35. STELLAR CONSTITUTION (CONSTITUTION DES ÉTOILES)

PRESIDENT: A. G. Masevič.
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During the period under review, theoretical work in the field of stellar constitution and evolution of stars has been effectively continued by several teams permanently working in Belgium, Denmark, France, German Democratic Republic, German Federal Republic, Italy, Japan, Poland, the United Kingdom, the U.S.A., the U.S.S.R. as well as by individual scientists in Argentina, Bulgaria, Czechoslovakia, India, Sweden and others. Most attention has been given during the past three years to analysis of late stages of stellar evolution, rotation, evolution of binaries, loss of mass on various stages of evolution, stellar stability, neutrino astrophysics, physical processes in the pre-supernovae stage. The discovery of pulsars has raised extremely the general interest for white dwarfs and neutron stars, and consequently the number of papers with new hypotheses concerning quasi-stellar sources has substantially dropped.

Many new evolutionary sequences of stellar models for various masses and different chemical compositions have been computed using improved numerical techniques and large computing programs. It is regretted that many of these results are difficult to compare mainly because of the differences in the input physics and the way the numerical results are being published. This is a field in which a closer international co-operation is highly desirable, especially on the following points: exchange of ideas on the programs presently under way and the planned programs in order to avoid unnecessary duplications: agreement on the numerical results which should be published; exchange of technical informations: (input physics, computing methods, detailed results of computations, opacity tables, etc.). Several attempts in this direction have been undertaken during the period under review (for example, Commission 35 Circular Letters NN 1–7 containing information on current work, publication by the U.S.S.R. Academy of Sciences of the Cox and Stewart's Opacity Tables for 23 mixtures, several joint international projects for using the same programs, etc.), but the problem still remains to be solved.

A large discussion has followed the new results of the solar neutrino experiment resulting mainly in a reexamination of the nuclear reactions rates and the theoretical analysis of the solar interiors. It is somehow disappointing that several investigators (luckily only a few) have taken this opportunity to shed doubt on the theory of nucleosynthesis in stars in general.

It should be mentioned that less attention has been devoted recently to comparisons between theoretical results and observations. This is due to the fact that such a comparison requires uncertain theoretical transformation of observational data – data that are for most cases incomplete. This is especially true for the effective temperature scale of Red giant stars on very late stages of evolution on which theoretical work has been mostly concentrated. On the other side those comparisons, that actually have been made, are carried out on a noticeably higher level than it has been done before. It should be emphasized that at least for Main Sequence Stars the present theory allows to some extent to improve observations, for example to determine masses and the helium abundance of individual, binary and cluster stars with a very satisfactory degree of accuracy. Evolutionary tracks for late stages of evolution allow to predict observable phenomena concerning ratios of some isotopes in stellar envelopes, etc.

In the past period several international symposia and colloquia have been held, handling problems of stellar constitution, and the respective proceedings have been, or are to be published. As the length of the IAU commission reports has been recently considerably restricted, this Report contains only the following sections: hydrodynamical problems of stellar interiors, stellar instability, evolution of binaries, nuclear reactions in stars, neutrino astrophysics, opacities and numerical techniques relevant to stellar constitution. In choosing the above-mentioned problems it has been taken into account that the problems of mass-loss, pre-main sequence evolution and stellar rotation have been covered recently by the Proceedings of the Colloquium *Mass Loss from Stars*, Trieste 1968, Astrophysics and Space Science Library, Vol.13; the 1969 Elsinore Colloquium "On Mass Loss and Evolution in Close Binaries"; the 1969 Liège Astrophysical Symposium "Pre main Sequence-Evolution" and the Colloquium on Stellar Rotation held at the Ohio State University, Columbus 1969. (See also a review paper of P. A. Strittmatter "Stellar rotation", *A. Rev. Astr. Astrophys.*, 1969, **7**, 665). Quasi stellar objects have been reviewed thoroughly in *A. Rev. Astr. Astrophys.*, **5**, 399, 1967, "Quasi Stellar Objects", by E. Margaret Burbidge; *ibid.*, **6**, 351, 1968, "Variable Radio Sources", by K. I. Kellermann and I. I. K. Pauling-Toth; and *ibid.*, **7**, 527, 1969, "Quasi Stellar Objects", by Maarten Schmidt.

Proceedings of several national colloquia on pulsars are being published (see also an extended review by Maran and Cameron on the Fourth Texas Symposium in 1968). Besides, special meetings on Pulsars and on white dwarfs will take place before the coming IAU Meeting in London.

Also according to the new rules, only selected bibliographical references are given in the Report. A complete bibliography on stellar constitution will be circulated to all the members of Commission 35 before the General Assembly.

I. HYDRODYNAMICAL PROBLEMS OF STELLAR INTERIORS

A. *Radiative zones*

Hydrodynamics enters the theory of convectively stable (sub-adiabatic) stellar zones through the possible presence of non-uniform rotation and through the deviations from a spherically symmetric thermal-gravitational field due to centrifugal and magnetic force. These problems have acquired a renewed interest following the observations by Dicke and Goldenberg (**1**) of a solar oblateness of $5\text{–}10^{-5}$, about five times that induced by the observed surface rotation. Dicke's interpretation in terms of a solar quadrupole moment due to a rapidly rotating radiative core has raised queries about the stability of this model. Howard *et al.* (**2**) and Spiegel (**3**) have suggested that a process would occur analogous to the Ekman pumping, so that a dynamically-driven circulation is set up, with viscous force balancing Coriolis force in the thin Ekman boundary layer. Continuity forces the flow to extend through the bulk, yielding the very short spin-down time.

The treatment of this problem contrasts with that customary for a non-barotropic stellar gas, obeying the law $P \sim \rho T$. A non-conservative field of centrifugal (or magnetic) force can be balanced by suitable variations of ρ and T over isobaric surfaces. The consequent breakdown in radiative equilibrium yields buoyancy forces that drive a generalized Eddington-Sweet circulation. This already sets a possible difficulty for the Dicke model, for in the absence of an inward gradient of mean molecular weight μ, capable of suppressing the circulation as was found by Mestel and Kippenhahn, the postulated large gradient of Ω near the base of the convective zone will yield a substantial modification of the Ω-distribution within a solar lifetime. The question is whether an analogue of the Ekman suction will yield a much shorter spin-down time. The thermally-driven Eddington-Sweet circulation is replaced by a dynamically-driven flow if the scale of variation of Ω is less than $d_c \simeq r \times [(\Omega^2 r/g)(\lambda/r)]^{1/2}$, where λ is the local scale-height. One is led at first to a model in which a rapidly rotating core and a more slowly rotating envelope can co-exist but with the transition region between them always comparable with *dc*. The braking by the magnetically-controlled solar wind would be limited effectively to the convection zone.

The subsequent evolution of the Ω-field (in the absence of magnetic coupling between the two zones) would be given by the Eddington-Sweet theory, with the fairly sharp Ω-gradient and any μ-variations playing an important role. However, a much shorter spin-down time will result if the transition layer were to become unstable. One would then arrive at a picture in which the slow but persistent braking of the star would drive a weak turbulence in the sub-photospheric radiation zone.

According to Howard *et al.* (2) one may suggest that the Li depletion could be qualitatively explained by the presence of turbulence below the convection zone. A very important observational correlation between the Li content and the rotational velocities of solar type stars has been found by Conti (4). He finds that stars that still have appreciable rotation have the greater Li content. This means that they had less Li destruction. Conti's work has to be considered as the first quantitative result in favour of the above-mentioned phenomenon (see also the review paper by Wallerstein and Conti (5)).

The importance of mass motions in radiative zones arises in studies of gravitational separation of the elements. Schatzman (6) considers main-sequence stars of masses ranging from 1 $M_\odot$ to 1·6 $M_\odot$, with sub-photospheric convection zones that decrease greatly in depth and mass along the sequence. The violent turbulence in the convective zone is expected to keep the composition uniform, but gravitational separation of the elements can occur in the radiative zone, at a rate proportional to the microscopic diffusion coefficient λ_D. The separation of the elements would be negligible in the sun, but would be effectively complete in stars of mass greater than 1·25 $M_\odot$. However, mass motions in the radiative zone – e.g., those associated with modified Ekman-type spin-down or meridional shear flow yield a macroscopic diffusion coefficient λ which can be much larger than λ_D. The fall of the heavier elements in an initially uniform star is then negligible. Schatzman argues that the fact that we observe e.g., metals or lithium at the surfaces of F stars can be explained only by a sufficiently fast mixing below the convective zone.

Gravitational setting has been appealed to also to explain the under-abundances of He, Ne and O in those Ap stars with appropriate values of surface temperature and gravity, with selective radiation pressure explaining simultaneously the over-abundances of Mn, Sr, Y, Zr and the rare earths (Michaud (7)). Greenstein *et al.* (8) have similarly tried to explain the weakness of the He lines in old horizontal branch B stars with presumed slow rotations. Such mechanisms require the atmospheres to be non-turbulent. The surface layers of an Ap star will probably satisfy local radiative equilibrium, without any circulation of gas so that Michaud's explanation remains plausible. The suggestion of Greenstein *et al.* will also break down if circulation persists (Smith (9)). Again it is possible that a photospheric magnetic field, too weak to be optically significant, is present and allows the star to achieve local radiative equilibrium without circulation.

Large-scale meridian circulation over the bulk of a rotating magnetic star can influence the structure of the superficial magnetic field. In a rapidly rotating star the magnetic flux may ultimately be trapped beneath the surface (Mestel (10); Wright (11)). Magnetic coupling with a stellar wind may explain the slow rotations of the Ap stars (Mestel (10)), and will also tend to change the angle between the rotation and magnetic axes (Mestel (12)); but whether towards the large values required by the oblique rotator model, seems to depend critically on the details of the superficial flux distribution (Mestel and Selley (13); Selley (14)), and so ultimately on internal stellar magnetohydrodynamics.

B. *Convective zones*

The hydrodynamical problems of super-adiabatic zones are those of laboratory turbulent convection, greatly increased by the enormous density changes over at least sub-photospheric zones. The linear stability analysis for an incompressible (Boussinesq) fluid can be plausibly applied to a star if a density scale-height is used for the depth: the critical Rayleigh number then predicts that a very small degree of superadiabaticity is sufficient to ensure instability.

A start has been made on non-linear (developed) convection in Boussinesq fluids (Gough *et al.* (15)), with some success in predicting the Rayleigh-number dependence of the Nusselt number (the ratio of total heat transport to that by conduction alone), but we are a long way from an extension to compressible fluids. The conventional phenomenological model adopted for stellar structure work is the mixing-length theory with the size of the convective elements put equal to the density (or pressure) scale-height. The super-adiabaticity required to transport the stellar luminosity is very small except in the ionization zones near stellar surfaces, or in very rapid late phases of stellar evolution, so that it is only in these cases that lack of an adequate theory of convection is serious for studies of stellar structure and evolution.

Recently there has been some discussion as to whether or not an inversion of density occurs in the convective zones of stars with $T_{eff} \leqslant 10^4$ K. According to Chitre and Shaviv (**16**) density inversion occurs always if the pressure scale-height is applied. Krishna Swamy (**17**) obtains similar star models in which, depending on the assumed efficiency of convection, the inversion of density may or may not appear. A. Ergma (**18**) showed that density inversion for evolved stars of large masses ($M > 10\,\mathscr{M}_\odot$) cannot be avoided and that the structure of the convective zone for these masses is independent of the efficiency of convection. For small masses the density inversion is the smaller the more efficient the convection and may disappear completely if a critical (for the given mass of a star) value of the efficiency is reached (for $1\,\mathscr{M}_\odot$ the critical value of $\alpha = 1{\cdot}5$ where α is the coefficient in the mixing length theory).

The granulation pattern observed at the solar photosphere can plausibly be described in terms of irregular Bénard-type cellular convection, typical velocities being $\simeq$ 2–3 km/s, and a characteristic cell-size $\simeq$ 1000 km, as compared with a scale height of $\simeq$ 400 km. Superposed on this is the supergranulation with horizontal velocities $\simeq 0{\cdot}4$ km/s and a characteristic scale of $\simeq$ 30000 km. To account for this second preferred scale, Simon and Weiss (**19**) have suggested a modification to mixing length theory, by which convective motions can extend over several scale-heights. They show that in a polytropic atmosphere the variation of the scale-height yields maximum efficiency when the vertical dimension of a cell is about three density scale-heights.

The question has been asked whether a *primeval* general magnetic field could interfere seriously with convective heat transport over the whole sphere, especially in the pre-main sequence phase; this with a view to explaining the infrared objects in the forbidden region to the right of the Hayashi tracks. Moss (**20**) has discussed in detail how the requirement of a fair degree of superadiabaticity (due to interference with or suppression of convective transport) can restore the vertical Hayashi tracks to the roughly horizontal Henyey-type tracks. However, Gough and Tayler (**21**) and Moss and Tayler (**22**) have applied the hydromagnetic energy principle to show that only very strong magnetic fields can suppress convection: in regions where the field has a large vertical component the field energy needs to be comparable with the kinetic energy of the turbulence that would be driven by the assumed superadiabatic gradient. Where the field is nearly horizontal, stabilization becomes much more difficult, as rolling motions about the field-lines are hardly impeded. The general conclusion is that only magnetic fields strong enough to be hydrostatically important (at least in the fraction of a star with temperatures below 10^5 K) could seriously reduce the Hayashi superluminosity, and there is no evidence that even the stars with the strongest surface magnetic fields contain that amount of magnetic flux (Wright (**11**)).

C. *Interaction between rotation and convection*

By considering local disturbances of sufficiently low symmetry, Cowling showed that although rotation has a stabilizing effect for axi-symmetric modes, there always exist non-axisymmetric modes without detailed angular momentum conservation and which are hardly affected by Coriolis force. Thus even in a rapidly rotating star we may expect just some reduction in convective efficiency rather that complete suppression. The Coriolis interference with general motions can be thought of as due to the fluid's attempting to satisfy the Taylor-Proudman theorem for slow inviscid motions, a constraint that is a maximum at the poles and decreases towards the equator. This shows up in Busse's study (**23**) in the Boussinesq approximation of the growth of large-scale modes in a spherical shell. He finds that the Rayleigh number of his modes is unaltered to the first order in rotation, but the diminishing inhibiting effect of rotation with approach to the equator is shown up by the first unstable mode's having a pronounced maximum at the equator. Busse also shows that the dependence on latitude of the disturbance velocities necessarily yields in the second order a non-uniform rotation similar to that in the sun, both in sign and order of magnitude.

This work is in contrast with the earlier model of Biermann and Kippenhahn, which employs a phenomenological anisotropic viscosity tensor to describe the dynamical effect of the thermal turbulence. The consequent radially-dependent rotation low is inconsistent with hydrostatic support in a nearly adiabatic convective zone. The non-conservative centrifugal force field therefore drives a meridian circulation, which in turn sets up a latitude-dependent rotation field, with equatorial acceleration at the surface if the circulation is from pole to equator at the surface.

The most radical hypothesis on the interaction between rotation and convection is that of Gough and Lynden-Bell (**24**) following an earlier suggestion by Scorer. Noting the analogy between vorticity and magnetic field, and studies on expulsion of magnetic flux by systematic fluid motions (Parker, Weiss) they suggest that a convection zone attempts to achieve a state with zero large-scale vorticity, so that $\Omega \varpi^2 \simeq$ constant, ϖ being the axial distance. Because it would imply a singularity on the axis, this asympotic state is never reached; instead, the star continually spews out angular momentum a rival picture to the more popular magnetic braking. Some experimental support for the picture is claimed, though this has recently been questioned (Strittmatter (**25**)).

D. *Semi-convection*

A "semi-convective" region is one in which the stability criterion is initially violated, but which becomes stable if mixing of material reduces the opacity, e.g., by mixing core helium with envelope hydrogen. There is a continuing debate as to what criterion to use in stellar model computations.

Franzman, and Varshavsky (**26**) studied how different assumptions about mixing in the semi-convective layer influence the results of computations for massive stars. It appears that the structure and the evolution of the star are not affected substantially, but the time of evolution increases when partial mixing is taken into account (for 60 $\mathscr{M}_\odot$ Δt–$0{\cdot}4 \times 10^6$ y).

Tayler (**27**) has published a model of a slightly evolved massive star without a semi-convection zone. He has suggested that this model might be unstable and that this might lead to the setting up of a semi-convection zone.

Tutukov and Varshavsky (**28**) have investigated the behaviour of semi-convection during the hydrogen exhaustion phase with special attention to the turning points of the track. An intermediate fully convective zone appears near the hydrogen burning shell for the last stages of hydrogen exhaustion.

Gabriel (**29**) studies the overstability problem in details, finding that the stable layers above the semi-convective zone prevent overstability from arising. Gabriel concludes that if overstability is the only means of mixing, the Sakashita-Hayashi models are more likely to be accurate.

E. *Time-dependent convection*

The difficult question of time dependent convection and its effect on pulsations and stability has been considered by Kamijo (**30**) using Unno's method (**31**), by Gough (**32**) and by Castor (**33**) while the question of the boundary conditions was discussed by Takeuti (**34**) and further work on the one-zone model is due to Okamoto and Unno (**35**).

Edwards (**36**) has studied the influence of the failure of the quasi-static approximation on the helium flash. He finds the dynamical terms can be much more important than appears from a quasi-static calculation and the core of the star may explode; whether or not this happens depends on the behaviour of time dependent convection. Fraley (**37**) used Cowling's method for the derivation of the convective model (time dependent convection) for the investigation of supernovae explosions.

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II. STELLAR STABILITY AND STELLAR OSCILLATIONS

A. *General*

A review paper by Lebovitz in *A. Rev. Astr. Astrophys.*, **5** is mainly concerned with the effects of rotation on equilibrium configurations and their stability. Chapter 27 of the second volume of J. P. Cox and R. T. Giuli's, *Principles of Stellar Structure* 1968, New York presents a fairly complete survey of the theory of stellar radial pulsations and vibrational stability. A set of lectures given by P. Ledoux at the "11e Cours de perfectionnement de l'Association Vaudoise des Chercheurs en Physique" Saas-Fee, Suisse 1969 (to be published) covers many of the results up to the beginning of 1969 including the case of non-radial perturbations but neglecting mostly the effects of rotation, magnetic fields and external gravitational fields. An attempt is also made there to present the general time-dependent problem as it should apply for instance to rapid phases of stellar evolution.

Successful methods to find directly the complex solutions of the complete fourth order problem of linear non-adiabatic pulsations have been or are being developed in various groups at Colorado, Liège, Paris.

This approach seems to have been mainly directed at the problem of vibrational stability but, in principle, it covers also the problem of secular (or thermal) stability. It might also prove useful to learn something on the difficult case where two or more of the typical time-scales become comparable. This might have interesting applications, for instance, in stars of very large mass or very high density on the verge of dynamical instability.

Glansdorff and Prigogine's generalized principle of minimum entropy production has guided

Unno (1) in a reformulation of the general problem of stellar stability. Perdang (2) has tackled the general problem of the effects of the kinetics of nuclear reactions on the stability problem with a discussion of the new associated time-scales and of the stability of the reactions themselves.

B. *Dynamical stability and adiabatic oscillations*

1. *Radial modes*

Dynamical instability towards radial perturbations occurs only if some appropriate average of Γ_1 is smaller than $\frac{4}{3}$. This can happen in the very early prestellar stages of contraction as shown again by Upton, Little and Dworetsky (3) using the energy principle. Their model has also been studied by Van der Borght using the small perturbation method which, in particular, shows that, for unstable modes contrarily to the cases of stable ones, $\delta r/r$ may decrease strongly towards the surface. Dynamical instability could also occur for the same reasons in a strongly evolved star when it reaches the red giant phase at very high luminosity and could be responsible for the formation of planetary nebulae or for the excitation of the oscillations of Long-Period Variables. Langer (University of Colorado) has computed a line in the H-R diagram, above and to the right of which models become dynamically unstable.

Very advanced stages of stellar evolution with nuclear equilibria getting established at very high temperatures and densities in a central core provide another range of conditions favourable to dynamical instability.

The problem has been discussed anew by Rakavy *et al.* for carbon and oxygen stars and by Itoh for high temperature non-degenerate stars taking into account most of the possible nuclear equilibria as well as the general relativity corrections. The results show that the instabilities due to the creation of electron pairs and more effectively, to the decomposition of Fe^{56} and He^4 extend outside the relativistic instability region. It is however no longer clear whether this dynamical instability plays a dominant role in the origin of the supernova phenomenon, other types of instabilities, more akin to secular instability albeit with a very short time-scale (neutrino emission as in White and Colgate's theory or explosive nuclear reaction as in Imshenik and Nadezhin's (4) and in Arnett's models (5) being perhaps more significant).

Another possibility of dynamical instability is related to relativistic degeneracy ($\Gamma_\mu \to \frac{4}{3}$) combined with extrafactors like nuclear equilibrium between β-decay and electron capture and (or) general relativity corrections which reduce further the effective value of Γ_2. A. Baglin found that, under the effects of these factors, a white dwarf would become dynamically unstable for $\rho_c \simeq 8 \times 10^8$ g/cm^3 while Wheeler, Hansen and Cox, taking into account the finite relaxation time of the equilibrium, push back this critical density to $\rho_c \simeq 10^{10}$ g/cm^3.

Another destabilizing mechanism (secular rather than dynamical instability) which might operate at $\rho_c \simeq 2 \times 10^9$ g/cm^3 has been further studied by Wheeler *et al.* (6) who find severe difficulties with this mechanism.

There are still problems with the equation of state for matter at very high densities but it seems established that no stable configurations can exist in the intermediate range between the most condensed stable white dwarfs ($\rho \simeq 10^9$–10^{10} g/cm^3) and neutron stars ($\rho \simeq 10^{13}$–10^{16} g/cm^3). A summary of work done in this field may be found in *Relativistic Astrophysics* by Zeldovic and Novikov, Moscow 1968.

The discovery of pulsars also renewed interest in the periods of radial oscillations of very condensed stars. (See Proc. 4th Texas Symp. 1969).

2. *Non-radial modes*

Smeyers results on the complete 4th order problem of the non-radial oscillations of main sequence stars of fairly high masses have been published (7).

Robe (8) has cleared up completely the question of the classification of the $f-p$ and g-modes, all modes subsisting but the lower ones acquiring extra-nodes, due to the apparent singularities, as the central condensation increases.

The asymptotic behaviour of the non-radial modes has been studied by Vandakurov, Iwens and Smeyers using Langer's method while Tassoul has improved the results by extending Olver's method to this case.

A. Baglin and J. Heyvaerts have appealed to *g*-modes of non-radial oscillations of neutron stars to explain the periods of pulsars. However Thorne and his coworkers (**9**) in an exhaustive analysis of these non-radial modes for fully relativistic models have shown that gravitational radiation is emitted by such pulsations and damps them rapidly, typically in a time of the order of 10^3 to 10^4 times the period for a neutron star.

Perdang has applied a group-theoretical treatment to the case of non-radial oscillations in presence of various perturbing factors.

A general variational principle for the oscillations of a differentially rotating configuration as developed by Lynden-Bell and Ostriker (**10**) was applied by Clement (**11**) to the problem of the β Canis Majoris stars. The same approach is used by Lebovitz (**12**) to show that rotation has practically always a stabilizing influence.

The same general problem can also be tackled by the virial tensor approach as shown by Tassoul and Ostriker (**13, 14**) and Simon has discussed it for an arbitrary low of rotation up to terms in Ω^2 by a generalized perturbation method (**15**).

For uniformly rotating polytropes, Tassoul and Ostriker (**16**) find that secular and dynamical instabilities occur respectively for ratios of the kinetic to the gravitational energy $T/|W| \simeq 0{\cdot}14$ and $T/|W| \simeq 0{\cdot}26$ whatever the value of the polytropic index. Influence of other factors such as a tidal force has also been taken into account by Tassoul (**17**) and by Zahn (**18**) who discusses especially the excitation of fairly high *g*-modes in a component of a binary system.

Kato (**19**) has also considered the problem of the excitation of non-spherical waves in a differentially rotating stellar convective envelope with possible applications to the Sun.

C. *Vibrational stability and variable stars*

1. *Radial modes*

A number of investigations concerning especially large mass stars (around or above the critical mass M_c) are due to Simon and Stothers with application to the blue supergiants (**20**) and Wolf-Rayet stars (**21**) some of which, in their views, might derive from masses originally much larger than M_c. They found a correlation between vibrational instability and the eigenfrequency of the fundamental mode (**22**). They also point out a new mechanism for enhancing vibrational instability (**23**) namely, an increase of the mean molecular weight $\bar{\mu}$ in the external layers as might result from accretion of evolved material in close binary systems. They suggest that this may be responsible for the observed oscillations of the β Cephei stars. In case of subsequent mixing, instability may still arise due to the uniform increase of $\bar{\mu}$ in the star which may account for the variations of some Wolf-Rayet stars. Boury and Ledoux have also discussed the interpretation of Wolf-Rayet stars in terms of vibrational instability and mass-loss but from homogeneously evolving stars of large masses.

Other applications to a helium rich variable star (**24**) and to M supergiants (**25**) have also been considered by Stothers. Kamijo (**26**), on the other hand, has studied the vibrational stability of the primary in a close binary on its way to the white dwarf stage following mass loss and determined the phase of maximum instability.

The direct linear approach (complex solutions) was applied at the university of Colorado by Langer (**27**) to models of Long Period Variables with some success and by Ziebarth for a general stability survey.

Non-linear effects also have been receiving more attention either following the more or less classical approach by series developments or analytical approximation not only for the adiabatic case but also to ascertain the development of the instability due to nuclear reactions in large mass stars. This important problem has now been tackled directly by numerical methods by various people: J. P. Cox at Los Alamos, Ziebarth at Colorado, Talbot at the Massachusetts Institute of Technology, who find that it implies some loss of mass.

Of course the problem of finite pulsations in classical variables like the Cepheids or RR Lyrae star is still receiving a good deal of attention and general accounts of the present status of the problem have been published. A long-range program in collaboration between J. P. Cox (Colorado), D. S. King (Univ. New-Mexico) and A. N. Cox (Los Alamos) is being continued. Christy has obtained some general results (unpublished) for Cepheids concerning the value of Q $(=P\sqrt{(\bar{\rho}/\bar{\rho}_{\odot})})$, the instability region and the theoretical Period-Luminosity relation. He confirms also his interpretation of secondary humps.

Oscillation of a red supergiant with $M=M_{\odot}$ has also been studied (**28**), the non adiabatic convection just outside the H-ionization zone playing a prominent part in the excitation of the pulsation. Let us note also in this respect the work of Graham (**29**) who finds instability and finite somewhat erratic pulsations for a star which is just reaching the Hayashi track after gravitational contraction.

The problem of vibrational stability towards non-radial perturbations is also receiving attention and Zahn (**30**) has studied Baker's one-zone model in this respect showing that instability can occur in the region of the H-R diagram where the δ Scuti-variables occur. Somewhat similar techniques were also used by Ishizuka to derive a criterion for the excitation of non-radial pulsations.

The behaviour of the amplitudes of g^+ modes in small mass stars with a large convective envelope (relatively small amplitudes) and a small radiative core (relatively large amplitudes) also points to a possibility of vibrational instability which is studied by Robe (Liège).

D. *Secular or thermal instability*

Gabriel and Noels (**31**) have found secular instability in carbon stars at Deinzer and Salpeter's minimum mass.

Rakavy and Shaviv (**32**) have discussed the stability of nuclear burning using an "effective specific heat" which is probably related directly to the integral criterion of secular stability as treated by Ledoux (cf. for instance "Stars and Stellar Systems", Vol. VIII). Unno in collaboration with Kato, has also discussed the thermal instability of a shell-source model (**33**).

Rose and Giannone and Weigert have been able to follow the non-linear development into successive pulses of instabilities of this type. Rose (**34**) has shown that the star can become vibrationally unstable during such a pulse.

J. P. Cox, Hansen and Miss Hertz at the University of Colorado have started a general investigation and numerical program allowing for both real and complex solutions.

Secular stability towards non-spherical perturbations of a chemically inhomogeneous zone has been investigated by Kippenhahn. Although possibilities of instability are present, P. Biermann has found none up to now in applications to transition zones from hydrogen rich envelopes to helium rich interiors (unpublished).

These non-radial perturbations are especially significant for the secular stability of stars in presence of rotation, magnetic fields or tidal field. In the case of rotation, Goldreich and Shubert (**35**) and Fricke (**36**) have obtained the same conditions for secular stability of differentially rotating stars. According to Kippenhahn (**37**) the time-scale of these instabilities is however rather long, at least of the order of the Kelvin-Helmholtz time-scale. Extension to the case when magnetic fields with various geometries are present have already been made.

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III. EVOLUTION OF CLOSE BINARIES

Most of the work in the last three years in this field dealt with the mass exchange during post main sequence stages of close binary components. According to the evolutionary stage of the primary at the onset of mass exchange three types of mass exchange have been distinguished, the socalled cases A, B, C:

Case A (onset of mass exchange while the primary is burning hydrogen in its center): Several case A systems are investigated now by Kippenhahn and Weigert (**7**), Paczynski (**13**), Plavec (**14**), Smith (**18**), Ziolkowski (**19**) and Snezhko (**20**) and therefore quite a number of theoretical post mass exchange systems are available in order to compare with observed semi detached systems. Comparisons (**5, 18**) give good agreement for systems with total masses higher than 3·0 solar masses.

Case B (onset of mass exchange after the primary has finished its central hydrogen burning, but before the ignition of helium): After mass exchange of this type the star which has lost mass ends up as a helium burning star or as a white dwarf, both having only a thin hydrogen envelope (**6, 7, 8, 10, 14, 19**). In some cases the mass exchange becomes rather slow (**16**) and the systems acquire the properties of semi detached systems for a while. There are good reasons to believe, that the observed Algol systems with a total mass below 3 solar masses are case B systems in their final phase of mass exchange. There are reasons to believe that there exist many systems which via a case B mass exchange will form a white dwarf in the future (**7, 8**). WR stars may be end products of case B mass exchange (**1, 13, 18**). Although the computed models resemble many properties of WR binary systems the mechanism of mass ejection in these systems is still not known. There is also indication, that mass has been lost from the system during mass exchange.

Gorbatzky and Koroviakovsky (**21**) have studied the behaviour of the gas stream in semi-detached binaries including the effects of gas pressure in the flow.

Case C (onset of mass exchange after the primary has finished its central helium burning, but before the ignition of carbon): Only one system has been investigated (**11**). Similar to certain case B systems (**6**, **16**) a quick and effective phase of mass exchange is followed by a second phase of slow mass transfer. The original primary ends up as a white dwarf of one solar mass. The possibility has been discussed (**11**) that the white dwarfs in systems like Sirius and Procyon might have been produced by case C mass exchange.

Besides the mass exchange calculations based on the normal simplifying assumptions (spherical models, conservation of total mass and orbital angular momentum of the system, circular orbits) work is in progress or should be started in the following topics:

1. Details of the flow of matter from one star to the other during mass exchange. Especially the problem, whether the system loses mass and angular momentum. Already a two-dimensional solution would be worthwhile (**9**, **21**). Some Algol systems seem to have undergone mass loss during their case A mass exchange phase (**13**). U Gem binaries give similar suggestions. The influence of mass exchange on the eccentricity of the system is unknown. In principle mass exchange could feed enough mechanical energy into the system, even that the system can be disrupted.

2. Work has been done on the Novae and U Gem problem along two lines:

(a) assuming that the contact component of a semi detached close binary system becomes unstable (**2**, **12**)

(b) assuming that hydrogen is accreted on top of a white dwarf component of a close binary system (**4**, **17**).

There is observational evidence that the cool giant component in U Gem systems is responsible for the outburst but in T Cr B the white dwarf seems to cause the outburst (**15**).

3. No system up to now has been computed which undergoes mass exchange forth and back. In principle one should be able to derive a crude picture of this type of event, for instance from the scheme of the generalized main sequence (**7**, **5**) introduced to determine properties of post mass exchange systems.

4. Although the post main sequence evolution of binary systems has been computed for many cases no efforts have been made recently to understand how the close binaries have been formed during the pre main sequence evolution. The fission theory might become attractive again since considerable progress in stellar rotation theory has been made during the last years (**3**).

5. Contact systems seem to be still difficult to explain. The theory still fails to give contact systems of the right mass ratio.

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IV. PROGRESS IN THE STUDY OF NUCLEAR REACTIONS IN STARS

In his talk "The Empirical Foundations of Nucleosynthesis" (**1**) at the Paris Symposium, W. Fowler presented a comprehensive review of the evidence as of early 1967 from nuclear physics experiments and from astrophysical observations that forms much of the empirical foundations of the theory of nucleosynthesis. Ordinary stars, supermassive stars, and the early high-temperature stage of the expanding universe were included in his analysis.

Considerable progress has been made in the study of massive objects, of supermassive stars, and of the synthesis of elements at very high temperatures (**2**, **3**, **4**). The study of explosive nucleosynthesis has been particularly active (**5**, **6**, **7**, **8**). Wagoner (**9**) has reviewed the thermonuclear reaction rates of interactions that are important in the synthesis of elements within objects exploding from very high temperatures. He has used these rates to analyze the relative abundances of the elements produced.

Fowler *et al.* (**10**) have reviewed the available experimental data on cross sections for the nuclear interactions of neutrons, protons, deuterons, and α particles with light and medium-mass nuclei that are important in nucleosynthesis. They compiled tables of resulting reaction rates, nuclear lifetimes, and energy-generation rates. Bahcall and Fowler (**11**) have examined the effects of excited nuclear states on stellar reaction rates and have used available experimental data to determine the reaction rates for several endoergic (p, n) and (α, n) reactions and their reaction rates. In their work on these reaction rates Fowler and his collaborators have been materially aided by the compilations of nuclear data in *Nucl. Phys.*, (**78**, 1) 1966–68 by Lauritsen and Ajzenberg-Selove, Endt and van der Leun (*ibid.*, **A105**, 1) and Ajzenberg-Selove and Lauritsen (*ibid.*, **A114**, 1). In addition they have used data from private communications or published papers for the reactions $^{14}N(p, \gamma)^{15}O$; $^{13}C(\alpha, n)^{16}O$; $^{9}Be(\alpha, n)^{12}O$; $^{3}He(^{3}He, 2p)^{4}He$; $^{27}Al(p, \gamma)^{28}Si$; $^{24}Mg(\alpha, \gamma)^{28}Si$ and $^{3}He(\alpha, \gamma)^{7}Be$.

The recent study of the reaction $^{12}C + {}^{12}C$ at low energies by Patterson *et al.* (**12**) has brought the data for that reaction much closer to energies of astrophysical interest and has shown that the cross section is lower at these energies than previously believed. Arnett and Truran (**13**) have used these new data to reexamine the problem of carbon-burning nucleosynthesis.

Theoretical calculations by Bahcall and May (**14**) have made possible improved reaction rates for proton capture by protons, a reaction for which there are no experimental data.

Audouze and Reeves (1969, Preprint) have analyzed the experimental data available on reactions that destroy ^{6}Li and ^{7}Li by proton capture. Audouze *et al.* (**15**) have studied spallation reactions induced in CNO targets by proton capture.

Bodansky *et al.* (**16**) have examined the silicon-burning reactions and their effects on abundances of nuclei between $A = 28$ and $A = 62$. They found good agreement with solar-system abundances and that the reactions are strongly exoergic. In a further study of these reactions Clayton and Woosley (**17**) have examined the long-standing problem of the production of ^{58}Ni.

At the Paris Symposium, Clayton discussed three mechanisms: the *s*-process, the decay of short-lived *r*-process transbismuth progenitors, and the decay of long-lived *r*-process transuranic progenitors and their effects on the abundances of the isotopes of lead.

Imshennik *et al.* (**18**) have pointed out the important role of the β-processes on early stages of gravitational collapse of a stellar core.

In their study of the spectrum of the hydrogen-poor star HD30353, Wallerstein *et al.* (**19**) found high nitrogen abundance suggestive of equilibrium abundances in material that has been processed through the CNO bi-cycle.

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V. NEUTRINO ASTROPHYSICS

During the last few years the rates of many different neutrino-antineutrino pair producing reactions have been calculated, based upon the assumption that there is a universal Fermi interaction which provides a direct electron-neutrino coupling to lowest order in the coupling constant. From these investigations it appears probable that the principal contributions to energy loss in stellar interiors are from the following three processes:

(a) electron-positron pair annihilation; (b) photoneutrino process (an electron scattering process in which a photon is converted into a neutrino-antineutrino pair); (c) plasma neutrino process (transformation of longitudinal and transverse plasmons into neutrino-antineutrino pairs). An approximate analytical formula by Beaudet, Petrosian and Salpeter has been derived, (**1**) which reproduces the energy loss rate to 15% or better in the range 10^8–10^{10} K and with less precision outside this temperature range. Included in these results are additional calculations of the rate of the photoneutrino process by the same authors (**2**) and for plasma effects on this process (**1**).

The same authors have also reviewed the rates for several other processes: the recombination process, the bremsstrahlung process, electron-electron scattering, photon-photon scattering and the URCA process. The recombination process may give a significant contribution to the energy loss in models near the helium flash. The URCA process (alternate electron captures and beta decays) may be important in certain circumstances.

Radiative corrections to the neutrino-electron interaction have been calculated by Hebb (**3**) and have been shown to alter energy loss rates by only a few per cent.

Neutrino-antineutrino emission from stellar interiors with intense magnetic fields, due to a synchrotron process, has been calculated by Landstreet (**4**) and has been shown to be unimportant.

Electron-electron neutrino bremsstrahlung rates have been calculated by Cazzola and Saggion (**5**, **6**), who have found that it contributes not more than one percent of the energy loss rates due to other processes under conditions of astrophysical interest.

Neutrino-pair bremsstrahlung, in which a hot degenerate electron gas Coulomb scatters on imbedded nuclei, has been calculated by Festa and Ruderman (**7**). They find that this process will dominate at high degeneracy, since it is not quenched by degeneracy as is the plasma process. The process may also dominate at low temperatures (below 10^8 K).

Bandyopadhyay (**8**) has suggested that there may exist a photon-neutrino coupling process which could give neutrino-antineutrino emission in all of the usual ways and also by a photon-photon scattering process. The rates are smaller than for the usually-considered current-current coupling in the common process. Chaudhuri (**9**) has argued that such a coupling may give a very important synchrotron process. However, the photon-photon process may be much more important than in either of these schemes if it is mediated by an intermediate vector boson (**10**).

The URCA process has also received additional attention (**11**, **12**, **13**). Tsuruta and Cameron (**13**) have calculated URCA rates for shells in white dwarf stars in which the electron Fermi level is in the vicinity of an electron capture threshold, and have shown that the process can dominate the cooling.

The solar neutrino experiments of Davis, Harmer and Hoffman (**14**) gave results approximately half as large as were expected on the basis of theories of the solar interior. Extensive reviews concerning the physical and the astrophysical aspects of this problem have been published by Bahcall *et al.* (**15**), Iben (**16**), and Kotcharov (**17**). Iben (**18**) has shown that the upper limit on the solar neutrino flux places an upper limit on the solar helium abundance that is low compared to a mean Y found for other objects in the galactic disk and in the halo. The discrepancy persists even if the pertinent nuclear cross section factors are varied as far as possible within experimentally estimated limits. The possibility that the presence of a solar convective core will reduce the discrepancy (**16**) suggests that every effort should be made to improve solar opacities.

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VI. CALCULATIONS FOR STELLAR MATERIAL PROPERTIES INCLUDING OPACITIES, CONDUCTIVITIES AND EQUATION-OF-STATE

Since 1965 when opacities were given for twelve new astrophysical mixtures there have been only a few additional opacity tables published. However, with computing programs, which were being frequently changed, an additional series of opacity tables was computed at Los Alamos. The mixtures of general interest are given in Table 1.

Table 1. Opacity Mixtures

Name	X	Y	Z	
Demarque I	0·97	0·00	0·03	
Demarque II	0·00	0·97	0·03	
Demarque III	0·999	0·001	0·001	
Demarque IV	0·000	0·999	0·001	
Demarque V	0·99	0·00	0·01	
Demarque VI	0·00	0·99	0·01	
Baerentzen	0·700	0·297	0·003	
Forbes I*	0·913	0·080	0·007	
Forbes II*	0·8750	0·1249	0·0001	
Forbes III	0·75	0·25	0·00	
Forbes IV*	0·600	0·396	0·004	
Forbes V*	0·5000	0·4997	0·0003	
Forbes VI	0·0	1·0	0·0	
Hydrogen	1·0	0·0	0·0	
Cameron III*	0·500	0·479	0·021	
Cameron IV*	0·250	0·729	0·021	
Cameron V*	0·100	0·879	0·021	
Cameron VI*	0·050	0·929	0·021	
Torres I	0·00	0·94	0·06	
Torres II	0·7	0·2	0·1	
Torres III	0·0	0·9	0·1	
Torres IV	0·3	0·6	0·1	
Demarque VII	0·94	0·00	0·06	
Schatzman I	0·70	0·27	0·03	
Schatzman II	0·60	0·37	0·03	
Schatzman III	0·700	0·252	0·048	
Schatzman IV	0·9000000	0·0983364	0·0016635	
Lambert Mix*	0·7877	0·1974	0·0149	
Lambert I*	0·49255	0·49255	0·01490	
Iben I (Demarque III)	0·999	0·000	0·001	
Iben II	0·800	0·199	0·001	
Iben III	0·500	0·499	0·001	
Iben IV	0·200	0·799	0·001	
Iben V (Demarque IV)	0·000	0·999	0·001	
Iben VI	0·9999	0·0000	0·0001	
Iben VII	0·8000	0·1999	0·0001	
Iben VIII	0·5000	0·4999	0·0001	
Iben IX	0·2000	0·7999	0·0001	
Iben X	0·000	0·9999	0·0001	
Iben XVIII	0·00000	0·49995	0·0001	$Z(\mathrm{C}) = 0{\cdot}49995$
Iben XIX	0·0000	0·0000	0·0001	$Z(\mathrm{C}) = 0{\cdot}9999$
Iben XX	0·0000	0·0000	0·0001	$Z(\mathrm{C}) = 0{\cdot}49995$ $Z(\mathrm{O}) = 0{\cdot}49995$
Iben XXI	0·0000	0·0000	0·0001	$Z(\mathrm{O}) = 0{\cdot}9999$
Kutter I	$Z(\mathrm{O}) = 0{\cdot}13$; $Z(\mathrm{Ne}) = 0{\cdot}32$; $Z(\mathrm{Na}) = 0{\cdot}07$; $Z(\mathrm{Mg}^{24}) = 0{\cdot}043$; $Z(\mathrm{Mg}^{25}) = 0{\cdot}05$			
Vila I	$Z(\mathrm{C}) = 0{\cdot}2$	$Z(\mathrm{O}) = 0{\cdot}8$		
Vila II	$Z(\mathrm{C}) = 0{\cdot}05$	$Z(\mathrm{O}) = 0{\cdot}90$	$Z(\mathrm{Ne}) = 0{\cdot}05$	
Vila III	$Z(\mathrm{O}) = 0{\cdot}8$	$Z(\mathrm{Ne}) = 0{\cdot}1$	$Z(\mathrm{Mg}) = 0{\cdot}1$	

* Mixtures do not have the same inter-metal ($Z > 2$) ratios as in the Aller (1961, *The Abundance of the Elements*. Interscience Publishers, Inc. New York) mixture.

It is to be emphasized that these tables are not necessarily consistent with each other. They are, however, from the same version of the programs when they all have the same name except for the number (for example, Demarque I–VI), 23 mixtures have been published in the publication of the U.S.S.R. Academy of Sciences (**1**) and 10 more mixtures are to be published in the Astrophysical Journal with all 33 from the same (most modern) generation of the opacity programs.

Auman (2) has given monochromatic absorption data for water vapor which can be added to the other sources of opacity and then integrated to give Rosseland mean opacities. The water vapor can appreciably affect the opacity of stellar material below about 3500K. No tables of opacity exist, which include the water vapor absorption; but water vapor has been considered in construction of stellar atmospheres, and has been introduced into computations for late stages of evolution by the Warsaw and the Moscow groups. Tsuji (**3**) has also discussed molecules in a more general but less complete manner, and some general graphical results have been given. The effects of CO and OH, as well as other molecules, might be important to stellar opacities. The addition of molecular absorption to usable opacity tables is a current high priority job.

The hydrogenic approximation has been criticized by Carson and Hollingsworth (**4**) and a small table of opacities is given. Opacities depend strongly on the wave functions of the bound and free electrons, and large differences from the less elaborate hydrogen-like results have been found.

To overcome the assumption of the hydrogen-like approximation, Carson, Mayers and Stibbs have gone to the Thomas-Fermi atomic model and have shown that the total effect of this model on bound-bound, bound-free, and free-free absorptions can reach to almost a factor of three at temperatures like a million degrees and near unity density. Again not enough data are given to evaluate corrections to the Los Alamos tables, and indeed the corrections must be somewhat composition dependent.

Another important factor in increasing opacities near 10^6K is the absorption by autoionizing lines as discussed by Watson (**5**). A paper by Watson (**6**) gives ten small tables which can be compared with the new Los Alamos results for the same mixtures. Large factors like 3 or 4 can again be found at 2×10^5K and $\rho = 10^5$ gm/cm^3. The addition of the Thomas-Fermi equation-of-state or even more elaborate schemes as discussed by Rouse (*Ap. J.* in press) and the inclusion of autoionization lines to opacities are two more high priority opacity table requirements. Watson (*Ap. J.* in press) has discussed the collective effects of Thomson scattering when densities become high enough to cause some ordering of the free electrons. This effect is also discussed by Diesendorf and Ninham in an Imperial College of Science and Technology preprint. Decreases up to perhaps 20% or more may occur in the opacity of stellar matter in the high density hydrogen burning phases of stellar evolution.

To the radiative opacity one can add the effects of electron conduction. In the Los Alamos tables this has been done using the Mestel (**7**) results. Discussions by several authors such as Hubbard (**8**), Iben (**9**), Lampe (**10**), and most recently Hubbard and Lampe (Orange Aid Preprint) have resulted in tables (neglecting relativistic effects at $\rho > 10^6$ gm/cm^3) which can be used to produce effective stellar opacities.

There are six desirable additions to the production of stellar opacity tables.

1. Addition of H_2O absorption.
2. Addition of CO, OH and possibly other molecular absorptions.
3. Use of Thomas-Fermi model for bound-bound, bound-free and free-free absorptions.
4. Allowance for the autoionization lines.
5. Corrections for Thomson scattering for collective effects.
6. Addition of recent electron conduction theories and extension to higher densities.

Some of these improvements are now being pursued at Los Alamos.

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VII. NUMERICAL TECHNIQUES RELEVANT TO STELLAR CONSTITUTION

A. *General theory of quasi static calculations*

Over the past three years, at least two extensive reviews of the relaxation techniques for solving the stellar structure equations have been prepared (**1**, **2**). Valuable discussions have appeared regarding (a) the choice of variables appropriate for specific situations, (b) alternate schemes for treating sets of variables explicitly or implicitly, and (c) alternate choices for space centering variables (**3**, **4**, **5**).

Special schemes have been demonstrated to be advantageous for several specific situations. For example, numerical instabilities that may occur in calculating the helium flash may be avoided by an appropriate choice of the luminosity variables or by an appropriate space centering of the flux variable (**6**). The calculation of shell burning phases may be speeded up by taking advantage of the near invariance of the shell wave form. For some investigations it is adequate to replace the detailed variation of shell quantities by analytic boundary conditions on either side of the shell. This approximation has been extended by Eggleton to shells of finite thickness (**7**). Uus (**8**) and Paczynsky (in press) have improved this method for computation of late stages of evolution of Red giants and Paczynski has calculated evolutionary tracks up to the carbon ignition. Modifications necessary when surface mass loss is important have been discussed (see References Section III).

Methods other than that of relaxation have received attention. In particular, the possible advantage of employing standard integration techniques, but replacing a single interior fitting point by multiple fitting points has been demonstrated (**7**, **9**). Ruben, Lomnev and Vedjashkina have showed that the "particle in cell" technique holds promise for the calculation of evolution when the symmetry is other than spherical (**10**).

B. *Instabilities*

The very slow growth rate of pulsation amplitude relative to pulsation period has hampered attempts to determine whether or not the pulsation amplitude of massive main sequence stars will grow without limit. Growth rate may be artificially speeded up by multiplying $\varepsilon - \partial L/\partial m$ by an arbitrarily large factor. It has been shown (**11**) that the pulsation amplitude usually reaches a finite limiting value. However, it is not entirely clear that the artificial damping introduced may not be responsible for this. The nature of the thermal instability that arises in thin helium burning shells has been further clarified (**12**, **13**). The beginning of the transition from an isothermal core under non-degenerate conditions to a degenerate isothermal core and giant envelope has been shown by a linear stability analysis by Gabriel and Ledoux to correspond to a neutral point. Further insight into the nature of the Schönberg-Chandrasekhar limit has been given by the discussion of an analogous phenomenon in the structure of stellar systems (See References to Section II).

The machinery for detecting the onset of "one-way" instabilities according to Rakavy and Shaviv and for calculating their growth has been further developed by May and White (**14**).

C. *Dependence of realistic models on input physics*

There have been some suggestions in the literature that evolutionary tracks and the corresponding internal development are influenced by the mode of calculation: standard integration as opposed to relaxation of difference equations, one mode of space and time centering as opposed to another, etc. While it is true that numerical differences must occur simply because any computational scheme is an approximation, it is also true that in most instances such differences, are, from a practical standpoint, extremely minor. The major differences among computed tracks are due to differences in the input physics. This is particularly true if a modicum of common sense is used in applying criteria for adequate approximation.

Opacity and convection theory differences account for many of the variations in track details as do differences in nuclear cross section factors, particularly during helium burning phases (see discussion and references in the review paper by Iben (**15**) also 16–20). Mass loss may be important even for stars not in binaries and can significantly affect internal and track behavior (**21, 22**). The manner in which the semiconvective zone is handled may strongly affect whether or not massive stars can burn helium in the core as red super-giants.

A discussion on the influence of input physics on the calculation of evolutionary tracks for stars of large masses can be found in the paper by Massevitch *et al.* (**25**).

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