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IV. STELLAR STRUCTURE AND STELLAR EVOLUTION

(*a*) *General*

A general review of the problem of stellar evolution has been written by C. Hayashi, R. Hôshi and D. Sugimoto (**1**) which contains also original contributions or suggestions concerning various points which are reviewed in their respective sections. R. L. Sears and R. R. Brownlee have also prepared a general account (**2**) in which computational methods, evolutionary models and evolutionary tracks and their application to the determination of cluster ages are reviewed. To these we may add the lectures of M. H. Wrubel (**3**) which present a concise and very clear summary of the main physical and methodological aspects of the problem.

L. Henyey (**4**) has prepared a general account of the revised numerical methods used in his latest programme to compute evolutionary sequences complying as much as possible with the actual physics of the conditions encountered.

On the basis of a discussion of the ages of hot stars (under different assumptions for their evolution) and cold stars (still in the stage of gravitational contraction) in the Orion Nebula, A. G. Massevitch and E. V. Kotok (**5**) conclude that the duration of the process of star formation in this cluster is considerable of the order, of the age of the cluster itself.

(*b*) *Pre-main Sequence Contraction*

In a very important and now well-known paper, Hayashi (**6**) has shown that contracting stars in the low luminosity, low temperature part of the H-R diagram cannot be in equilibrium. Readjustment of the boundary conditions at the photosphere show that a gravitationally contracting star will be in convective equilibrium throughout its whole mass during a considerable part of this contraction and that the corresponding track in the H-R diagram will be very different from the usual radiative one and nearly vertical offering a possibility of explaining the H-R diagram of very young clusters like NGC 2264. This also reduces very considerably, especially for small masses, the duration of the contraction phases. The consequences for small mass stars are further discussed in (**1**, §10) ($M \simeq 2$ to $0{\cdot}6\ M_\odot$) and applied to the M-type stars in the Orion Nebula indicating masses of the order of $0{\cdot}1$ to $0{\cdot}2\ M_\odot$. It is also shown that for stars with $M < 1{\cdot}3\ M_\odot$, lithium but not beryllium may just burn at the bottom of the convection zone as they complete their evolution towards the main sequence. This discussion has been extended by Hayashi and Nakano (**7**) down to masses as small as $0{\cdot}05\ M_\odot$ taking also into account the dissociation of H_2 in the external layers. In following the contraction, they find that H-burning occurs for $M > 0{\cdot}08\ M_\odot$ but not in stars with $M < 0{\cdot}08\ M_\odot$ which contract directly to degenerate configurations. On reaching the main sequence, stars of the first group which may be compared with actual red dwarfs develop a radiative core if $M > 0{\cdot}26\ M_\odot$ while they remain wholly convective if $0{\cdot}25\ M_\odot \geqslant M \geqslant 0{\cdot}08\ M_\odot$. The Helmholtz-Kelvin time scale for these small masses is much reduced with respect to the previous radiative gravitational contraction, perhaps by as much as factor of 100 and, as shown by Kumar (**8**), cannot be much larger than 10^9 years.

The case of the Sun has been discussed by Weymann and Moore (**9**) who confirm Hayashi's result that such a star remains wholly convective as long as $T_{eff} < 4300°$ and show that the question of the depletion of lithium by the implicated mixing down to regions of fairly high temperatures is very delicate. This same problem has been discussed by Cameron and Ezer (**10**) who find a greater probability for lithium burning. General energy considerations on the dynamical instability arising in the early phases of contraction ($R > 57R_\odot$) due to ionization of H and He and dissociation of H_2 are also presented in (**10**) while comments on the 'jump' of a proto-star to a state of convective quasi-static equilibrium are contained in (**1**, §10).

The general problem of the convective phases of gravitational contraction has been re-investigated by Faulkner, Griffiths and Hoyle (**11**) who find that no factors related to the opacity or non-thermodynamic processes are likely to destroy the convective structure. However, they suggest that the presence of a magnetic field might have reduced very much the efficiency of convection at some phases, particularly when the planetary material separated from the Sun.

(*c*) *Main Sequence*

Using homogeneous models, Iben (**12**) has critically discussed the assumption of a universal 'age-zero' main sequence independent of composition and its consequences as far as cluster ages are concerned. He finds, in particular, that the helium-content of the Hyades and Pleiades cannot be the same and raises the question of the possible variation with chemical composition of the ratio (l/H) of the mixing-length to the scale height. Faulkner, Griffiths and Hoyle (**13**) also report work in preparation on this question from which it results that with realistic assumptions the more probable compositions yield a fairly narrow main-sequence band.

I. M. Kopylov (**14**) has evaluated the main parameters $(S^0_p, (B-V)^0, R^0, T^0_{eff}, M^0_{bol}, M^0_v)$ of the initial main sequence by linking through M the theoretical sequence of homogeneous stellar models with the observed (M, Sp) relation for spectral classes O5 – M5. The resulting values of Sp^0 and M^0_v are in good agreement with the initial main sequence evaluated from distances to galactic clusters ($\Delta M_0 \cong \pm 0^m.15$ except for spectral types O5–O7 and K7–M5 in which they may reach 1^m). An analogous procedure can be used (**15**) to yield a new scale of effective temperatures (Sp, T_{eff}) which is in good agreement with the relation (T_{eff}, Sp) obtained from models of stellar atmospheres but deviates substantially from Kuiper's scale, especially for types O5–O7 and B9–A5.

The lower main-sequence of Population II stars has been studied by P. Demarque (**16**). Kumar (**17**) has discussed the structure of wholly convective stars of very low masses (0·1 to 0·04 $M_\odot$) for different chemical compositions to determine the limiting masses (0·07 $M_\odot$ for Pop. I; 0·09 for Pop. II) under which H-burning never occurs (cf. also **7**). In view of determining the limits on solar neutrino fluxes, Sears (**18**) has computed an extensive series of solar models in a range covering the uncertainties in the different parameters (composition, opacity, age, nuclear cross-sections) which may affect these fluxes.

Boury (**19**) has published his results on very massive stars (up to 6000 $M_\odot$) formed initially of pure hydrogen. A somewhat similar investigation with comparable results has been carried out by Van der Borght and Meggit (**20**).

(*b*) *Post-main Sequence evolution*

Work on the giant branches of clusters is going on and a general discussion embodying various improvements in the physics of the models has been published by Demarque and Geisler (**21**). Their results which cover the effects of a slight variation in the mass and those of independant variations of the initial metal and helium content reproduce fairly well the observed slope of the giant branch but the helium content remains undeterminate. R. L. Sears (**22**) is constructing evolutionary sequences for stars of appropriate mass and composition to determine the ages of the globular cluster M_2 and NGC188. In this respect, one may recall the restriction on these ages imposed by the fuel supply limit as discussed by Woolf (**23**).

Faulkner, Griffiths and Hoyle (**24**), on their side, report that work in progress tends to show that the shape and position of the giant branches are determined solely by surface composition.

Härm and Schwarzschild (**25**) have continued their investigations of the helium flash in Population II stars but the question of whether or not this leads to a total mixing of the star cannot yet be answered. In discussing these same phases, Hayashi, Hôshi and Sugimoto

(**1**, § 6) find that stars with $M < 0{\cdot}53\ M_\odot$ never reach the region of the helium-flash their evolutionary tracks turning to the left before that and bringing them down later to the white-dwarfs region.

Considerable success has also been achieved by now in following the post-main sequence evolution of stars much heavier than the Sun. From the study of a star of mass equal to $47\ M_\odot$, Sakashita and Hayashi (**26**) concluded that the effects of the transition semiconvective zone which, in heavy stars, develops between the convective core of increasing molecular weight and the envelope remain small.

The evolutionary tracks of stars of 4 and 5 $M_\odot$ were computed in details up to the onset of helium burning by Hayasho, Nishida and D. Sugimoto (**27**) and by Pollak (**28**) respectively.

C. Hayashi and R. C. Cameron (**29**) have followed the evolution of a Population I star of $15{\cdot}6\ M_\odot$ and initial composition $X = 0{\cdot}90$, $Y = 0{\cdot}08$, $Z = 0{\cdot}02$ through the stages of hydrogen exhaustion in the convective core, subsequent contraction of the core leading to helium burning and finally the onset of carbon burning. In about $1{\cdot}4\ 10^6$ years this leads the star from the main sequence to the region of the M-supergiants, the main gap being crossed in only $2{\cdot}10^4$ years. According to the same authors (**30**) these very late stages (C, Ne and O-burning) could account for the giant branches of clusters such as *h* and χ Persei only if the neutrino loss due to direct electron-neutrino interaction is disregarded.

G. V. Ruben (**31**) has constructed a homogeneous model for $M = 5{\cdot}2\ M_\odot$, $X = 0{\cdot}90$, $Z = 0{\cdot}01$ and four inhomogeneous models with an isothermal core and transition layer (for $M = 3{\cdot}8\ M_\odot$, $X_e = 0{\cdot}90$, $Z_e = 0{\cdot}01$; $M = 5{\cdot}2\ M_\odot$, $X_e = 0{\cdot}90$, $Z_e = 0{\cdot}02$, $0{\cdot}01$, $0{\cdot}003$) as a start for the study of the evolution of the components of the binary system γ Leo. Similar work has been carried on by U. K. Dservitis (**32**) to check the sensitivity of the models on different parameters while the evolution from the main sequence of stars of masses greater than $10\ M_\odot$ is being tackled.

E. Hofmeister, R. Kippenhahn and A. Weigert (**33**) have carried the evolution of a Population I star of $7{\cdot}0\ M_\odot$ from the main sequence through the exhaustion of hydrogen in the core, helium burning, exhaustion of helium in the core and the formation, besides the previously established hydrogen burning shell, of a deeper helium burning shell to the point where the carbon burning temperature is reached. They find that this evolutionary track crosses five times the Cepheid strip.

Other work in progress is also reported from Caltech: by A. Boury (**34**) on the evolution of a $30\ M_\odot$ model through 3α-burning to stages of C^{12}, O^{16}, and Ne^{20}-α burning (the effects of assuming that C^{12}-α-burning is faster or slower than the 3α-burning will be discussed); by I. Iben, Jr. (**35**) for a whole range of masses ($0{\cdot}1\ M_\odot < M < 30\ M_\odot$) including the Hayashi contracting phases and, for the small mass stars (no He flash), their cooling to the white dwarfs stage.

P. Pochoda and M. Schwarzschild (**36**) have investigated the evolution of the Sun under the assumption that the gravitational constant has been steadily decreasing in the past.

(*e*) *Late Stages of Stellar Evolution*

Some of these stages were already encountered in the previous subsection as the natural end of evolutionary sequences but, in some cases, they can also be studied by themselves without a detailed description of their previous history. White-dwarfs provide a good example in this respect and Mestel (**37**) has prepared a general review of the present state of their theory. On the basis of a discussion by Kirzhnitz (**38**) of the effects of potential barriers in dense matter on the *p*-*p* chain, Seidov (**39**) found that this chain would be 10^5 to 10^8 times slower in white dwarfs than in ordinary stars. This, according to the author, would permit an internal abundance of hydrogen as high as several percents, a conclusion which should however be revised in the light of the corrections introduced by V. P. Kopyshev (**40**).

Coulomb and beta-decay corrections to the equation of state were calculated for a high-density plasma by Salpeter (**41**) and used by Hamada and Salpeter (**42**) to construct white dwarfs models with and without discontinuities in chemical composition. In Paris, A. Baglin (**43**) is working on white dwarfs models with finite (non zero) temperatures.

Savedoff (**44**) has evaluated the total energy (gravitational + kinetic energy of electrons) of completely degenerate configurations for a series of values of the degeneracy parameter. He has also discussed (**45**) the evolution of energy-free gas into white dwarfs with a view to evaluating their age. He finds that the pressure of the non-degenerate nuclei couples with the gravitational field to give a contribution larger by a factor of the order of three than that given by the internal energy only. Further detailed numerical work on this problem is being carried on by S. Vila.

Integrations for highly degenerate isothermal cores ($\Psi_c \cong 70$ to 200) of collapsed stars have been performed by K. Kaminisi (**46**).

Models for pure He-stars have been published by J. B. Oke (**47**) and J. P. Cox and R. T. Giuli (**48**). M. Nishida and D. Sugimoto (**49**) as well as J. P. Cox and E. E. Salpeter (**50**) have discussed models with a hydrogen-rich envelope and the location of their representative points in the H-R diagram. With W. Deinzer (**51**) these last authors have now built models for pure helium stars, including the effects of degeneracy and radiation pressure, for a large range of masses and they find that the minimum mass allowing helium-burning is 0·35 $M_\odot$. The build-up of C^{12} and O^{16} as the core burns out was also calculated. Some of the problems related to stars with helium-rich cores were reviewed by Kippenhahn in his Varenna lectures (**52**).

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V. STELLAR PULSATIONS AND STABILITY; SHOCK WAVES AND NON-STATIONARY PROCESSES IN STARS

Some aspects of the current interpretation of Cepheids have been reviewed by Ledoux and Whitney (1) and Zhevakin (2) has written a clear and up-to-date account of the pulsation theory of variable stars. The latter has continued his investigations (3) on stellar variability due to the vibrational instability arising, mainly in the second ionization zone of helium assumed in radiative equilibrium, on account of the reduction of the Γ's (and consequently of the temperature variations) and the behaviour of the opacity there. On the basis of the linear nonadiabatic pulsations of his 'discrete' models, Zhevakin has discussed in great detail the phase-shift between the radiation flux and the radial velocities and the factors that affect it in view of explaining the peculiarities of this phase-shift in different types of variable stars.

The de-stabilizing influence of the second helium ionization for stars in the general vicinity of the Cepheids strip has been confirmed by the detailed investigations of Baker and Kippenhahn (4) and J. P. Cox (5) provided that the main transfer of heat there be by radiation and not by convection as detailed investigations seem indeed to indicate.

As to the exact location of the zone of maximum (linear) instability in the H-R diagram one might expect on general ground that it should coincide rather exactly with the actual Cepheid strip providing, at the same time, an explanation of the Period-Luminosity relation. Detailed computations (6) however seem to show that it is shifted to the right by about 600° in effective temperature.