of the convective envelope reaches a mass fraction which is sensitive to the initial abundances used. Perhaps for some initial composition, more extreme than those considered here, the convective envelope would extend far enough to include most of the region reached by the main sequence convective core, restoring its hydrogen abundance to almost the initial value. During core helium burning the hydrogen shell would then be burning into a region of uniformly high hydrogen abundance, which could well result in most of the helium burning lifetime being spent in a small region round the blue tip of the loops, in agreement with the observations of NGC 1866.

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Population I Helium Burning Red Giants. Observations

R. D. Cannon

Mount Stromlo and Siding Spring Observatories, Research School of Physical Sciences, Australian National University

The basic observational evidence for helium-burning red giants in open clusters has been given elsewhere,[1] and I shall give here only a summary and then describe in more detail new results for one cluster, NGC 2477.

A typical intermediate-age cluster is NGC 7789,[2] which is about 10^9 years old and has red giants of about 1.7 $M_\odot$. Theoretical isochrones, e.g. from models by Iben,[3, 4] give a reasonably good fit to the observations, but there is no explanation for the very marked concentration of most of the red giants in the Colour-Magnitude diagram. A similar clump of red giants is found in all open clusters more than 10^8 years old, although it becomes less conspicuous in the older clusters such as NGC 2420.[5] When the observations of many clusters are compared,[1] it is found that the clump position is remarkably constant in all clusters with ages greater than 3.10^8 years, at about $M_V = +1$, $(B - V)_0 = +1.0$.

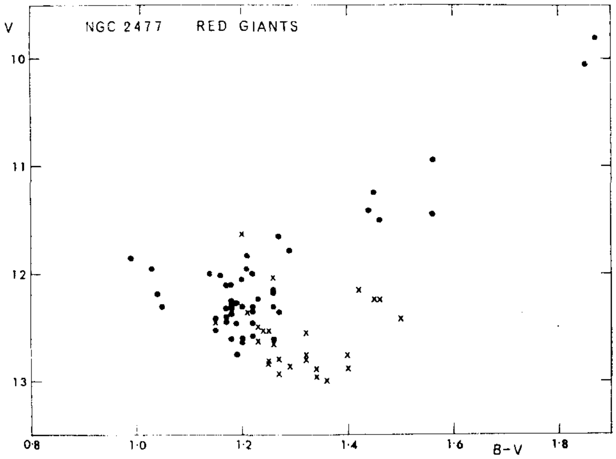

Figure 1.

There are very few clusters with sufficient red giants to provide a good check on theoretical models. One of the richest is the Southern cluster NGC 2477, and I have obtained photoelectric observations for about 75 red giants in this cluster. The aim was to find the internal structure, if any, of the clump in the C-M diagram. The C-M diagram of the cluster[8] is similar to that of NGC 7789. Figure 1 shows only the red giant region; filled circles represent stars lying within 7′ of the cluster centre, crosses represent stars in an annulus out to 20′ radius. The observed colours and magnitudes have to be corrected for interstellar reddening, which amounts to $E(B - V) = 0^m.28$. About 85% of the red giants are plotted, the remainder being too crowded for accurate measurement.

The most notable feature of the clump is the unexpected marked difference between stars in the inner and outer zones. This makes a detailed comparison with theory very difficult, since one of the basic assumptions, that the stars in a cluster all have the same age and composition, is apparently wrong. The tendency for clump stars in the outer parts to be on average $0^m.5$ fainter and $0^m.1$ redder than those in the centre is certainly real, having been found also in a preliminary photographic survey, and the internal accuracy of the individual photoelectric observations being certainly better than $\pm^m.05$. Apart from large variation in the basic parameters of age and composition, the only plausible explanation would seem to be a variation in interstellar reddening. However, this is not supported by the U-B versus B-V diagram, which indicates differential reddening of at most $0^m.05$, and it also requires a very special distribution of interstellar matter. If the effect is intrinsic to the stars, a possible explanation is that the clump stars have different core masses, in turn caused by different chemical composition. However, there are several obvious observational checks to be made, in particular is there a similar effect for main sequence stars, and does it occur in other clusters? Existing data are inconclusive on these points.

If attention is restricted to the nucleus of the cluster, a homogeneous sample of stars may be provided. The basic features are a small spread in *B-V* with no evidence of any trend with magnitude, a range of $0^m.6$ in *V*, and a slight thinning out as brightness increases.

A simple explanation for the clump appears to follow from an analogy with the horizontal branch of globular clusters, namely that these red giants are in a post helium-flash phase of evolution, with two energy sources, a He-burning core and an H-burning shell. This was originally suggested by comparison with the horizontal branch models of J. Faulkner,[6] but the identification was tentative because no theoretical models were available for the composition and masses appropriate to old open clusters. New models which fully support this identification will be described in the following paper by D. J. Faulkner.[7]

The principal observational properties of the clump which have to be explained are as follows:

(1) The existence of the clump, which implies a slow phase of evolution lasting about 2.10^8 years for clusters of all ages.

(2) The position of the clump, typically at $M_V = +1$, $B\text{-}V = +1.0$, corresponding to $\log L/L_\odot = 1.6$, $\log T_e = 3.70$.

(3) The size and shape of the clump, which typically covers ranges of $\Delta \log L/L_\odot = 0.25$, $\Delta \log T_e \lesssim 0.02$.

(4) The constancy in position of the clump from cluster to cluster, for cluster ages from 3.10^8 to 10^{10} years, corresponding to red giant masses from 2.25 to 1.0 $M_\odot$.

This last property appears ultimately to be observational evidence that electron degeneracy occurs in the cores of red giants with masses $\lesssim 2.25 M_\odot$, as found theoretically by Iben.[4] All such stars are expected to undergo the He flash, and to begin He-burning evolution with the same core mass, almost independent of the total mass. The luminosities of the clump models are also almost independent of total mass, although they are dependent on core mass.

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Population I Helium Burning Red Giants. Theory

D. J. FAULKNER

Mount Stromlo and Siding Springs Observatories, Research School of Physical Sciences, Australian National University

In the preceding paper, Cannon[1] has outlined the observational evidence for the existence of a distinct concentration of stars near the base of the red giant branch in intermediate-age galactic clusters, which he tentatively identifies with the core helium burning phase of evolution occurring after the helium flash. This paper reports preliminary results of evolutionary calculations to test this identification.

Since the computation of hydrogen shell-burning evolution up the red giant branch is extremely time-consuming, the present calculations have been commenced at the stage immediately following the helium flash. It is assumed that no overall mixing occurs at the flash, so that the composition discontinuity at the hydrogen-burning shell remains sharp. The initial stellar composition was set at $(X, Y, Z) = (0.68, 0.30, 0.02)$, corresponding to Population I material.

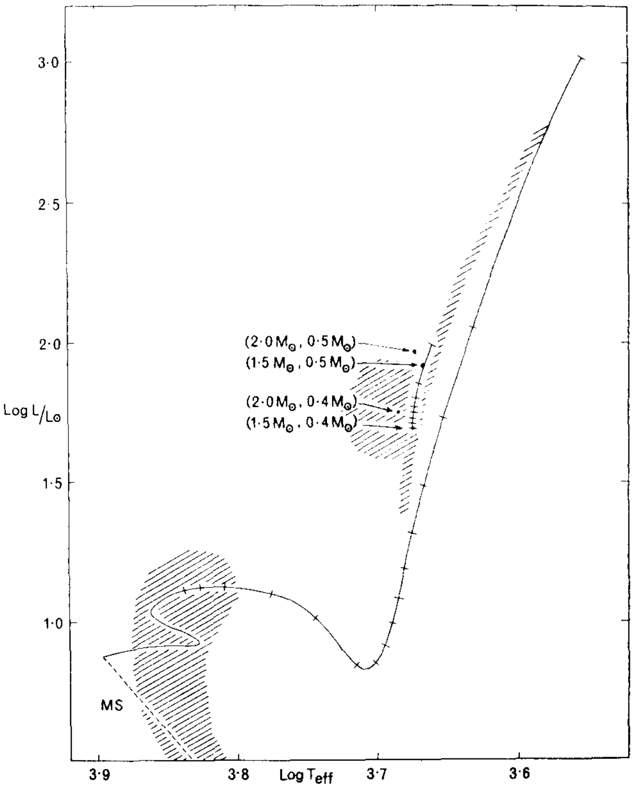

Figure 1. A comparison of the evolutionary tracks for the red giant and helium core-burning stages, with the observed stellar distribution for NGC7789 (shaded). The bracketed parameters are the total mass, and core mass, for the initial helium-burning models. Time markers are at intervals of 25 million years.

Each initial clump-star model is characterized by two parameters, *M*, the total mass of the star (which is known only approximately from a comparison of cluster observations with theory), and M_c, the mass contained within the hydrogen-exhausted core (which is also known only approximately since the red giant evolution to the helium flash has not been performed in every case). Two values were chosen for *M* (1.5 $M_\odot$ and 2 $M_\odot$) and two for M_c (0.4 $M_\odot$ and 0.5 $M_\odot$), and initial clump-star models were obtained for all four combinations. The locations of these models in the Hertzsprung-Russell diagram are indicated in Figure 1. It will be seen that all four fall close together. The position of a model is almost independent of total mass *M*, but the luminosity increases slightly with increasing core mass M_c.

For each of these initial models the hydrogen shell-burning remains the dominant energy source. Helium-burning in the convective core contributes only 12-13 per cent of the luminosity for the $M_c = 0.4\ M_\odot$ models and 21-23 per cent for $M_c = 0.5\ M_\odot$. The extent of convection in the helium core ranges from a mass fraction of 0.046 for the (2 $M_\odot$, 0.4 $M_\odot$) model, to 0.080 for the (1.5 $M_\odot$, 0.5 $M_\odot$) model. Neutrino energy losses