CONCLUDING REMARKS

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In commencing this personal review of what we have heard in this Symposium, it is a great pleasure to congratulate Professor Hayashi on his 60th birthday today. For those participants like myself who were working on stellar evolution more than twenty years ago, the appearance of the famous review article by Hayashi, Hoshi and Sugimoto was a landmark in our subject. Together with Schwarzschild's book a few years earlier it marked the close of the second stage of the subject in which quite elaborate calculations had been made, but in which the contribution of the electronic computer was still small. The first stage in the subject perhaps ended with the publication of Chandrasekhar's book in 1939. What is obvious in this Symposium is that Professor Hayashi has created a very flourishing research school and that young Japanese astronomers are making many important contributions to the present third stage in the subject.

The principal emphasis in the subject has changed in the past twenty years. Then we were mainly concerned with the evolution of single stars and we used stellar systems, such as globular clusters, to give us information about single stars which we could not obtain if they were truly isolated. Now the emphasis has switched to the problem of galactic evolution; can we understand the variation of properties from place to place inside one galaxy and from one galaxy to another in terms of star formation, stellar evolution and nucleosynthesis and stellar mass loss, either quiet or catastrophic? The study of stellar birth and stellar death remains difficult and we continue to be grateful that the long main sequence lifetime enables us to discuss stellar evolution without understanding stellar birth.

There has been essentially nothing in this Symposium about main sequence and post main sequence evolution of single stars except a discussion of the influence of rotation and magnetic fields. This is not because there are no fundamental problems. The topic of mass loss was excluded from the Symposium at the request of the IAU Executive Committee, because it has recently been discussed at other IAU supported meetings. There are still some uncertainties in the opacity, nuclear

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energy release and equation of state, although we may believe that these are relatively unimportant in early evolutionary phases. We cannot forget the solar neutrino problem even though we may hope that this will be solved by something outside stellar evolution such as the recently reported neutrino mixing. Above all there are serious problems involving stellar hydrodynamics. For example, UV observations are telling us that chromospheres, coronae and mass loss are much more common than was previously believed. We still lack a good theory of convection and of semi-convection. Mixing processes and mass loss which may seem relatively unimportant at the time that they occur may nevertheless have significant effects on later stages of evolution.

One fundamental problem that has not been raised in this Symposium, except perhaps in Mirzoyan's discussion of the formation of stars from very compact protostars, is whether the presently established laws of physics are adequate for the subject of stellar evolution. We have heard nothing of such things as variable G. Although we must be ready to accept changes in the laws of physics if they prove necessary, I am personally happy that the present laws provide all the necessary complications.

I now turn to points which have been specifically discussed in the Symposium. For single stars we have mainly been concerned with birth and death. The development of large computers has meant that it has been possible for much more ambitious calculations to be performed and for more physical processes to be included. However this has not always led to greater agreement amongst different workers either about the method of star formation or about the mechanism of supernova explosions. It is in fact quite easy to understand why both of these topics should present serious problems.

Consider first star formation in the solar neighbourhood. There remains between ten per cent and twenty per cent of matter in the form of interstellar gas. If we assume that stars are primarily formed as a result of compression in spiral shocks, it is clear that the fraction of gas used up in each passage through a shock is very small. If we had neither observations of dense clouds nor calculations of cloud collapse and fragmentation, we could consider two extreme possibilities. In the first we could assume that only a small amount of gas is compressed but that star formation is very efficient; in that case it might be easy to understand star formation once a dense cloud had formed. In the second case we could assume that all the gas is compressed but that star formation is very inefficient. In fact, both the observations of dense clouds and the calculations presented at the Symposium suggest that star formation is very inefficient. This means that it may be very difficult to obtain a definite result. We have seen that different workers are getting quite different answers, but what is impressive is that they are unanimous in saying that their results may not be correct. That in itself implies that the problem is difficult. There are obvious numerical problems involved with spatial resolution and with the existence of very different timescales. Because of these difficulties and of the variation of results from author to author, I hope that those working in the field will try to tell us what can be done and what cannot be done with the present, and indeed the next, generation of computers.

Consider next the final stages of stellar evolution. Despite many attempts to calculate the explosions of supernovae, there is no clear agreement about how a supernova is formed and what is its end product, although Wheeler and Nomoto gave us very impressive accounts of the highly detailed work which is at present being undertaken. What we particularly wish to know is what is the degree of mass loss in the explosion, what is its chemical composition and whether the end product is a neutron star, a black hole or nothing. Again it is obvious that the solution of the supernova problem must be difficult. If a stable neutron star is to be formed, the binding energy of such a star must be dissipated. However, the binding energy of a neutron star is several orders of magnitude greater than the energy obviously released in a supernova explosion. Most of the energy is probably lost in the form of neutrinos and gravitons and it is hardly surprising that it is difficult to determine whether the relatively small amount of energy required to remove the outside of the star is deposited in the correct place at the correct time.

A topic which was not discussed in the Symposium was the relation between the total numbers of neutron stars, visible supernovae and supernova remnants. The production rate of neutron stars appears to be significantly greater than that of supernovae and supernova remnants and we have heard that the explosions of supernovae may produce black holes or nothing. It is important to know whether a neutron star can ever be produced without either a visible supernova display or a subsequent optical or radio supernova remnant. Wheeler suggested that in one mass range neutron star production might not be accompanied by a visible supernova but that case would not make much difference to the total numbers. It is possible that, as has been suggested, many supernovae explode deep inside dense clouds and that neither they nor their subsequent remnants are observed and this possibility requires further investigation.

We heard from Lucy that there are at present difficulties in a numerical study of either of the more popular ideas concerning the formation of binary stars, fission and fragmentation. Numerical studies do indicate the formation of binary stars but they do not at present give the mass ratios most commonly observed. However we know that binary stars are common and that many of the most exciting objects in the Galaxy are included in binary systems. This is perhaps one of the two major developments in the theory of stellar evolution since the review by Hayashi, Hoshi and Sugimoto, the other being the recognition of the importance of mass loss. A further major development is in the attitude of astronomers. Although neutron stars had been discussed in 1934 and black holes in 1939, it was still a common belief amongst astronomers in the early 1960's that all stars must end their lives below the

Chandrasekhar mass as white dwarfs. At that time astronomers only believed what they saw and they did not see neutron stars and black holes; now they are much more likely to believe what they are told.

As we have heard, the number of stars which will become close binaries at some stage in their evolution is very large indeed. It is no longer sufficient to say that single spherical stars are the rule and close binaries the exception. Tutukov and van den Heuvel presented us with a variety of scenarios for the evolution of binary systems to form objects of all of the observed types and probably some others as well, but I think that they would agree that there are many difficult details to be discussed before the scenarios become real theories. We have heard about the problems of mass and angular momentum loss from the binary system and there may also be important effects due to departures from sphericity of the component stars. Once again we perhaps need a realistic assessment of what is the most that can possibly be included in numerical calculations in the foreseeable future and whether it is inevitable that progress must be made by ad hoc assumptions and comparison with observation.

When we consider planetary formation we have an uncertainty of a different order of magnitude. We know that there are very many binary stars, so that binary star formation must be an almost natural event. We have no idea how many planetary systems there are. We may have a post-Copernican prejudice that there is nothing very special about the Sun, but whether almost every G dwarf has a planetary system or whether less than one per cent have planets will make considerable difference to the difficulty of numerical work on the formation of planets. If we believe that the observed rotation speeds of main sequence stars tell us that late type stars have discs and planetary systems, that may be a clue; however the loss of angular momentum by stars with convective envelopes is probably very different from that by stars with radiative envelopes even in the absence of disc formation. The early stages in the formation of a planetary system were not discussed in this Symposium but Hayashi presented a very detailed theory of how the planets are formed once the protoplanetary disc is in existence.

We have heard two very interesting review talks about shell flashes in accreting degenerate stars. For someone like myself who almost runs away if the word computer is mentioned, it was very refreshing to hear Sugimoto's semi-analytical discussion of the occurrence of shell flashes. He did well to remind us that, if we do not have a physical understanding of what comes out of a computer, we shall have great difficulty in making progress. It is however equally true that, as Kippenhahn commented, it may be difficult to estimate the ultimate effect of an extremely large number of flashes, either by semi-analytical methods or by direct computation. The study of non-linear systems with two or more very disparate timescales is inevitably difficult. Having said that, it is very gratifying that the theories and observations of X-ray bursters appear to be in such good qualitative agreement.

Most stars rotate and contain magnetic fields. There are various effects related to them. The first is simply that of departures from spherical symmetry, if the rotation velocity or magnetic field strength is sufficiently great. However, even when departures from sphericity are small, we have problems related either to the lack of genuine equilibrium or to the occurrence of new instabilities. I do not think that either Kippenhahn or Mestel will complain for long if I say that we gave them an impossible task to discuss the effects of rotation and magnetic fields on stellar evolution and that they did not succeed. What they did do was very relevant to the subject of this Symposium. They demonstrated that there are very important fundamental problems related to rotation and magnetic fields which must be understood before they can be included with confidence in calculations of stellar evolution.

What for example is the natural rotational state of a star? Is it one of solid body rotation or a state nearer to constant angular momentum per unit mass? Given that many configurations are unstable, is the time for significant redistribution of angular momentum short compared to evolutionary timescales or is it long? Kippenhahn expressed a personal preference for a rather long time which would mean that in at least some cases what appears to be unstable differential rotation might survive. In the case of magnetic fields, we again have the prediction of many instabilities for magnetic fields of simple topology but as yet there are no good discussions of their non-linear development. At present I do not think that we have any convincing evidence in favour of "fossil" magnetic fields but we do have evidence that some fields must be produced by dynamos. Although both white dwarf and neutron star fields may be produced by approximate flux freezing in the collapse of a normal star, it is also possible that, as has been suggested in the case of pulsar formation, there might have been a dynamo process at the time of the collapse. In that case, even though the field is not at present being maintained by a dynamo, it will not be possible to relate it to the field at earlier stages of evolution. If magnetic fields do exist at all evolutionary phases, they couple different layers of a star in a manner which must strangely inhibit purely rotational effects.

In addition to the fluid dynamical effects related to rotation and magnetic fields, we cannot forget convection. Convection was not made a central theme of the present conference because it is only four years since an IAU colloquium was devoted specifically to this topic. This does not however mean that the problem has been solved. We continue to use the mixing length theory with its free parameter because we lack a better theory and there are particular uncertainties related to time dependent convection in variable stars. One role of convection and semi-convection is to mix different layers in a star. As several speakers have indicated there are less violent mixing processes caused by instabilities which may also have important effects.

To conclude, I select two fundamental problems which I believe to require particular attention before we can hope to be fully satisfied with our knowledge of stellar evolution. These are:

1) Numerical methods. We need to know what can be done and what cannot be done with the present and immediately foreseeable computers. There is no point in doing ever more elaborate calculations unless we can be certain that, given the physical input, the results are reliable;

2) Fluid dynamics. A major source of uncertainty at most stages of stellar evolution is mass loss and mixing. Can we hope to develop a true theory of mass loss and mixing or must we continue to have parametrised models which we try to fit to observation?