CONCLUDING REMARKS

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The following remarks cannot possibly be a summary of the wealth of data and ideas which were presented and discussed during this symposium. May I rather indicate a broad-brush picture for late stellar evolution as it seems to me to emerge from the many diverse investigations we have heard about. Before doing so, however, I would like to touch on one subject that is not directly connected with late evolution phases but may turn out to be relevant to it.

A. MISSING SOLAR NEUTRINOS

I consider the negative result of the solar neutrino test a sufficiently serious matter that I would not want simply to ignore it. It is true that our present theory of stellar evolution has so many substantial contacts with observational data that it is hard to believe that any required corrections would entirely alter the picture. Nevertheless, we surely cannot feel safe as long as a test as fundamental as the solar neutrino test is strongly discordant with our predictions. Resolution of this discrepancy may lie in any one of three fields: the solar neutrino detection experiment itself, the nuclear physics built into our stellar structure theory, or the rest of the physics and mathematics that goes into our model stars. For each of us it is easy to persuade himself that the resolution of the discrepancy must lie in one of the two fields other than the one in which our expertise lies. However, if all of us follow this natural reaction and in consequence do nothing about the neutrino discrepancy, its resolution is not likely to come forth soon. Accordingly, it would seem to me more effective if we all accepted the working hypothesis that the actual problem lies in our own field of expertise, kept an active watch for any new ideas relevant to this critical discrepancy, and tried to work them out whenever they lie in our field of specialty.

B. EVOLUTION CLASSES OF STARS

Now to the broad-brush picture of advanced stellar evolution. To sort out the great variety of phenomena we have heard about and have discussed during the past three days it would seem to me useful to consider all stars in terms of four evolution classes. Even though these classes will divide all stars more or less according to their initial mass, it would seem to me more useful to base the definition of the classes on the nuclear processes dominating the entire life of a star, most specifically the late part of its life, rather than on fixed mass limits.

C. FEATHERWEIGHT STARS

Under this name we might understand that class of stars which during their entire life never burn nuclear fuel – except possibly such minor fuels as deuterium and lithium. Such a definition implies masses of less than about 0.07 $M_{\odot}$. This class of stars has

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not entered the discussions of our symposium, for good reason: their entire life is dominated by nothing other than contraction, cooling and steady decrease in luminosity. However, in the study of the stellar content of our Galaxy featherweight stars may not be ignorable. Indeed, recent new observations have caused a lively discussion about the relative frequency of stars of low luminosity among which featherweight stars might well be the dominant component. Accordingly, it seems to me that the further studies of this class of stars, specifically, the tracks in the Hertzsprung-Russell diagram, and most importantly, their cooling rates, may become an important contribution for the determination of the stellar content of our Galaxy.

D. LIGHTWEIGHT STARS

Let us include in this class all stars which burn hydrogen and helium but never in their life reach carbon burning. This class contains at its bottom end a sub-class of stars burning only hydrogen but never reaching helium burning. We have not considered the evolution of this subclass during the symposium nor do I want to do so now. For the bulk of the stars in lightweight class which burn both hydrogen and helium, there seems to exist ample observational evidence that mass ejection plays a decisive role during the late red-giant phases. A major portion of this mass ejection may appear in the form of planetary nebulae. From the theoretical side, excessive ionization energy, radiation pressure – particularly if ample grain formation occurs in the extended atmospheres – and runaway pulsations appear to be the main causes of this mass ejection. However, our quantitative knowledge of the mass ejection process is clearly still insufficient to determine with satisfactory accuracy the rate and extent of the ejection. One of the consequences of this uncertainty is that we do not yet know with any accuracy the upper limit of the initial mass of the stars belonging to this class. A reasonable working value appears to be 4 $M_\odot$. However, we have heard emphatic warnings that this value may require substantial revision. Fortunately one result seems to be little affected by the uncertainties regarding the extent of mass ejection: the end product of a lightweight star is nearly certainly a white dwarf.

E. MIDDLEWEIGHT STARS

It would seem useful to define this evolution class as containing those stars which not only burn hydrogen and helium but reach temperatures required for carbon burning in a degenerate core. This last condition permits one to determine the upper limit for the initial mass of middleweight stars with some accuracy: 8 $M_\odot$ appears to be a good working value (barring unexpectedly high mass ejection at relatively early evolution phases). Regarding the final fate of middleweight stars, the discussion during this symposium seems to me to indicate that at this moment we cannot choose between two quite different versions. In version A the carbon burning in a highly degenerate core leads to a complete explosion, with the nuclear reactions going all the way to the iron peak elements and with no dead remnant left. In version B the carbon burning is effectively subdued by URCA neutrino cooling. This postpones the end but not for long since the degenerate core will soon reach the Chandrasekhar limit, whereupon it must catastrophically collapse with the possible consequence of ejection of the envelope and formation of a neutron star. A decision between these two versions from the theoretical side depends, if I understand correctly, mainly on a more precise assessment of the efficiency of URCA cooling, an obviously difficult topic. From the observational side we have listened to discussions suggesting that a plausible decision between the two versions might be achieved either by a comparison of the birth rate of neutron stars (derived from pulsar observations) with the death rate of stars belonging to different evolution classes, or by a comparison of the relatively high rate of iron peak element production under version A with spectroscopic observations. Finally, both versions appear to lead to the conclusion that the death of middleweight stars leads to a type of supernova.

F. HEAVYWEIGHT STARS

This class of stars should comprise the top end of the stellar mass scale and might be defined as containing those heavy stars which are capable, after hydrogen and helium burning, to enter carbon burning in a non-degenerate and hence non-explosive manner. In spite of the success of a heavyweight star in surviving the carbon burning phase, the discussions during the symposium have left me with the impression that there exists no plausible alternative to an eventual gravitational collapse of at least the core if not the entire star. In spite of the remarkable progress that has been made in detailed dynamical calculations, including great grids of nuclear reactions, calculations which surely point the way to the necessary future steps, it still seems hard at this time to speculate regarding the actual outcome of the death of a heavyweight star. It appears to me highly likely, at least for the upper mass end in this class that a substantial fraction of the stellar mass will form a black hole. On the other hand, the amount and, most importantly, the chemical composition of the mass ejected at the death of a heavyweight star still seems fairly uncertain. On one point we seem tacitly to agree: the death of a heavyweight star is not likely to occur with less visibility than that of a supernova event.

G. RESULTS OF STELLAR DEATHS

The simplest, though far from proven, picture that one may draw from our discussions during the last three days seems to me as follows. At their death lightweight stars produce white dwarfs, middleweight stars produce neutron stars and most heavyweight stars produce black holes. Supernovae occur at the death of both middleweight and heavyweight stars. Most of the enrichment of the interstellar matter in heavy elements is due to the ejection of processed material at the death of middleweight and heavyweight stars, though the relative importance of these two evolution classes in this process is far from clear. The role of lightweight stars for the heavy element enrichment of the interstellar matter appears likely to be small and probably restricted to special items such as carbon and the s-elements. Obviously, a broadbrush picture such as this one, with its over-simplifications and its gross uncertainties, should be looked at as nothing but a set of possible targets to be shot down or to be solidified.