35. STELLAR CONSTITUTION (CONSTITUTION DES ÉTOILES)

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In preparing the Draft report, the following meetings (published or unpublished reports) have been taken into account.: *Stellar Rotation* (04.012.007); *Mass Loss and Evolution in Close Binaries* (04.012.029); *Supernovae and Their Remnants* (04.012.018): *Evolution stellaire avant la séquence principale* (05.012.001); *White Dwarfs* (05.012.003); *Late Type Stars* (05.012.009); *Evolution of Population II Stars* (07.012.024); *Cosmogony of the Solar System* (Nice, 1972); *Ages of the Stars* (Paris, 1972); *Physics of Dense Matter* (Boulder, 1972). Many review articles: *Evolutionary Processes in Close Binary Systems*, by B. Paczynksi, (06.117.004); *Convection in Stars*, by E. Spiegel (06.065.020) and *Ann. Rev. Ast. Astrophys.*, 1972; *Degenerate Dwarfs* by J. Ostriker (06.065.020); *Neutron Stars* by A.G.W. Cameron (04.065.061); and books: *Stars and Relativity* by Ya. B. Zeldovich and I. D. Novikov (05.003.022).

It has been agreed to restrict the reports to: *Collapse and Star Formation*, by R. B. Larson; *Neutron Stars* by G. Greenstein; *Neutrinos in Internal Structure*, by Imshenik; *Transport Processes* by E. Schatzman; *Stellar Structures, Age and Rotations,* by L. Mestel.

PROSPECTS IN INTERNAL STRUCTURE

It is probably in theoretical astrophysics that defining scientific orientation is the most difficult. Wishes are likely to be just wishful thinking, and it is easier to set up goals than to achieve them.

(1) Improve the microscopic physics. This is obvious. To be more specific, it is necessary to mention the properties of very dense matter, the diffusion coefficients, and the rate of thermonuclear reactions.

(2) Improve the hydrodynamics. This implies the convective zone, the theory of turbulence and turbulent transport, the instabilities associated to large scale motion (meridional circulation and differential rotation).

(3) Improve the theory of basic evolutionary processes: built up a theory (not a phenomenology) of mass loss, exchange of angular momentum, microscopic separation of the elements and mixing. This would lead undoubtedly to a better fit of the theoretical Hertzsprung-Russel diagram to the observations.

(4) Improve the theory of gravitational collapse: theory of star formation, origin of supernovae and neutron stars.

However, thinking of the directions in which new observations are carried, it seems especially important to consider the subjects related to infra-red observations, X-ray sources, high resolution spectroscopy.

E. SCHATZMAN
President of the Commission

TRANSPORT PROCESSES

E. Schatzman

Transport processes in the ordinary meaning of the kinetic theory of gases, are the transport of mass, momentum and energy and are respectively related to the diffusion coefficient, the viscosity, and the conductivity.

Transport of heat is a classical subject of astrophysics (absorption coefficient, conductivity),

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and will not be considered in this report. We shall, on the other hand, concentrate on transport of mass (microscopic and turbulent diffusion) and of momentum (microscopic and turbulent), leaving out the effect of large scale circulation.

Concerning mass transport, a new idea was set up by G. Michaud (03.064.037), when including in transport equation the effect of radiation pressure. G. Michaud showed that, if the heat flue is sufficiently large, and falls in the proper range of wavelengths, metals can be supported by radiation pressure. In principles, this gives the possiblity of explaining metallic line stars and peculiar A stars. Confirmation of the importance of the radiation pressure was given by W. D. Watson (05.064.047) who took into account the place where separation takes place, defined by the lower boundary of the shallow convective zone. In this connection, after S. Vauclair and H. Reeves (07.065.067) had shown the impossibility of explaining the abnormalous helium ratios by spallation processes in stellar surfaces, it is interesting to notice that, according to G. Michaud and S. Vauclair (07.114.117), the helium 3 abundance is 3 Cen A can be explained by the combined effect of gravity and radiation pressure at the bottom of a moderately deep convective zone.

Competition between microscopic separation and turbulent mixing is likely to explain the situation in the area of δ Scu and Am stars in the Hertzsprung-Russel diagram. According to A. Baglin (07.065.098), fast rotarion induces, though meridional circulation, a turbulent mixing, which prevents microscopic separation from taking place. In such stars (V equatorial larger than 50 to 100 km s^{-1}), the abundaces are normal and the kappa mechanism can drive pulsational instability (δ Scu stars). In slow rotators, helium falls inside the star by gravity and radiation pressure pushes up the metals (Am stars). A similar result, including stellar envelope calculations, leads D. J. Stickland and F. A. J. Whelan (07.114.001) to account for the appearance of the metallic line stars, their position on the H. R. diagram and their absence among rapidly rotating stars.

The lithium and beryllium problem is closely connected to the question of transport. It has to be recognized that the bottom of hydrogen convective zones is unlikely to be just at the right place to explain the litium burning and the lithium deficiency in the Sun. The difficulty of the problem comes from the fact that lithium burning seems to take place, whereas beryllium seems to be unburnt or even enriched in the FG sequence (E. Schatzman, C.E.R.N., Th. 1200; *Solar Wind*, NASA, 1972) R. H. Dicke (07.065.015) (06.080.002) explains the lithium burning in the following way. Turbulent transport induced by differential rotation and Goldreich-Schubert instability, brings lithium from the bottom of the HCZ to the place where it is burnt. According to Dicke (04.080.027), the central core of the Sun is fast rotating and the Goldreich Schubert Fricke instability does not extend much deeper than the region of lithium burning; therefore, beryllium burning after turbulent transport, does not take place. However, S. Vauclair (unpublished, 1972) shows that in F and G stars, lithium cannot be supported by radiation pressure whereas beryllium is. If this were confirmed, the abundace peculiarities of Be would be a surface effect and would have no meaning as far as the deep layers are concerned. The stable value of the Be abundance would be due to a compensation between gravity and radiation pressure in the continuum and not due to nucleosynthesis combined with burning (or no burning).

The importance of mass transport both for the understanding of stellar abundaces and of internal structure shows the necessity of improving our knowledge of the physical mechanisms. Microscopic diffusion is still limited to test particles, except when stationarity is reached. (Notice in this respect the explanation of the difference between DA and DB, DC sequences of white dwarfs by competitions between gravitational sorting in stable radiative inner layers and mixing in convective outer layers, by A. Baglin and G. Vauclair (to be published)). Turbulent transport is important, both for mass transport and angular momentum transport.

Standard procedures, based on mixing length theory are still widely used. E. Ergma (07.064.027) shows the difficulty of the m.l. theory for main sequence A and F stars. E. Spiegel (05.064.042) compares the assumption of adiabaticity with the m.l. theory in case of strong convection. V. P. Starr (06.080.038), in connection with solar rotation, takes into account the negative eddy viscous process. F. Winterbury (06.063.010) studies the spectrum of steady state turbulent convection. W. Unno (04.064.043) gives a theoretical treatment of stellar convective zones, inspired by the

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Heisenberg-Kolmogoroff solution. Coupling of turbulence in HC zone with momentum transport produces a differential rotation. This is considered by H. Köhler (04.080.001) and by F. H. Busse (03.065.014) and, in the convective core, by J. J. Monaghan (06.065.038). Various attemps have been made to improve the theory of convection. R. K. Ulrich has studied a model of moving cells (03.064.028, 03.064.042) and a multistream model (04.064.049). R. K. Ulrich has also studied the the effect of a gradient of chemical composition in stellar interiors by the method of thermoshaline convection, and has tried to derive a mixing rate. This is similar to the work of R. A. James and F. D. Kahn (03.065.059) who consider the non linear limiting of the Goldreich-Schubert instability They are lead to a time scale of the transport of angular momentum much larger than the Kelvin-Helmholtz time scale, which implies the possibility of a fast rotating core.

The problem of the rigorous treatment of the HC zone has been approached with help of the analysis of the motion in eingen modes. P. Souffrin (06.064.048) uses an analytical method which produces very small vertical velocities. E. A. Spiegel (06.065.019) analyses the basic Boussinesq convection. Further work by E. Spiegel (*Ann. Rev.*, **10**, 1972) and J. Latour (Thesis, 1972) uses a numerical method for calculating the vertical velocity. J. Latour uses one cell or roll in a shallow convective zone. His results are especially important for the estimates of the overshooting and the conditions of element separation at the bottom of the surface convective zone.

R. van den Borght (04.064.044) considers the non linear convection at high Rayleigh number.

Applications to transport process are scanty. T. Sakurai (04.080.018) considers the spin down of Boussinesq fluid in the circular cylinder as a simulation of the solar spin down procedure. R. H. Dicke (04.080.027) considers the viscous spin down of the Sun. Assumptions of complete mixing in a finite volume were used by Shaviv as an attempt to solve the solar neutrino problem, whereas A. G. W. Cameron (1972, *Nature*) suggests that recurrent mixing in the central region of the Sun could explain both the ice ages and the present neutrino deficiency.

COLLAPSE AND STAR FORMATION

Richard B. Larson

In recent years the study of collapsing clouds and star formation has entered a new era of widespread interest and rapid development as new theoretical and observational techniques have been applied to the problem. On the theoretical side, the development of computer programs for doing numerical gas dynamics has made it possible to compute the collapse of interstellar gas clouds and protostars in considerable detail; and on the observational side, infrared and microwave techniques have provided new tools for observing the properties of dense collapsing clouds and protostars. Current interest in star formation is reflected in the number of review articles which have recently been written on the subject; these include articles by Field (*16th Liège Symposium*), Kippenhahn (*Naturwiss.*, **58**), Penston (*Contemp. Phys.*, **12**), McNally (*Rep. Prog. Phys.*, **34**), Bok (*Sci. Am.*, **227**), and Larson (*ARAA*, **11**). More detailed reference articles on the evolution of protostars and pre-main sequence stars have been written by Bodenheimer (*Rep. Prog. Phys.*, **35**) and Larson (*Fund. Cos. Phys.*, **1**). Recent books and conference proceedings on the subject include *Évolution stellaire avant la séquence principale* (*16th Liège Symposium*, hereafter abbreviated *L16*; Université de Liège, 1970); *Dark Nebulae, Globules, and Protostars* (*DNGP*) (B. T. Lynds, ed., Univ. of Arizona Press, 1971); and *The Origin of the Solar System* (*OSS*) (proceedings of a symposium in Nice, April 1972, in press). Additional information relevant to star formation is contained in *IAU Symposium 39*: *Interstellar Gas Dynamics* (H. J. Habing, ed., D. Reidel, 1970).

1. *Dense clouds and gravitation instability*

The manner of formation of dense gravitationally unstable clouds is not yet fully understood, although a number of probably relevant processes involving thermal or magnetic instabilities and the agglomeration of small clouds into larger ones have been discussed (Field, *L16*). In special circumstances, the formation of an H II region may be instrumental in compressing small clouds or

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protostars into gravitational collapse (Hjellming, *L16*). Recent interest has centered on the connection between star formation and spiral structure, and Roberts (*Ap. J.*, **158**) and Shu *et al.* (*Ap. J.*, **173**) have shown that the compression produced in a density wave shock front may compress many interstellar clouds to the point of gravitational instability and collapse. Quirk (preprint) has suggested that star formation may be initiated by large scale Jeans instabilities associated with a density wave shock.

Whatever may be their origin, it is well established observationally that there exist dark clouds which are sufficiently dense and massive to be gravitationally bound, and many of them may already be collapsing (Heiles, *ARAA*, **9**). Many of the dark globules described by Bok *et al.* (*DNGP*) also appear to be on the verge of gravitational collapse, and some of them may in fact be protostars.

2. *The collapse of spherical clouds*

There is now considerable theoretical and observational evidence that dense collapsing clouds and protostars have low temperatures of the order of 10K, and that the temperature remains roughly isothermal during the early stages of the collapse (eg., Hattori *et al.*, *PTP*, **42**). The collapse of isothermal gas spheres was first explored numerically by Penston (*ROB*, **117**) and Bodenheimer and Sweigart (*Ap. J.*, **152**) with a variety of different assumptions concerning the intitial and boundary conditions, and a similarity solution for the isothermal collapse has been given by Penston (*MN*, **144**). The numerical calculations always show that the density distribution in an isothermally callapsing cloud becomes strongly centrally condensed and approaches the form $\varrho \propto r^{-2}$ predicted by the similarity solution.

Collapse calculations incorporating a detailed treatment of the thermal behavior of the gas have also been undertaken by Hunter (*MN*, **142**), Penston (*MN*, **145**), and by Disney *et al.* (*MN*, **146**) following a project originally started by McNally (*Ap. J.*, **140**). These calculations verify that the inner part of a collapsing cloud soon attains a nearly constant temperature of the order of 10–20K, and they show the same nonhomologous development of a sharp central density peak that is found in the isothermal calculations. The calculations of Hunter show in addition that the collapse can be initiated by a thermal rather than gravitational instability, and that under some circumstances the mass of a collapsing cloud can be as small as that of an upper main sequence star. In all of these calculations the qualitative results are found not to be very sensitive to the details of the initial or boundary conditions.

3. *Effects of magnetic fields, non-sphericity, and rotation*

Some of the effects of a magnetic field on the gravitational instability and collapse of an interstellar cloud have been discussed by Field and Mestel (*L16*). The presence of a magnetic field does not greatly alter the instability condition, but may tend to inhibit fragmentation during the collapse (although fragmentation can still occur if the collapse is anisotropic). A clearer understanding of the effect of a magnetic field on the dynamics of the collapse will require detailed numerical calculations, which are not yet available. The escape of a magnetic field from a collapsing cloud and the interaction between a magnetic field and rotation have been discussed by Nakano and Tademaru +*Ap. J.*, **173**) and Nakano (*PASJ*, **25**). These authors have shown that a magnetic field will excape from a collapsing cloud when the density reaches about 10^9 cm^{-3}; however, if cosmic rays are screened from the cloud, the magnetic field can escape at a much lower density, as is suggested in some cases by the observations (Verschuur, *Ap. J.*, **165**). These authors also show that a magnetic field cannot remove much angular momentum from a rotating cloud during its free fall time; if angular momentum is to be lost, the cloud must spend a long time in a quasi equilibrium configuration supported by rotation and magnetic fields, but the stability of such a configuration has not been demonstrated.

Calculations of the collapse of a uniform ellipsoid by Mizuno and Fujimoto (*PASJ*, **22**) show that when finite pressure effects are included, deviations from spherical symmetry do not always grow as in the pressure-free case but instead tend to oscillate between prolate and oblate shapes. Hydrodynamical calculations by Larson (*MN*, **156**) of the collapse of an axisymmetric isothermal cloud also show that moderate deviations from spherical symmetry, both prolate and oblate, do not usually grow during the collapse but instead tend to oscillate; the results are in all respects quite similar to those found in the spherical case. The only case in which a deviation from spherical symmetry is found to grow during the collapse is that of an elongated cloud whose mass per unit length exceeds a certain critical value; in this case the cloud collapses toward a thin filament, but at the same time it fragments into several smaller condensations along its length.

The callapse of an isothermal, axisymmetric rotating cloud has been studied by Hara *et al.* (preprint) under the assumption that the mass distribution can be represented by spheroidal shells; the results of these calculations show that regardless of the initial conditions the cloud always becomes centrally condensed, and the central part of the cloud always collapses to a flat disc. Preliminary hydrodynamical calculations by Larson (*MN*, **156**) of the collapse of an initially uniform and uniformly rotating isothermal cloud show some similarities to these results, but they show that the density distribution deviates strongly from a spheroidal shape and tends instead to assume a doughnut-like or toroidal shape. The resulting configuration seems likely to be unstable to non-axisymmetric deformations leading eventually to fragmentation into a system of two or more condensations orbiting around each other. Thus it is not clear that a rotating cloud will ever collapse to a flat disc, and instead it seems likely that in many cases the effect of rotation will be to produce fragmentation.

Porfiriev *et al.* (*Nature*, **222**) and Zhilyaev *et al.* (*Nauch. Inf.*, **16**) have considered some implications of the hypothesis that a rotating cloud collapses to a toroid which then fragments into stars.

4. *Fragmentation*

The problem of how fragmentation occurs continues to be a difficult and poorly understood one, although a number of authors have discussed various effects which are likely to play a role in fragmentation. Hunter (*MN*, **142**) and McNally (*L16*) have emphasized the importance of the thermal behavior of a collapsing cloud; the enhanced cooling occurring in the denser parts of the cloud will tend to promote fragmentation during the early states of the collapse before isothermal conditions have been reached. Falle (*MN*, **156**) has shown that prolate condensations will tend to collapse more rapidly than oblate ones. Arny has suggested that fragmentation may be most favored in the dense inner part of a collapsing cloud (*Ap. J.*, **155**) and that the internal velocity field may be important in controlling fragmentation (*Ap. J.*, **169**). These suggestions are supported by calculations of the collapse of a rotating cloud (Larson, *MN*, **156**) which indicate that instability to fragmentation first occurs in the dense inner part of the cloud and that the rotation plays an essential role in causing fragmentation to occur. The way in which fragmentation might proceed in a rotating cloud is suggested by recent unpublished calculations by Quirk of the fragmentation of a rotating thin disc of gas; the results show that the disc soon breaks up into a number of small dense condensations orbiting around each other, with much leftover uncondensed material swirling around them. Similar results are found if the disc is not rotating, but the condensations then all fall together at the center soon after they are formed. It seems likely that similar results would also be found in the more realistic case of a 3-dimensional cloud, but this remains to be confirmed by detailed calculations.

Several authors have attempted to develop theories of fragmentation which predict the masses of the stars formed. Reddish (*L16*) has developed a theory of star formation and fragmentation based on the hypothesis that all of the hydrogen in a dense cloud freezes out on the dust grains. However, Nakano (*PTP*, **45**) finds that this process is unimportant and that only about 1% of the hydrogen freezes out on the grains. Williams (*MN*, **146**) has used McCrea's floccule theory to suggest that the average stellar mass may increase with the mass of the initial collapsing cloud and may be unusually large for clouds of galactic mass. Larson (M*N*, in press) ass proposed a probabilistic theory of fragmentation which predicts that the initial mass spectrum (fraction of the total mass per unit logarithmic mass interval) is given by a Gaussian function, in approximate agreement with the observations.

Considerable interest has centered on the problem of the formation of binary stars, a special case of the fragmentation problem. The dynamical calculations referred to above suggest that most binary and multiple systems are formed as a result of the fragmentation of a rotating protostellar cloud. However, very close binaries are probably formed by the fission of a rapidly rotating pre-main sequence star as it contracts toward the main sequence. This point of view, once controversial, has received renewed support from the work of Ostriker (*Stellar Rotation*, ed. A. Slettebak; *OSS*), Bodenheimer and Ostriker (*Ap. J.*, **161** and recent preprints), and Lebovitz (*Ap. J.*, **175**). These authors have shown that differentially rotating polytropic configurations show the same stability properties as the classical Maclaurin spheroids, which evolve into non-axisymmetric ellipsoids and eventually reach a point of dynamical instability leading presumably to the formation of a binary system.

5. *The evolution of protostars*

The evolution of collapsing protostars with masses of the order of one solar mass has been computed in detail by Narita *et al.* (*PTP*, **43**; see also Hayashi, *L16*)); Larson (*MN*, **145**, **157**; see also *Fund. Cos. Phys.*, **1**); and Appenzeller (*Mitt. A. G.*, **31**). The results of all of these calculations are qualitatively similar in that they show the formation of a hydrostatic stellar core at the center which accretes matter from an extended envelope of infalling material and eventually becomes a normal pre-main sequence or main sequence star. Quantitatively, the assumptions and the results of Narita *et al.* are quite different from those of Larson and Appenzeller; Narita *et al.* assumed a much higher initial density, and consequently they obtained a much shorter collapse time and a larger radius and luminosity for the resulting star. At present not all of the observations thought to relate to protostars or newly formed stars have been completely explained theoretically, but most of the observations appear to be at least qualitatively consistent with the theoretical models (Larson, *MN*, **157**). In particular, it appears that the following types of objects can be consistently interpreted as forming an evolutionary sequence: the dense dark clouds described by Heiles (*ARAA*, **9**) and Bok *et al.* (*DNGP*); certain infrared sources associated with H II regions (Neugebauer *et al.*, *ARAA*, **9**); T Tauri-like stars with dense circumstellar nebulosity and strong infrared emission (Mendoza, *L16*; Strom *et al.*, *Ap. J.*, **173**); and other pre-main sequence stars with varying amounts of circumstellar material (Strom *et al.*, *Ap. J.*, **165**, **171**). Walker's (*Ap. J.*, **175**) observations of infall of matter in some T Tauri-like stars are also consistent with present protostar calculations.

The calculations referred to above have assumed that protostars are formed by gravitational collapse and fragmentation processes; however, it has been shown by Stein *et al.* (*Ap. J. Lett.*, in press) that under some circumstances protostars with similar properties can also be formed by thermal instabilities in the interstellar medium.

6. *Formation of massive stars and* H II *regions*

The development of a 'cocoon star' consisting of a massive star embedded in an opaque shell of remnant interstellar material has been studied by Davidson (*Ap. Sp. Sci.*, **6**); the formation of and H II region inside such an opaque circumstellar cloud might explain certain observations of compact H II regions and strong infrared sources. Some effects important for the formation of massive stars and H II regions have been discussed by Larson and Starrfield (*AA*, **13**), who showed that both radiation pressure and ionization effects will eventually become important in a protostellar envelope surrounding a massive stellar core, and will tend to limit the mass which the core can attain by accretion. The predicted limiting mass of $\approx 60\ M_\odot$ is in approximate agreement with the observed upper limit of stellar masses. The formation of an H II region is a natural byproduct of the formation of a massive star; the H II region forms in an extended protostellar envelope with a density distribution of the form $\varrho \propto r^{-3/2}$ as soon as the central stellar core has grown in mass into

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a main sequence O star. Some properties of H II regions formed in protostellar envelopes of this type have been studied by Berruyer-Desirotte (thèse, Université de Paris, 1972).

7. *Formation of planetary systems*

The way in which a planetary system forms is still a controversial and unsettled problem, although some fairly detailed models have recently been proposed. Some of the numerous theories which have been proposed for the formation of the solar system have been discussed by McCrea and Mestel (*OSS*). Most approaches to explaining the origin of the planetary system begin by assuming that at the time of its formation or soon afterwards, the Sun somehow acquired a disclike 'solar nebula' of relatively small mass ($\lesssim 0{\cdot}1\ M_\odot$) orbiting around it (eg. Nakano, *PTP*, **44**; Kusaka *et al.*, *PTP*, **44**; Alfvén and Arrhenius, *Ap. Sp. Sci.*, **8**, **9**; Safronov, *OSS*; Lyttleton, *MN*, **158**). Cameron (*OSS*) has proposed a quite different theory in which it is assumed that a rotating cloud collapses to a flat disc in which the planets first form by accretion and the Sun forms later by central condensation of the remaining material. This model has been worked out in considerable detail by Cameron (preprint) and Cameron and Pine (preprint). However, the stability of the postulated flat disc has not been demonstrated, and Ostriker (*OSS*) has argued that it is probably unstable. In any case, it is not clear that a rotating cloud will collapse to a disc at all, and the presently available collapse calculations suggest that a rotating cloud will instead fragment into a binary or multiple system. Larson (*OSS*) has suggested that the solar system formed in a more non-homologous fashion: a central condensation or embryo Sun developed first, and a preplanetary disc then formed in orbit around it through the accretion of leftover protostellar material with higher angular momentum. A somewhat similar proposal by Dormand and Woolfson (*MN*, **151**) is that the Sun captured pre-planetary material from a passing protostar. More detailed 3-dimensional hydrodynamical calculations will be required to cast further light on the very complex gasdynamical problems associated with the origin of the solar system.

STELLAR STRUCTURE, AGE AND ROTATION

L. Mestel

Shibata (05.065.094) has modified the earlier models of *M* dwarf stars by taking account of departures from perfect Boltzmann or Fermi statistics due to pressure ionization and dissociation, and (most important) to electrostatic inter-particle interactions, treated by the Debye-Hückel approximation. The latter effect lowers the luminosity by about 30%, increases the radius by 5%, and (for $M = 0{\cdot}4\ M_\odot$) increases substantially the mass of the radiative core.

Nariai (04.065.152) has constructed envelope models for hydrogen-deficient stars, using mixing length theory. The Hayashi limiting lines are determined for various masses: those for helium-rich composition are to the left of and parallel to those for normal composition; those for carbon-rich composition are still further left. The star R CrB is interpreted as being helium-rich.

Owen (06.065.039) has investigated the effect of nitrogen burning and neutrino losses on the location of the helium flash, finding a shell flash for Population I composition, but for Population II a flash that moves rapidly towards the centre.

Castellani *et al.* (05.065.030, 05.065.092, *Astrophys. and Space Science*, 1972) have shown how the structure and evolution of globular cluster horizontal branch stars is affected by the presence around the helium-burning core of a semi-convection zone, caused by convective overshooting. The duration of the central helium-burning phase is nearly double that found for models with a constant core-mass; likewise the extent in the theoretical H–R diagram of the slow evolution parts of the tracks. These results will clearly affect the interpretation of observed cluster diagram, estimates of the cluster ages, and the helium problem. (Unpublished computations by Sears of evolution from main sequence to giant stage of stars of mass 1–2 $M_\odot$ also show semi-convection zones in the hydrogen-rich regions surrounding convective cores). These authors find that the Schwarzschild-Härm criterion (with the temperature gradient in the semi-convection zone nearly adiabatic) is a

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good approximation. A similar argument put forward by Gabriel to justify the Schwarzschild-Härm criterion in massive main-sequence stars is criticized by Mimura and Suda (06.065.108) as inadequate within the time available.

Ikeuchi *et al.* (*Prog. Theor. Phys.*, **46**, 1713, 1171; in press) treat evolution towards the pre-supernova stage of carbon and oxygen stars of 30, 10, 5, 2·6 and 1·5 $M_\odot$. The last case is just above the Chandrasekhar limit; the 2·6 $M_\odot$ case is the mass of the carbon-oxygen core forming in a 15·6 $M_\odot$ star studied earlier; and likewise the higher-mass models represent the cores inside the helium-burning shell-sources of evolved stars. Evolution is studied with and without neutrino losses via the (hypothetical) electron-neutrino interaction. Without neutrino losses all the stars become ultimately unstable on account of photo-disintegration of iron except for the 30 $M_\odot$ star, which becomes unstable by electron-pair production in a central neon-burning phase. With neutrino losses, all are unstable by photo-disintegration of iron except for the 15 $M_\odot$ star, which succumbs to the silicon inverse-beta process. Neutrino losses greatly decrease the lifetime of the pre-carbon burning phase and so also the total evolution time. The mass fraction of carbon and heavier elements just before the onset of instability is much greater when there are no neutrino losses, implying considerable differences in the consequences of the subsequent supernova process – e. g. in the production rate of heavy elements in the galaxy and in the vital statistics of pulsars.

The use of a *constant mass* star as an approximation to the core of an evolved star is excellent if neutrino losses occur. Without neutrino losses the increase of core mass by helium-shell burning may not be negligible. On the other hand Sugimoto (04.065.044; 04.065.104; 05.065.105) has shown that the surface convection (if strictly adiabatic) invades the core and causes a substantial *reduction* of the core mass. However, the effect may be greatly reduced if the convection zone is markedly superadiabatic (Nomoto and Sugimoto (*Prog. Theo. Phys.*, **48**, 46, 1972)).

In an earlier paper (03.065.041) Nakazawa *et al.* studied the evolution of iron stars of mass 2·6 $M_\odot$ and 10 $M_\odot$ through gravitational contraction and ultimate collapse initiated by photo-disintegration of iron, again with and without neutrino losses. Before instability sets in the evolution is essentially as for carbon stars studied earlier. Following the iron-helium phase change the collapse is essentially adiabatic. It is found that collapse of a 2·6 $M_\odot$ star is initiated by this phase change and not by electron capture.

Vila (06.117.008) has studied evolution of a solar mass star with a carbon core and helium envelope. Without neutrino losses, there is a phase of helium shell burning, a phase with thermal oscillations, and a phase with central carbon burning. With neutrino losses the star acquires a giant-like structure, with a much higher luminosity. Comparison with observations of nuclei of planetary nebulae may validate the neutrino reactions. In both cases the star becomes ultimately a white dwarf, but with differing core composition and mass in the helium envelope.

Vila (06.065.096) has computed the cooling time of a 0·6 $M_\odot$ white dwarf with an oxygen core and a helium envelope, taking into account the outer convection zone and the crystallization of the bulk of the ions. The star becomes invisible after about 7×10^9 yr, supporting the suggestion that cold degenerate dwarfs may contribute significantly to the local galactic mass density.

Takeuti and Shibata (*Sci. Rep. Tohoku*, **54**, 207, 1971) have calculated the pulsation constant for ten model envelopes of population I Cepheids. They find very little influence of variation of chemical composition and of details of the outermost convective regions, so that Cogan's Q—(M/R) relation (04.065.094) can be used with confidence in future studies. Takeuti (preprint) has applied this relation to thirteen Cepheids in galactic clusters and five Cepheids with beats. Assuming Stobie's non-linear results for the transition region (03.122.023), a mass-luminosity relation is derived which implies substantial mass-loss during evolution. Tayler (03.065.078) has suggested that mass-loss and mixing of helium to the surface may also be necessary to eliminate discrepancies between evolutionary and pulsational calculations. Fricke, Stobie and Strittmatter (*Ap. J.*, **171**, 593, 1972) emphasize the sensitivity of computed evolutionary tracks to input physical data and other uncertainties, which suggest caution in estimates of mass-loss requirements.

Moss (preprint, 1972) has constructed models of rapidly rotating, largely convective, low-mass stars contracting homologously towards the main sequence. He concludes that rotation may

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increase discrepancies between estimates of cluster ages deduced respectively from the turn-off point at the top of the main sequence and the point at which contracting stars join the main sequence, if a coeval origin of the cluster members is assumed.

Jackson, Sanderson, Smith and Hazlehurst (103.116.002), (05.116.004) have shown that the reduction in luminosity due to centrifugal forces of uniform rotation is considerably below that claimed in earlier work. Whelan, Papaloizou and Smith (05.065.120) have made similar calculations for uniformly rotating massive main-sequence stars, finding disagreements with previous polytropic models. For all these models, the maximum luminosity reduction is about 8–10%. Hazlehurst and Thomas (04.153.015) have used published models of rotating stars to correct the observed brightness and colour of the bright stars in the Pleiades for rotational effects, so deriving a cluster age of $5{\cdot}8 \times 10^7$ yr. Smith (05.153.014) has made a statistical study of rotational effects on the HR diagrams of Praesepe and the Hyades. He concludes that the spread of the main sequence is too large for the stars to be in uniform rotation, but that the actual rotation law cannot be deduced from the observations. Tuominen (*Annales Academiae Scientiarum Fennicae*, 1972, **391**, 5; **392**, 3; **393**, in press) has studied the structure of non-uniformly rotating stars. He claims that the upward displacement of a non-uniformly rotating main-sequence star from the zero-rotation main sequence is not so large as for a uniformly rotating star, and that the displacement is downwards for sufficiently large ratio of central to surface rotation. The results are in striking discrepancy with those of Roxburgh and Strittmatter (*MN.*, **133**, 345, 1966), for reasons that are not clear. Interpretations of the observations will remain ambiguous until there is a concensus on the theoretical predictions. Aikawa (06.065.107) emphasizes that reasonably accurate results for rapidly rotating polytropes require retention of terms higher than the second in the rotational parameter.

Sakurai (*Pub. Astr. Soc. Jap.*, **24**, 153, 1972) has studied the evolution of a postulated primeval uniform solar rotation of 20–65 times the present surface value under the influence of Eddington-Sweet circulation and the solar wind torque, but without internal magnetic coupling. Only the P_0 and P_2 parts of the centrifugal field are retained. The circulation tends to spin up the radiative interior. The convective envelope therefore loses angular momentum via both the circulation and the solar wind; it reaches its present value in 10^7–10^8 yr, clearly implying that there must be some mechanism that restores angular momentum to the envelope. Dicke (*Ap. J.*, **171**, 331, 1972) has argued that the evidence from the lithium and beryllium abundances is consistent with a model based on a rapidly rotating radiative core, weakly coupled via Goldreich-Schubert type turbulence which interchanges both angular momentum and matter with the envelope. Argument continues about the solar observations and their interpretation as an oblateness due to an enhanced quadrupole moment (05.080.002, Chapman and Ingersoll, Dicke, 1972; *Ap. J.*, **175**, 819 and 831), and about the non-linear development of the Goldreich-Schubert modes (05.065.106).

Smith (03.064.038) and Brand and Smith (06.064.023) have studied circulation in uniformly rotating stellar envelopes (without magnetic fields), concluding that the rapid flow near the surface must become turbulent. Clement (*Ap. J.*, 1972, **175**, 135) shows that if this turbulence yields a conservative rotation law with the stellar suface a streamline, then the consequent circulation field is relatively slow, and without the break-up into two zones characteristic of a uniform rotating star.

Smeyers and Denis (*Astron. and Astr. Phys.*, **14**, 311, 1972) have studied the effect of rotation on the non-radial oscillations of a star up to second order in Ω, taking account of the centrifugal distortion of the equilibrium configuration.

Hazlehurst (03.117.023), Whelan (*M.N.*, **156**, 115, 1971) and Moss and Whelan (03.117.024) have developed Lucy's model of contact binaries with a common convective envelope. They find that zero-age systems can be built only with extreme population I composition. Systems of normal composition can be made if the primary is evolved, but there remain some stars with anomalous positions in the period-colour diagram. Moss (*M.N.*, **157**, 433, 1972) has found that angular momentum loss (e.g. via magnetic transport) from zero-age main sequence systems causes the separation of mass-centres and the ratio of secondary to primary both to decrease. The system adopts a dumb-bell configuration, and may ultimately coalesce into a single star. The results may explain the absence of observed systems with mass-ratio unity.

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Whelan (03.117.025) has investigated mass-transfer between pre-main sequence binary components, approximated by polytropic models. He finds a tendency towards mass-ratios well below unity.

Vila (06.117.008) and Faulkner (06.117.023) have studied evolution through gravitational radiation of angular momentum from a semi-detached close binary system with the primary a white dwarf and with the secondary filling its critical lobe. Mass flow from secondary to primary causes the separation and period to decrease when the secondary is massive enough to be essentially a non-degenerate star in thermal equilibrium (Faulkner), but (Vila) to increase when the secondary has mass $< 0.1\ M_{\odot}$ and so is also degenerate. Both authors suggest their models apply to recurrent dwarf novae such as W. Z. Sagittae.

Bath (*Ap. J.*, **137**, 121, 1972) has studied dynamical instability of the contact component in semi-detached systems in general. Estimated variations in surface luminosity are similar to changes observed in *U* Geminorum.

The observations of the strongly magnetic Ap stars may plausibly be interpreted in terms of the oblique rotator model, with the angle of obliquity χ either near zero or $\pi/2$ (06.116.007). The lack of correlation between spectrum, rotation and surface magnetic field can be used (06.116.010) as an argument against dynamo-maintenance of the fields of these stars and in favour of the oblique rotator model with the field a slowly-decaying 'fossil'. A large-scale stellar field is probably dynamically stable only if toroidal flux loops link the loops of the poloidal field (Wright, *M.N.*, 1973). Dissipation of the energy of the dynamically-driven internal motions within a star with general angle χ causes the instantaneous axis of rotation to approach the axis of maximum moment of inertia, yielding large or small χ according as the star is dynamically prolate (toroidal flux dominant) or oblate (poloidal dominant) about the magnetic axis (Mestel and Takhar, 1972, *M.N.*, **156**, 419). Stars will be visibly magnetic as long as flux is not dragged below the surface by rotationally driven circulation (06.065.087, 02.116.011); thus the magnetic stars should be mainly slow rotators, as observed (04.116.014). The angular momentum may have been lost via magnetic coupling with a wind emitted during the Hayashi convective phase. (Such coupling will also affect the angle χ (03.064.047), though probably less powerfully than the dissipation process). More plausibly, braking occurs by direct coupling with the interstellar gas, a hydromagnetic variant of the accretion mechanism, better described by fluid equations (Chia and Henriksen, 1973, *Ap. J.*, in press) than by a single-particle approach (Havnes and Conti, 06.065.009). Analogues of some of these ideas are relevant to the dynamics of pulsars (Henriksen, Feldman and Chau, *Ap. J.*, **172**, 717, 1972, 06.141.118), due account having been taken of the modifications introduced by quasi-rigidity of the pulsar crust (03.065.047).

STELLAR (AND SOLAR) NEUTRINOS

V.S. Imshennik

A brief review of neutrino astrophysics problems including the literature on them published up to 1969 was presented by Massevitch (**1**). Here only papers published in 1970 and later are reviewed, all other works only being mentioned if necessary.

1. *Computation of late stages of stellar evolution*

The great difficulties of evolutionary computations of stellar structure for the later stages of evolution are well known, for example, those for helium-burning stage. The development of giant-like structure, the increasing number of nuclear-burning shells, nonadiabatic convection, and thermal instabiliteis prevent the extension of evolutionary computations up to stages when nuclear fuel is exhausted in stellar interiors or when nuclear reactions are terminated due to cooling of the matter. It is likely that mass loss and accretion (in binary systems) are of great importance. As yet it is impossible to compute stellar structure including the already mentioned complicated effects. Under such circumstances it is valuable to start computations from some kind of 'intermediate

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point' under rather arbitrary initial conditions. Some calculations of this kind are reviewed below. The evolution of carbon-oxygen stars with neutrino loss for wide mass intervals was investigated by Ikeuchi, Nakazawa, Murai, Hoshi, Hayashi (**2**, **3**). It is possible to regard these stars as cores of stars with helium-burning envelopes. This assumption is more justified when neutrino loss is taken into account. Evolution without mass loss was followed up to the approach of dynamical instability, i.e., to presupernova stage in certain sense (for $M = 5$, $30\ M_\odot$ in (**2**), for $M(1{\cdot}5;\ 2{\cdot}6\ M_\odot$ in $M_\odot$).

The evolution and presupernova structure were considerably changed by neutrino loss (all computations were repeated with- and without neutrino emission).

A sharp decrease in the duration of evolutionary stages prior to instability (up to two orders as compared with the 'no-neutrinos' case) changes in presupernova chemical composition (or more precisely, a decrease in the content of iron and other heavy elements), considerable deviations from the homology of contraction are caused by neutrino emission. It is interesting to mention that if ν-emission is included, the instability is caused by the photo-disintegration of iron, independently of stellar mass, but if 'no-ν' evolution is assumed, $1{\cdot}5\ M_\odot$ star starts contraction due to silicon neutronisation prior to formation of the iron core.

The reviewed papers are very interesting in the sense of providing initial conditions for the investigation of dynamical instability. But is necessary to bear in mind that rather arbitrary initial conditions were assumed, in particular that the relation between presupernova (**2**, **3**) and main sequence mass is unknown. Besides, not all neutrino processes were taken into account, e.g., the very important URCA process (see below). The question also arises how those investigators passed the thermal flashes which, as some other authors (**4**) believe, may even lead to disruption of the star. More complicated and more realistic initial model for **1** $M_\odot$ star composed by carbon core $0{\cdot}67\ M_\odot$ and helium envelope of $0{\cdot}33\ M_\odot$ was assumed by Vila (**5**). If neutrino emission is taken into account, some considerable effects manifest themselves: the evolution time is decreased, high luminosity is attained simultaneously with the development of giant-like structure in certain stages of evolution, and the transformation into white dwarfs occurs without carbon ignition. If a 'no-ν' assumption is made, the star also evolves to a white dwarf, but only after a considerable part of core carbon has been burned. All computations were performed very carefully, six thermal oscillations in helium-burning shell were followed (for the 'no-ν' version) and proofs for the lack of mass ejection from the envelope were given (for the 'ν-emission' version). The author associates his models with observed nuclei of planetary nebulae and believes that models where the neutrino loss is taken into account fit the observations better. Vila (**6**) showed that neutrino loss is not essential for the cooling of a low-mass star $0{\cdot}6\ M_\odot$ into a black dwarf. The initial model was taken like that for $1 M_\odot$ star, but the helium envelope was very thin and existence of oxygen core was assumed. Thus, above-mentioned computations of late stages of stellar evolution (up to presupernova for $M \geqslant 1{\cdot}5\ M_\odot$ and to white dwarf for $M = 1 M_\odot$) showed the great importance of neutrino losses.

2. *The URCA process and other processes of neutrino losses*

The investigation of different sources of the neutrino emission playing a role in stellar evolution was continued. Especially the URCA process has received much attention. Tsuruta and Cameron (**7**) investigated the URCA process in very dense matter, with strong relativistic electron degeneracy. In this case, neutrino emission occurs from narrow spherical shells in stellar interiors, where the threshold energy of electron capture by stable nuclei is equal to the local Fermi energy. The authors not only took the temperature effects into consideration, but also stellar pulsations of sufficiently low amplitude. They obtained a rather simple law for neutrino energy flux from the star:

$$F_\nu = aT^5 + b\zeta_0{}^5.$$

(T – temperature, ζ_0 – relative amplitude of pulsations, a and b – coefficients). The values of a and b were obtained for 132 pairs of odd-mass-number nuclei (these coefficients include a factor, depending on stellar structure). The theory was applied to a massive white dwarf ($M = 1{\cdot}373\ M_\odot$) – the rate of cooling and vibrational damping were computed (without radiative losses). In the course of discussion of the results obtained, the predominance of the URCA process over all other neutrino-processes playing a role in the evolution of this massive white dwarf was mentioned. This interesting paper by Tsuruta and Cameron is likely to stimulate further investigations of URCA shells. However, it seems to me that the exclusion of even-mass-number isobars from investigation is not fully justified, in the course of computation of cooling of a white dwarf the accompanying process of heating inside the URCA shell is omitted (see below), and finally, there is some imprecision in the evaluation of the rate of β-processes because of errors in the Coulomb factors and because of the lack of contribution of excitation levels of isobars.

Beaudet, Salpeter, and Silvestro (**8**) have computed URCA energy loss rates, but firstly asymptotic conditions were not used, and secondly computations were performed in more usual way, as functions of temperature and density. Generally speaking, their computations refer to regions of higher temperature in comparison with the foregoing paper and are performed for some most widespread even-even nuclei. Comparison with other neutrino processes also led the authors to a categorical conclusion: the URCA process as a rule dominates in high temperature regions $(1{\cdot}5 \div 5)$ 10^9 K but only in a comparatively narrow region of densities, where the degeneracy is sufficient. It is worthwhile mentioning the very careful analysis of β-transformation probabilities (especially, the consideration of exitation levels of nuclei, contrary to (**7**)).

The papers mentioned closely coincide with early work by Nadezhin and Chechetkin (**9**), who performed the computation of URCA energy loss rates for higher temperatures ($T \gtrsim 4 \times 10^9$ K), where it is possible to make use of the statistical equilibrium of nuclear abundances and where the simplified picture of partial equilibriums (**7, 8**) is not more valid. Then the URCA energy loss rate would be a function of temperature and density only and contrary to the results of (**8**) would not depend on choice of relative concentrations of isobars. This case is most interesting for the problem of development of dynamical instability of stars. The kinetic equilibrium of isobars, related by β-transformations (pairs in (**7**) and threes in (**8**)) is here spread to whole totality of nuclei with equilibrium distribution. The ratio of full concentrations of protons and neutrons, including those bind in compound nuclei, is determined by the condition of kinetic equilibrium. The authors of (**9**) also come to the conclusion that URCA processes dominate in the region of densities, most essential for investigation of stellar implosion after the dynamical instability is approached. A large contribution of neutron-rich nuclei in the URCA process is emphasised. This last effect is not sufficiently well-grounded experimentally because of small neutron-rich nuclei life-times. The rates of the URCA processes found in (**8**) and (**9**) agree qualitatively. The main difference in the region of the parameters, common to both investigations ($T = 4 \times 10^9$ K) is due to uncertainties in experimental data on β-decay (that of log (ft) value).

The high temperature URCA process rate was also recently discussed in the paper (**10**). There is a rather large number of investigations on neutrino-elementary particle interactions, different from those, expected in universal theory of weak coupling. Some of them, based on a speculative assumption of photon-neutrino weak coupling (for example (**11**)), were already seriously opposed (**12**). It is also worthwhile mentioning recent calculations of electron-nucleus neutrino bremsstrahlung (**13**). Due to the discovery of pulsars, much attention has been paid to the influence of strong magnetic fields on neutrino process rates (**14–18**). The neutrino opacity manifesting itself when density approaches $10^{12} \div 10^{14}$ g/cm^3 is of great importance for investigations of collapsing stars. Imshennik and Nadezhin (**19**) using general kinetic transfer equations inferred the neutrino-conductivity approximation valid for big 'optical' depth of the star.

This approximation is particularly simple if the URCA process on free nucleons dominates, when is is possible to obtain explicit form of neutrino conductivity and lepton charge conductivity coefficients.

3. *The role of β-processes and neutrino energy losses in the thermonuclear model of the Supernova*

β-processes and neutrino losses may play an essential role in the thermonuclear model of the

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Supernova suggested by Arnett (**4**) in 1969. As is well known, in this model no remnant is left after explosion, ie., it does not explain the origin of neutron stars-pulsars, which are related to Supernova remnants by observations. However, Arnett (**4**) did not take β-processes into account. Now there is a number of investigations into the influence of β-processes on carbon ignition and the further development of thermonuclear detonation. I shall mention the most characteristic of them by Barkat, Buchler, Wheeler (**20, 21**), Bruenn (**22, 24**), Arnett (**23**). Their conclusions are not yet fully recognized, but some examples of explosions leading to formation of a neutron star-like remnants are constructed (**24**). Unfortunately, the high initial central density $\varrho_c \approx 10^{10}$g/cm^3 used, is not compatible with the results of evolutionary computations. The main effect caused by β-processes, or more precisely, by electron-captures, is the decrease of pressure behind the detonation front, leading to the diminishing of detonation. It is possible that the central and densiest part of the star, where β-processes have a highest intensivity, would not reach the rate of expansion high enough to overcome gravitation. While the main part of efforts is directed to the investigation of β-processes, it is worthwhile to bear in mind that temperature determination under strong electron degeneracy, when the pressure is almost independent of temperature, is very complicated, as has already been mentioned in (**4**). The temperature determination under such circumstances requires very high accuracy of numerical method, but the computation of thermonuclear explosion with β-processes included is still more complicated. We are not sure if the required accuracy is observed, as for example, in (**24**) where a not altogether adequate program was used. By the way, let us mention that in the evolutionary computations (**2, 3**) carbon (and all following) flashes gradually damped.

Recently Paczynski (**25**) raised one more objection to the thermonuclear model of the Supernova. Using data on URCA losses in thin shells (**7**) he estimated such losses for the core-carbon ignition stage. He employed the analogy between stellar pulsations and convective motions, when the nuclei of stellar matter are sometimes capturing electrons and at other times are performing β-decay. If the motion is fast enough, the relations given in (**7**) are valid. Paczynski (**25**) concluded that URCA losses in the convective core (the convection in its turn is caused by carbon ignition) are preventing the development of thermal instability and would ensure quiet carbon burning. We should note that the already mentioned pressure diminishing by β-processes is not associated with the big energy losses which are most essential for the mechanism described in (**25**). For all the investigations of this series (20–25) it is important to check, as mentioned in a note (**20**), that the conditions of kinetic equilibrium of alternative β-processes are fulfilled. These conditions are used in (**7–9**) and consequently in (**25**).

Nonequilibrium investigations of β-processes greatly complicates the computations, but meanwhile the consecutive account of nonstationarity may influence the fate of a given model (**4**).

It is worthwhile paying some attention to another problem connected with Supernova explosions in nucleosynthesis. A large number of papers concerning this problem have been published, particularly by Arnett and his collaborators, but it is not expedient to list them here systematically. I would only like to mention the short note by Hansen (**26**), where it is shown that the final composition of the ejected envelope is very sensitive to initial values of temperature and density. Hansen reasonably interprets this fact as a difficulty for nucleosynthesis in the thermonuclear model of the Supernova. We must emphasize that the choice of initial conditions depends on neutrino losses to a high degree, because the ignition point of carbon or any other nuclear fuel is determined by the equality of the rates of energy generation and of that of neutrino losses. The β-processes are also important for other models of nucleosynthesis: for the generation of transuranic elements by the r-process (Chechetkin (**27**)), for the generation of normal abundances of iron-peak elements by the URCA process (not by pair-annihilation $e^+ + e^- \rightarrow \nu + \tilde{\nu}$) in the course of the Supernova explosion (in accordance with the classical model of Hoyle-Fowler) as predicted by Saggion and Scarinci (**28**).

4. *Thermodynamics of matter with β-processes and some other models of Supernovae*

As was mentioned above, it is necessary to secure a high precision of computation of stellar

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evolution and explosion in order to get a well-grounded estimate of the temperature of the matter with strong electron degeneracy. In particularly this requirement applies to the equation of state.

Imshennik and Chechetkin (**29**) discussed the influence of β-processes on the equation of state for the model with neutrinos leaving the star without interaction, and Imshennik and Nadezhin (**19**) in the case of neutrino-opaque star. Both (**29**) and (**19**) refer to high enough temperatures when the assumption of the statistical equilibrium of nuclear abundances is valid. In paper (**29**) the time of setting of the kinetic equilibrium of β-processes is also estimated and it is shown that the nonstationary case is very important if the dynamical instability is caused by neutronisation of the matter (see also the reference to note (**20**) in Section 3). The nonstationary character of β-processes (which is essential for sufficiently low masses, for example, $M = 1{\cdot}5\ M_\odot$ (**3**)), causes a slow initial development of instability, with a time-scale of β-processes, which is many times higher than the hydrodynamical time-scale of given configuration. This delay of events in the stellar centre may secure early and efficient detonation of nuclear fuel. One ought now to mention that despite of intense exploration of the thermonuclear model of the Supernova, other models of Supernovae, associated with stellar collapse in the advanced stages of evolution (**2, 3**) do maintain their importance. The careful investigation of dynamical instability caused by matter neutronization is now only beginning. We should mention the paper by Sugimoto (**30**), where the boundary for beginning of the collapse of low mass stars was determined using the simplified picture of β-process kinetics.

The same problem was discussed by Bysnovaty-Kogan and Seidov (**31**) in the case of the lower temperature and for the mass of a star slightly higher than Chandrasekhar's limit. In this paper they noted a new way of heating white dwarfs in the presence of non-equilibrium (or more precisely – of 'overthreshold') β-processes. As the threshold of the second stage of e-capture is lower than for the first stage, the two-stage neutronization of even isobars (see (**8**)) leads as the rule, to the dissolving of Fermi distribution. This corresponds to the heating of matter. We should note that an analogous effect takes place for odd-number isobars, if there exists a final excess of electron energy over the threshold (see note concerning (**7**). Nakazawa, Murai, Hoshi, Hayashi (**32**) evaluated the entropy growth effect associated with an analogous process during the following stellar collapse.

After a series of papers dealing with the influence of neutrino losses on the dynamics of star collapse (primarily for massive stars $M \gtrsim 10\ M_\odot$) published up to 1969, there is practically not a single new publication. Only a brief article by Wilson and Le Blanc (**33**) reported on a two-dimensional calculation of star collapse with neutrino opacity taken into account. Although the description given in (**33**) is barely understandable, the importance of such a complicated model of Supernova (even if only rotation and magnetic field have been included) is evident.

Concluding this Section I would like to emphasize the urgent need for the investigation of stellar collapse, even if this does not provide a satisfactory model of the Supernova.

5. *Detection problems of solar (and stellar) neutrino*

As I do not work in this branch of the neutrino problem and as the present state of the question of solar neutrinos is very controversial, the only possibility for me in this review is to discuss the problem from the 'stellar' point of view. The kind of difficulties in the theory of solar (and, in principle, stellar) structure which have arisen after Davies's experiments on the detection of solar neutrinos are well known. These difficulties have been aggravated during last few years, leading to the appearance of a very large number of different (and often controversial) ideas. My task has been facilitated by a recent critical review of the problem written by Bahcall and Sears (**34**). The authors concluded that the discrepancy between the predicted neutrino flux and the results of Davies's experiment could not be explained by standard solar interior models, and that no unconventional explanation was yet acceptable. It is interesting to note that the theoretical estimate of Cl^{37} detector counts rate even raised last time (the best prediction of the flux in (**34**)-9 SNU). It is likely now that it is premature to speak of overcoming the gap between the theory and the experiment (especially after Davies published his new data (**35**): $(1{\cdot}0 \pm 0{\cdot}6)$ SNU). After the review (**34**) surveying the literature up to the end of 1971 was published, some new papers appeared. The

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calculations of ^{37}A nuclear structure performed by Lanford and Wildenthal (**36**) are associated with interpretation of solar neutrino experiments. In an attempt to decrease the central temperature of the Sun, Gari and Huffman (**37**) continued the revision of *pp*-reaction rate, but Diesendorf (**38**)* tried to revise the radiative opacity of solar matter. It is interesting to note the idea of the existence of up to now unknown resonance in the *pp*-cycle nuclear reaction $He^3 + He^3 - He^4 + 2P$. This idea was almost simultaneously suggested by Kopysov and Fetisov (**39**) and Fowler (40). If the rate of the mentioned reaction does increase through the resonance, then the equilibrium concentration of He^3 is lowered and consequently the probability of formation of Be^7 and B^8, the sources of solar neutrino, also decreases. The investigation of other, accessory reactions of the *pp*-cycle (including $He^3 + p$, $He^3 + d$, $He^3 + e$), does not give such hope for decreasing the concentration of He^3 as the $He^3 + He^3$ resonance hypothesis. It is possible that this hypothesis is one of the last attempts to overcome the gap between theory and experiment within the framework of accepted ideas on the thermonuclear nature of the solar energy. Nonetheless it would be premature to consider the resonance of the $He^3 + He^3$ reaction as the key to the problem. Because of that, among other hypotheses, discussion of Pontecorvo's idea on the existence of oscillations between different kinds of neutrino (**41**) has continued (see (**34**)).

The neutrino-detection problem is now mainly associated with observations of solar flux. Nonetheless, even before reliable data on solar neutrino can be obtained, the possibilities for observing neutrinos from other stars are discussed. Primarily, this discussion deals with the observation of neutrino impulses from collapsing stars. The peculiar properties of expected neutrino-antineutrino fluxes were described by Arnett (**42**) and Ivanova, Imshenik, Nadezhin, and Chechetkin (**43**) (for collapsing stars the equal presence of neutrino and antineutrino has been predicted, distinct from solar neutrino flux). The conditions for their detection were analysed by Domogatsky and Zatsepin (**44**). If the collapse of the star is not accompanied by Supernova explosion (this is the case when conditions are not favourable for envelope ejection), it is possible that neutrino impulse detection would be the major source of information on this most important natural phenomenon. The authors of (**44**) suggest the organic scintillation counter as a neutrino detector. It is possible to detect the collapse only if it occurs in our galaxy (10 kps). The further concretization of a project is given in a report by Zatsepin, Ryashskaya, and Chudakov (**45**), where a plant with a scintillator mass of only 100 tons is described.

The neutrino detection problem has raised a large number of interesting questions, for example, that of excluding phenomena imitating the neutrinoaction, or changing the character of the neutrino-matter interaction. Some of these problems were investigated by Domogatsky (**46**). The imitating effect of a hypothetical pseudo-particle, a zero-mass pseudo-scalar meson, was investigated. Some additional effects, caused by the possible nonzero magnetic moment of the neutrino, were evaluated. It is possible now to recall the idea, long ago expressed by Frank-Kamenetsky (**47**), to obtain information on weak interaction by means of data provided by astrophysics. The astrophysical limitations of interaction constants of pseudon and of neutrino magnetic moments are stricter than those obtained by physical experiments. Stothers (**48**) evaluated the astrophysical limitations of alteration of effective value of the vectorial constants of weak interaction G. Stothers allows a rather wide degree of alteration of G: $10^{-2} < (G/G_v)^2 < 10^2$. The same value follows from the analysis of the most advanced stages of stellar evolution (**49**).

The problem of solar neutrinos remains the cardinal problem of present-day astrophysics. Now the main effort is being concentrated on experiments.

We can only hope to get the answer, an answer which will determine the whole future development of astrophysics. Everything said up to now clearly shows the decisive role of the neutrino in the advanced stages of stellar evolution, in Supernovae explosions and the gravitational collapse of stars. Unfortunately, all those conclusions have been reached by theorists and only very indirect observational data allows us to check them. Sometimes one cannot help wondering if it is really possible that the majestic construction of Nature depends so crucially on the existence

* This paper is mentioned in review (**34**).

of the most subtle elementary particle, the neutrino? Even if, however, our present notions on the evolution, explosion and collapse of stars should prove to be correct it will prove to be very difficult to get a direct experimental proof of a theory depending so vitally on a subtle neutrino.

Finally, I would like to express my thanks to Prof. A. G. Massevitch, Dr L. Yungelson, Dr G. V. Domogatsky, Dr B. I. Paczinski, Dr R. L. Sears, Dr S. C. Vila for providing interesting information and help in the course of compilation of this review.

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NEUTRON STARS*

George Greenstein

> "Has anything escaped me?... I trust that there is nothing of consequence which I have overlooked."**

A reference of the form '(3.022.013)' indicates an article abstracted in Vol. 3 of *Astronomy and Astrophysics Abstracts*, code 022.013 within that volume. '*PDM*' refers to papers in the *Proceedings of the IAU Symposium* #**53** on the physics of dense matter, Aug. 21–26, 1972, Boulder, Colorado (to be published). It is fondly hoped that this review is reasonably complete as of Oct., 1972.

Review articles

Cameron (4.065.061) and Ruderman (*Ann. Revs. Astron. Astrophys.*, 1972) give general surveys of the field. More detailed reviews of crystallization and superfluidity are given by Pines (*Proceedings of the XII International Conference on Low Temperature Physics*, hereinafter referred to as '*LT* 12') and Ruderman (4.065.144). Canuto and Chiu (5.061.014) review the physics of intense quantizing magnetic fields. *PDM* itself constitues the most recent review of the field. Elementary articles can be found in *Sky and Telescope* (4.141.189, 4.141.190) on pulsars and *Scientific American* (5.065.034) on neutron stars.

* The references indicated in *Astronomy and Astrophysics Abstracts* are referred to by their reference numbers. In other cases, especially for 1972 papers, references are given in usual way.

* Research supported in part by NSF Grant GP31410.

** A prize of undetermined magnitude will be offered to anyone correctly identifying the source of this quotation.

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Equations of state and models

This subject is reviewed by Börner (Springer tracts on Modern Physics, 1973).

Rosen (2.064.035) discusses the structure of neutron star atmospheres and processes of nucleosynthesis in them neglecting magnetic field effects. The density regime $10^7 < \varrho < 10^{11}$ g/cm^3 appears to be well understood – at any rate no opposition to the standard picture (see, e.g., 6.065.098) has been voiced. This regime – the 'outer crust' – consists of neutron rich nucleii bound into a rigid lattice (4.065.144, *LT* 12) coexisting with degenerate electrons. At about 4×10^{11} g/cm^3 neutrons begin to drip out of the nucleii. Beneath this point lies the 'inner crust' – a rigid lattice of nucleii coexisting with degenerate electron and neutron liquids. Most of the mass density in this regime is in free neutrons, which may form a superfluid (4.065.144). There exists a considerable body of work on the equation of state and the properties of nucleii in this regime. Langer, Rosen, Cohen and Cameron (2.065.056), employing a semi-empirical mass formula modified in an attempt to reliably represent nucleii far from the valley of beta stability, find the nucleii to dissolve into the background neutron sea at a density of $\simeq 5 \times 10^{13}$ g/cm^3. Similar results are obtained by Bethe, Börner and Sato (4.065.012). Because these papers apply the semi-empirical mass formula in conditions quite different from those under which it has been tested, their results cannot be taken as rigorous. Furthermore (Buchler and Barkat, 5.065.013; Tondeur, *Astron. Ap.*, **14**, 451), small changes in the functional form of the assumed mass formula give rise to major qualitative changes in the resulting nucleii and may (Carter and Quintana, 6.065.059) give rise to a major density discontinuity at the base of the crust (corresponding to a liquid-vapor phase transition – a 'water table'). Descriptions based on more fundamental physics have therefore been attempted. Baym, Bethe and Pethick (6.065.151) describe the energy of the nucleii by a compressible liquid-drop model and find the crust to survive up to densities of 2×10^{14} g/cm^3. At the highest densites they find enormous nucleii (mass numbers of several thousand!). Buchler and Barkat (6.065.017) and Barkat, Buchler and Ingber (*Ap. J.*, **176**, 723), using a Fermi-Thomas model of the nucleii, also find the crust to dissolve at 2×10^{14} g/cm^3 but find no tendency towards giant nucleii. Similar results are obtained by Ravenhall, Bennett and Pethick (*Phys. Rev. Lett.*, **28**, 978) who employ a more reliable theory of the nuclear surface than did Baym, Bethe and Pethick. The most recent and perhaps the most complete analysis is that of Negele (*PDM*). Although he finds nucleii similar to those found by Ravenhall, Bennett and Pethick they exhibit a phenomenon not previously seen: sharp jumps in Z with increasing density due to shell effects. All of the more recent calculations yield similar equations of state within the crust and predict it to dissolve without a major density discontinuity at $\simeq 2 \times 10^{14}$ g/m^3. Their areas of disagreement effect such parameters as the melting temperature and shear modulus of the crust.

The regime (2–10) $\times 10^{14}$ g/m^3 is thought to consist of uniform neutron, proton and electron liquids, the neutrons constituting all but a few percent of the mass density (see, e.g., Pandharipande and Garde, *Phys. Lett.*, **39B**, 608). They may form a superfluid and the protons may form a superconductor. Alternatively, it has been suggested (Banerjee, Chitre and Garde, 4.065.033) that the neutrons in this regime form a quantum crystal. Anderson and Palmer (5.065.135) and Clark and Chao (*Nature Phys. Sci.*, **236**, 37) attempt to determine the solidification pressure of neutron matter by scaling known properties of solid helium: their results make plausible that solidification does occur somewhere in this regime. A more detailed analysis (Canuto and Chitre, *PDM*) also suggests solidification. However Sawyer (*Phys. Rev. Lett.*, **29**, 382) and Scalapino (*Phys. Rev. Lett.*, **29**, 386) argue that somewhere in this regime neutron star matter makes a transition to a phase of approximately equal numbers of protons, neutrons and negative pions, the latter in condensed plane wave states of relativistic momentum. The *least* dramatic effect of such a state would be a drastic reduction in pressure relative to that of a free neutron fermi gas. Whether such an effect is incompatible with crystallization, superfluidity and/or superconductivity remains to be seen. Wang, Rose and Schlenker (3.065.048) have evaluated the equation of state in this regime and in the inner crust using the nuclear matter techniques of Bruekner, Bethe and Goldstone.

The composition and equation of state of matter at densities greater than 10^{15} g/m^3 remains largely conjectural. Early work (Langer and Rosen, 3.065.003) assumes a Levinger-Simmons interaction among hyperons. A number of discussions (Leung and Wang, 6.065.101; Wheeler, 6.061.023) of Hagedorn-type (i.e. bootstrap) equations of state in this regime have been given. The subject is reviewed by Frautschi, Bahcall, Steigman and Wheeler (6.065.035). These equations of state are exceedingly soft (relatively low pressure at a given density); nevertheless neutron star models based on them (Rhoades and Ruffini, 5.065.012) are quite similar to those based on the Langer-Rosen-Cameron equation of state (3.065.004; see also Cohen and Cameron, 5.065.028). On the other hand Leung and Wang (6.065.101) construct neutron star models based on a variety of possible equations of state at densities exceeding 10^{15} g/cm^3: these models have *maximum* masses ranging from 0·1 $M_\odot$ to 1·5 $M_\odot$. Clark, Heintzmann, Hillebrandt and Grewing (*Ap. Lett.*, **10**, 21) discuss how and why the maximum mass of a neutron star depends upon the details of the hard core of the nucleon-nucleon interaction. A nonbootstrap equation of state at high densities is given by Pandharipande (*Nucl. Phys. A*, **174**, 641). A further discussion of equations of state and the composition of ultradense matter is given by Bethe (*PDM*). At the highest densities expected in neutron stars hyperons are usually thought to be present in great numbers. However, Sawyer (*Ap. J.*, **176**, 205) argues that the hyperon spectrum may be less rich than is commonly believed. He considers for the sake of argument the Δ^- particle and shows that, because many of its virtual $\pi^- n$ states are denied to it, its mass is shifted upwards so greatly that it may never appear in stable neutron stars. Ruderman and Bludman (4.066.129; *Phys. Rev.*, **170**, 1176; *Phys. Rev.*, **172**, 1286) and Kistler, Mittelstaedt and Weyer (4.065.138) consider ultrabaric (pressure $>$ density $\times$ c^2) and superluminal (speed of sound $> c$) properties of ultradense matter. Chanmugam (3.065.104) argues that three-body forces may be crucial in any attempt to use many-body theory with a potential to describe such matter.

Neutron star models including the effects of general relativity are given by Cohen and Cameron (2.065.093; see also Cohen, 3.066.004); Wang, Rose and Schlenker (03.065.048); Baym Pethick and Sutherland (6.065.098); Leung and Wang (6.065.101) and Papoian, Sedrakian and Chubarian (6.065.113). The general features that emerge from these analyses are as follows. Neutron stars range in mass from 0·1 $M_\odot$ to *of order* 2 $M_\odot$; their radii are $\simeq$ 10 km, remarkably independent of mass (except for stars of low mass, whose radii reach hundreds of km); surface redshifts are negligible for low masses and $\simeq 50\%$ for the highest masses; radii, maximum and minimum masses are insensitive to the gravitation theory assumed (Newton, Einstein, Brans-Dicke) but very sensitive to what we know least – the equation of state at high densities.

Cohen and Börner (*PDM*) attempt to estimate the masses of the Crab and Vela pulsars through arguments involving the energy balance of the Crab and Vela supernova remnants. Greenstein (*Ap. J.*, **177**, 251) shows that either pulsar masses are correlated with their magnetic fields, or both the masses and the fields lie within relatively narrow limits. Bhatia, Bonazzola and Szamosi (2.065.016) show that there exists an electric field $\simeq$ 100 Volt cm^{-1} in neutron stars.

Oscillations

When formed a neutron star may be oscillating violently. These oscillations are rapidly damped out by weak interactions among hyperons (Langer and Cameron, 2.065.055; Jones, 3.066.001). It may be higly turbulent; turbulent motions are also rapidly damped out by weak interactions among hyperons (Jones, 6.061.050). Vandakurov (1.066.054; 3.065.076) argues that there may exist a self-excited non-radial mode of MHD oscillation of neutron stars. Hide (5.065.050) shows that the rotation of the star alters its modes of MHD oscillation and that typical periods of such oscillations range from 1/2 to many rotation periods. Any oscillation will be communicated to the pulsar magnetosphere: conceivably the 'drifting subpulse' behavior of certain pulsars (see, e.g., Huguenin, Taylor and Troland, 4.141.195) may be related to such a phenomenon. Radial and non-radial modes including the effects of general relativity (emission of gravitational radiation) with and without rotation are analysed by Faulkner and Gribben (*Nature*, **218**, 734); Hartle and Thorne (*Ap. J.*, **153**, 807); Price and Thorne (1.066.010); Cohen, Lapidus and Cameron (2.065.012);

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Thorne (2.065.042); Hartle and Thorne (2.065.064); Thorne (2.066.050); Battiston, Cazzola and Lucarni (6.065.137) and Hartle, Thorne and Chitre (*Ap. J.*, **176**, 177).

Origin of the pulsar magnetic field. Electrical conductivity

Three suggestions have been advanced concerning the origin of the pulsar magnetic field. The first is that of Sedrakian (4.065.158; 5.065.037), who proposes that the battery effect, which operates in ordinary stars, may also operate in neutron stars. The second involves Landau orbital ferromagnetism, or LOFER (Lee, Canuto, Chiu and Chiuderi, 2.022.009). The magnetism of this state arises from the sum of all microscopic magnetic moments associated with electrons in their respective Landau levels. The Landau levels themselves are maintained by the macroscopic magnetization. In neutron stars the magnetic field generated by this process can be of order 10^{12} G. The LOFER state corresponds to a relative, rather than an absolute, minimum of the free energy of the electron gas (O'Connell and Roussel, 6.065.139): however the time to make a transition to the $B = 0$ (stable) state is estimated (Canuto, Kumar and Lee, *Nature Phys. Sci.*, **235**, 9) to be very long. Pohl and Schmid-Burgk (*Nature Phys. Sci.*, **238**, 56) argue that LOFER states cannot exist at temperatures greater than about 10^4 K in neutron stars.

The third proposal involves nuclear ferromagnetism (Silverstein, 1.066.058). The argument here is as follows. The force between two neutrons is repulsive at short distances. If all neutron spins are aligned, so that their magnetic moments add to form a macroscopic magnetic field, the Pauli principle will lower their interaction energy by helping them to avoid each other. Whether such a state is energetically preferable to the non-aligned state depends on the balance between this effect and that of the increased kinetic energy of the neutrons. The outcome seems to depend sensitively on the details of the interaction assumed. Brownell and Callaway (2.066.059) and Rice (2.066.060) agree with Silverstein that nuclear ferromagnetism does occur in neutron stars. More recently Clark (2.022.099), Pearson and Saunier (*Phys. Rev. Lett.*, **24**, 325) and Pandharipande, Garde and Srivastava (*Phys. Lett.*, **38B**, 485) argue that it does not.

The electrical conductivity of neutron star crusts above the Debye temperature is given by Canuto (3.066.026) and Solinger (4.065.021; see also Canuto and Solinger, 4.065.010). Their results indicate magnetic field decay times in the crust on the order of 10^6–10^8 yrs. Beneath the crust conductivities are far larger (Baym, Pethick and Pines, 2.065.106; Gentile, 3.065.075) leading to decay times greater than the age of the universe. Chanmugam and Gabriel (5.065.018) calculate realistic decay modes for stars of inhomogeneous composition. They find that low-mass stars may exhibit field decay but high-mass stars may not. Grewing and Heintzman (6.065.150) investigate decay modes for homogeneous stars including the effects of general relativity.

Known pulsars appear to have ages between 10^3 and 10^7 yr. Therefore their magnetic fields have no dynamical origin: they are fossils. If neither the battery effect, LOFER nor nuclear ferromagnetism (nor anything else) takes place pulsar magnetic fields will eventually decay. If any of these effects does take place, and if it can produce a field greater than present fields, they will eventually *increase*.

Response of the star to a decelerating torque: field alignment, precession and nutation. Do pulsars turn off?

Consider a decelerating torque acting on a rotating neutron star. The response of the star to this torque is complicated. Ostriker and Gunn (2.141.066) treat the behavior of a perfectly spherical star rotating in a vacuum with a non-aligned point magnetic dipole at its center. They find the resulting magnetic dipole radiation to (a) slow the rotation, (b) cause the rotation axis to precess about the magnetic axis and (c) *not* cause the magnetic and rotation axes to align. However this last result is very model-dependent. Davis and Goldstein (3.141.024) and Michel and Goldwire (3.141.010) show that a non-aligned spherical star of uniform magnetization rotating in a vacuum will align in a time comparable to the spin-down time. The field will also align (Chau and Henriksen, 4.141.035) if the deceleration process involves the emission of magnetic dipole plus gravitational quadrupole radiation. It will *not* align if the star is non-spherical (crustal rigidity and/or magnetic distortion) and therefore precessing: if it is, the magnetic-dipole torque, instead of aligning the field, will act to excite a nutation (Goldreich, 3.065.047). If the precession and nutation can be damped by dissipative processes within the star it could end up as a stabilized oblique rotator. Chau and Henriksen (5.141.104) attempt to estimate time scales for these processes in order to assess the likelihood of this possibility.

It seems quite clear that pulsars turn off. Most of them have periods on the order of one second and spin-down time scales on the order of 10^7 yr. However, *no* pulsars are known whose periods exceed four seconds. This absence of long-period pulsars was first noted by Pacini (2.141.050) and Ostriker and Gunn (2.141.008) who considered it to be due to the effects of magnetic field decay. As we have seen such decay may or may not take place. Gunn and Ostriker (3.141.171) assume that it does and that the pulsed radio luminosity is proportional to B^2; under these assumptions they are able to reproduce successfully the observed number-period distribution. Alternatively, the absence of long-period pulsars may be due to magnetic field alignment. Henriksen (*Ap. Lett.*, **7**, 89) successfully reproduces the observed number-period distribution under this assumption. Given the relatively small data sample we have to work with the success of either analysis cannot be regarded as compelling: the number-period distribution fitted by Henriksen includes only five more pulsars than that fitted by Gunn and Ostriker but has a significantly different form! Setti and Woltjer (3.141.025) argue that the absence of long-period pulsars can be understood on the assumption that the pulsed radio luminosity is inversely proportional to some power of the period. The observed data sample of luminosity vs. period either does or does not show this effect depending on who is interpreting it. Finally Ruderman (6.065.083) argues (cf. following section) that neutron stars may have surfaces of work function $\simeq 1$ keV, and that field emission from these surfaces may be quenched when pulsar periods exceed several seconds.

Physics in 10^{12} G

In magnetic fields of 10^{12} G the Larmor radius of an electron can be comparable with its de Broglie wavelength. This circumstance effects (a) the star's modes of photon and neutrino emission, (b) the structure of atoms on its surface and of the surface itself, and (c) the opacity of its atmosphere. The first and third points are reviewed by Canuto and Chiu (5.061.014), the second by Ruderman *(PDM)*. The following processes in the presence of intense magnetic fields have been treated: electron bremsstrahlung (Canuto, Chiu and Fassio – Canuto, 2.061.032; Canuto and Chiu, 4.062.045), synchrotron radiation (Chiu and Fassio – Canuto, 2.061.033), scattering processes leading to electrical resistance (Canuto and Chiu, 4.065.148; Canuto and Chiuderi, 4.066.123), Thompson scattering (Canuto, Lodenquai and Ruderman, *Phys. Rev. D*, 2303), Compton scattering (Canuto, 3.061.025), renormalization of electron mass and magnetic moment (Newton, 6.022.128), plasmon neutrino emission (Canuto, Chiuderi and Chou, 3.065.072; 4.061.032), neutrino bremsstrahlung (Canuto, Chiu, Chou and Fassio-Canuto, 4.065.149) and the URCA process (Canuto and Chou, 5.061.008). [Flowers (*Ap. J.*, in press) has discussed modifications to neutrino pair emission processes arising from the existence of a periodic lattice – the crust.] From these discussions the following results seem most worth emphasizing. The opacity of the surface of a neutron star is greatly reduced in the presence of a strong magnetic field. Thus for a given internal temperature the surface will be hotter and the star will cool faster. Furthermore the opacity is anisotropic: it is preferentially reduced along field lines. Magnetic poles may therefore be somewhat hotter than the equator. Some consequences of this have been discussed by Fujimoto and Murai (*Pub. Astron. Soc. Japan*, **24**, 269). Finally, the dominant neutrino cooling process, the URCA process, is somewhat quenched.

The structure of atoms near the surface of the star has been discussed by Cohen, Lodenquai and Ruderman (4.065.032); Mueller, Rau and Spruch (5.022.060); Barbieri (5.065.145) and Kadomtsev and Kudryavtsev (*JETP Lett.*, **13**, 42). These atoms are small and cigar-shaped. Their ionization energies are higher than in the absence of a field. At temperatures one expects of neutron star surfaces light atoms such as H and He will ionize but Fe, which is more prevalent, will not. Thus the abundance pattern of matter accelerated to cosmic ray energies from the star will not reflect the abundance pattern of its surface. Rosen and Cameron (*Ap. Space Sci.*, **15**, 137) discuss the structure of neutron star atmospheres in 10^{12} G and processes of nucleosynthesis in them.

Kaplan and Glasser (*Phys. Rev. Lett.*, **28**, 1077) argue that a high-density electron gas in fields of 10^{12} G undergoes a transition, analogous to the Wigner transition, to a periodic two-dimensional lattice of 'charged rods' parallel to the field lines. Ruderman (6.065.083) argues that chemical forces between atoms in fields of 10^{12} G will bind them into a solid. If so neutron stars would have, not atmospheres, but solid surfaces with work function $\simeq 1$ keV. Electron field emission is far easier from such a surface than ion emission, so that pulsar magnetospheres may consist only of electrons. Pulsars of period greater than a few seconds are unable to lift electrons off such a surface: Ruderman suggests this is why pulsars turn off. Mueller, Rau and Spruch (6.411.237) discuss the equation of state of such a solid.

Superfluidity

This subject is reviewed by Ruderman [4.065.144; *Ann. Revs. Astron. Ap.*, (1972)], Pines (*LT* 12) and Greenstein (*PDM*).

Most of the mass of a neutron star, and most of its moment of inertia, lies in its neutrons. These neutrons may be superfluid and the protons superconducting (Baym, Pethick and Pines, 2.065.105). Within the crust the ${}^1S_0$ neutron-neutron phase shift is attractive: the superfluid energy gap is isotropic (Hoffberg, Glassgold, Richardson and Ruderman, 3.065.011; Yang and Clark, *Nucl. Phys. A.*, **174**, 49). Below the crust the ${}^3P_2$ phase shift is attractive: the gap is anisotropic (Hoffberg *et al.*, 3.065.011; Tamagaki, 4.065.124; Takatsuka and Tamagaki, 6.065.131). Richardson (*Phys. Rev. D.*, **5**, 1883) discusses the properties of vortex lines in an anisotropic superfluid. The superconducting energy gap is isotropic and of the same order of magnitude as the superfluid gap (Itoh, 2.065.094). Itoh and Tsuneto (*Prog. Theor. Phys. Japan*, in press) consider URCA processes in the presence of superfluidity and/or superconductivity. Baym, Pethick, Pines and Ruderman (2.141.085) formulate a two-component model of neutron stars. The first component in this model is the neutron superfluid. The second, whose rotation constitutes the pulsar clock, is composed of all the charged particles within the star. Feibleman (6.141.229) discusses one of the processes (electron-neutron scattering) whereby these two components interact. Greenstein (4.065.002; *PDM*) argues that the superfluid should be in a state of microscopic turbulence. Ruderman (*PDM*) argues that it should not.

Cooling and detectability

In 1966 Tsuruta and Cameron (*Canad. J. Phys.*, **44**, 1863) carried out an extensive investigation of the cooling and detectability of neutron stars. This work neglected the effects of superfluidity, crystallization and the intense magnetic field. Tsuruta, Canuto, Lodenquai and Ruderman (*Ap. J.*, **176**, 739) now reinvestigate the problem taking these effects into account. Their work neglects the possibility that a significant fraction of the rotational energy of the star might be dissipated as heat within (a) its crust (through the action of a steady wobble: Henriksen, Feldman and Chau; *Ap. J.*, **172**, 717) or (b) its superfluid (through the frictional coupling between charges and superfluid: Greenstein; *PDM*; 6.065.011; 6.065.094; *Nature Phys. Sci.*, **238**, 71). At present we are unable to predict neutron star blackbody temperatures with any degree of confidence; for instance the Crab Pulsar could be as cool as 10^5 K (making it essentially unobservable) or as hot as 5×10^6 K (making it eminently observable). Greenstein (*PDM*) has called attention to the forthcoming lunar occultations of the Crab Nebula in 1974 and 1975 as opportunities to search for blackbody X-radiation from the neutron star presumably associated with its pulsar.

Pulsar timing observations and 'theories' to account for them

From timing observations of a pulsar one can infer the rotation rate of its associated neutron star. Such observations have revealed two distinct types of anomalous behavior. The first, known variously as a 'speed-up', 'glitch' or 'period jump', is a relatively dramatic increase in both rotation rate Ω and slowing-down rate $|\dot{\Omega}|$, followed by a slow relaxation of $|\dot{\Omega}|$ back towards its pre-jump value. The second, discreetly referred to as 'timing residuals' or 'restless behavior', appears to be a continuous and irregular fluctuation of Ω about a mean.

Period jumps have been observed only in the two fastest pulsars; the Crab (Boynton, Groth, Partridge and Wilkinson, 2.141.231; Richards, Pettengill, Roberts, Counselman and Rankin, 2.141.232; Boynton, Groth, Huchinson, Nanos, Partridge and Wilkinson, *Ap. J.*, **175**, 217; Lohsen, Papaliolios and Carleton, 6.141.130; Lohsen, *Nature Phys. Sci.*, **236**, 70) and Vela (Radhakrishnan and Manchester, 1.141.068; Reichley and Downes, 1.141.069; 6.141.167). Each has sped up twice. For each pulsar the time between jumps was about two years. The magnitudes of successive jumps of each pulsar are about equal (but not precisely so) but differ between the two pulsars. In only one of the four events was a star actually observed to be pulsing more rapidly after the jump than before: the remaining three are consistent with the hypothesis that the pulsar simply stopped slowing down for a while. In no case has the post-jump behavior been observed in any detail. Scargle and Harlan (3.134.005) report a flurry of activity in the wisps near the Crab Pulsar following its first period jump and argue that the great energy associated with this activity shows that the event involved more than a simple change of state of the star.

At present the observational situation regarding pulsar timing residuals ('restless behavior') is exceedingly ambiguous. In particular it is not yet precisely clear what the phenomenon is that one would like to explain. The subject is reviewed by Michel (*Comm. Ap. Space Phys.*, **4**, 47). It began with a report by Richards, Pettengill, Counselman and Rankin (3.141.122) of a sine wave oscillation in the period of the Crab Pulsar. The observation was later withdrawn. It then appeared that the oscillation was irregular in nature. Nelson, Hills, Cudaback and Wampler (4.141.125) argue against this point of view and claim that the data can be understood as indicating (a) a succession of relatively small period jumps (about one a month) accompanied by (b) radical changes in the 'braking index' N (equal to $\ddot{\Omega}\Omega/\dot{\Omega}^2$) at the times of the jumps. Because no 'large' period jumps are accompanied by changes in N their point (b) appears difficult to understand. However it has not been shown that the observational data themselves argue against this possibility. Boynton *et al.* (*Ap. J.*, **175**, 217) argue that the Crab Pulsar residuals arise from a noise component in either Ω or $\dot{\Omega}$. They also describe a previously unrecognized and crucially important property of the residuals: that they are somewhat arbitrary and that they introduce an ambiguity into measurements of N. If one fits, say, three months of pulsar timing data to a smooth spin-down law one finds certain residuals and derives a certain value for N. If one then adds data from one more month of observations and makes a four-month fit both the residuals and N will be different. In particular, the amplitude of the residuals increases monotonically with the length of the data set being fitted. Previous attempts to measure the braking index yielded wildly discordant values because of this phenomenon. Boynton *et al.*, now find $N \simeq 2{\cdot}5$.

Greenstein and Cameron (1.066.039; see also Greenstein, *PDM*) argue that period jumps in pulsars could result from hydrodynamic instabilities in their interiors. Börner and Cohen (5.141.205) argue that they could arise from the sudden accretion of matter onto the star: masses on the order of that of the Moon are required to understand Vela. Michel (3.141.018) and Hills (3.141.139) show that planetary companions in eccentric orbits could reproduce the phenomenon (see, however, Boynton *et al.*, *Ap. J.*, **175**, 217). Scargle and Pacini (6.141.012) argue that period jumps could be due to explosive releases of plasma from the pulsar magnetosphere. Packard (*Phys. Rev. Lett.*, **28**, 1080) relates the jumps to relaxations of metastable vortex line patterns in the superfluid. The only suggestion that has been adequately explored is that of Ruderman (2.065.104), who argues that period jumps arise from starquakes – sudden relaxations of strain within the crust. Dyson (2.065.053) proposes that these strains are built up through volcanic activity. All other work has dealt with strains exerted by the decelerating torque. Smoluchowski (3.141.076) and Baym and Pines (6.141.231) analyze such starquakes in detail and show that the time between large quakes in the Vela Pulsar must be centuries or more: the fact that Vela has undergone two period jumps in two years therefore shows that they cannot be due to torque-induced quakes. Pines, Shaham and Ruderman (*Nature Phys. Sci.*, **237**, 83) argue that quakes in the solid core of the star (if it exists) could explain the Vela jumps. By scaling properties of known solids Smoluchowski and Welch (4.141.054) attempt to decide whether neutron star crusts can relieve stresses through plastic flow rather than cracking.

Baym, Pethick, Pines and Ruderman (2.141.085) interpret the post-jump behavior of a pulsar as a relaxation between its crust and its superfluid. Sutherland, Baym, Pethick and Pines (3.141.047) show how to estimate the mass of a pulsar on the basis of this interpretation.

Three suggestions were put forward to account for the non-existent sine wave in the Crab Pulsar's period: planetary companions (Richards *et al.*, 3.141.122), free precession of a non-spherical star (Chiuderi and Occhionero, 3.141.137; Ruderman, 3.141.217) and superfluid vortex lattice oscillations (Ruderman, 3.065.094; see however Fetter and Stauffer, 4.141.120). Although the observation has been withdrawn the theories remain viable: pulsars may exhibit precession and nutation and Ruderman (*PDM*) interprets the restless behavior of the Crab Pulsar in terms of vortex lattice oscillations. Greenstein (*PDM*) interprets it in terms of turbulent flow of the superfluid. As yet neither of these interpretations is sufficiently well-formulated to be refutable. Pines and Shaham (*Nature Phys. Sci.*, **235**, 43) give a detailed interpretation of the Crab's restless behavior in terms of large and small starquakes in its crust.

Chau, Henriksen and Rayburn (6.141.060) consider the evolution of an oblique rotator stabilized against alignment. They relate the effects of slow changes in geometry to the braking index, and wobbles to the restless behavior, of the Crab Pulsar. Their model is also applicable to Cen XR-3 (Henriksen, Feldman and Chau, 6.065.088).

INVESTIGATIONS ON STELLAR STRUCTURE IN THE U.S.S.R.

A. G. Massevitch

Convection in stars

The computed structure and the depth of the convective zone for main-sequence stars with a hydrogen convective zone ($T_{ef} < 10000$ K) are very sensitive to the value of the mixing length and the parameters in the equations describing the convective transfer of energy. At the same time the interpretation of physical processes in the external layers of stars depends strongly on the assumptions made concerning the mixing length (**1**).

The structure of the envelopes of red supergiants depends significantly on the treatment of superadiabatic convection. As to the choice of scale height for determining the mixing-length, the pressure scale height is preferable, since the density scale height leads to a physical contradiction (**2**).

If a non-local model of convection is used it can be shown that non-local treatment of convection does not change the structure of the convective zone. (Our non-local model is very similar to those given by Ulrich (**3, 4**)). Only the transition from non-effective convection to effective convection is more smooth than in the case of local convection for the same model. In the non-local model the density inversion is shifted to higher temperatures. Using the method described in (**5**), Uus (**6**) has calculated envelope models for the red giants and Ergma (**5**) for main sequence stars.

Satrs with about 1 to 10 $M_{\odot}$ go in the course of evolution through a stage of growth of degenerate carbon-oxygen core. At that stage in the case of more massive stars, if reasonably high convective heat conductivity is assumed, the convective envelope penetrates into the nuclear burning shell (**7**). As the lower part of the shell always remains radiative, there is no drop in the growth rate of the mass of the core. Penetration of convection results in changes of the envelope: the CN-cycle equilibrium concentrations are established, oxygen content decreases, and a part of the hydrogen is converted into helium.

Drobyshevsky (**8, 9**) considered the generation of the magnetic field of rotating stars having a partially ionized convective envelope. Computations were performed for the Sun. It has been shown that for a limiting case, when the accelerating forces act only through the electron component $\mathrm{Hp}_{\odot} \simeq 0{\cdot}005$.

Petruhin (**10**) found general formulae for the start of convection if the magnetic field is included.

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Comparison of theoretical results with observational data

Construction of theoretical H-R diagrams for open clusters

A net of time constant loci (isochrones) has been constructed by O. Dlujnevskaja and A. Piskunov (**1**) on base of models calculated by Paczynski (**2, 3**) for stars with 0·8, 1·5, 3, 5, 7, 10 and 15 $M_\odot$ and a chemical composition $X=0{\cdot}70$, $Z=0{\cdot}03$. Dependences $M-t$ and $\lg T_e - t$ (t-time) have been constructed for interpolation purposes. Interpolated masses and ages have been obtained with a step 0·02 $M_\odot$ and 0·1 in lgt.

Diagrams for 5 open clusters (Ngc 129, 6475, 1912, 1907 and Praesepe) have been investigated. The obtained ages of these clusters agree with those obtained by the method of the turn-off point.

Several peculiarities have been noticed in the diagrams of the investigated clusters. The net of isochrones has been extended on base of models computed at the Astronomical Council for masses $16 \div 64\ M_\odot$.

The new isochrones have been used to compare observational and theoretical data for single stars, stellar associations and groups. Models of open clusters for 58,285 and 580 member stars with masses larger than 1·5 $M_\odot$ have been constructed by Piskunov (**4**). The initial mass function was taken according to Salpeter.

The dissipation of stars and age differences are ignored. Evolutionary sequences of cluster models on the H – R diagram, luminosity, color and age dependences on the integral colors are obtained.

The obtained dependence ages on integral colors are compared with observational data for 67 open clusters according to Gray (**5**) and with integral colors and magnitudes of the open clusters: NGC 6231, 1805, 2581, 4755, 3766, 2464, 4103, 2516, 2451, 2391, 4665, 121 and Hyades estimated.

The agreement between observational and theoretical data allows one to conclude that theoretical dependences enable the estimation of the age and the mass of a cluster by its integral color.

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Evolution of close binaries

In the course of evolution of a close binary a considerable amount of mass and angular momentum may be lost from the system (**1**).

A. Tutukov and L. Yungelson (**2**) obtained equations describing the change of the distance between the components in the course of mass and momentum loss from the system. Two distinct

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cases were discussed: first, when the particle ejected in L_1 is lost by the system due to the acceleration in the gravitational field of the binary star; and second, when the matter is transfered to the secondary white dwarf star and after that is ejected by a Nova explosion. By means of mass and momentum loss it is possible to improve agreement between the theory and observational data (3). The same process may serve as an explanation for the evolution of binaries consisting of both stars – degenerate configurations, like HZ 29.

The second stage of mass exchange in a binary star, in which the white dwarf is already formed in the course of evolution may be accompanied by Nova explosions, due to hydrogen-burning in the degenerate layer formed by accreted matter on the surfade of the white dwarf. The estimates for this process, taking into account heating by inflowing matter (4) allow to explain the periodicity of explosions, energy and mass of ejected envelopes. Mass and momentum loss on the second stage of mass exchange may lead to the formation of ultra-short period binaries.

M. Kumsiashwili and L. Yungelson (51) and T. Galkina, G. Rodionova, L. Yungelson (6) discussed the evolutionary stages of binaries V 448 Cyg AO Cas, HD 190918, αVir, HD 193793, HD 47129 and some other massive systems ($M_1 \gtrsim 10\ M_\odot$), with absolute dimensions given in Svechnikov's catalogue (1). Almost all primaries of main sequence detached binaries reach their critical limits in the course of core hydrogen-burning or very soon afterwards, before core helium-burning occurs. Some arguments are given for possibility of a second mass exchange in the system V 448 Cyg. To explain the observed dimensions of some massive semi-detached systems it is necessary to assume mass loss from the whole system.

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Stellar structure and rotation

The structure of non-uniformly rotating main sequence stellar interiors have been studied (1), (2), (3). Approximative steps for obtaining numerical solutions using finite differences have been used to derive quasi-stationary models with meridional circulation for a 2·5 $M_\odot$-star with various distributions of angular momentum.

The results show that pressure and density increase and temperature decreases as a function of the total angular momentum. Similarly the models show a strong decrease of luminosity when the central rotation increases. Comparison with published models of larger masses, derived by different techniques, shows that the decrease of luminosity depends only on the ratio of the total angular momentum to the square of mass, and is practically independent of the distribution of angular momentum. The volume of the star decreases when the ratio of central to surface angular velocity increases, becoming at a certain stage smaller than the volume of the non-rotating star. The consequence of these changes on the luminosity-effective temperature diagram is that the displacement of a model from the zero-rotation main sequence upwards is smaller for a differentially than for a uniformly rotating star, and is downwards if the ratio of central to surface angular velocity is sufficiently large. So there appears an observational difficulty to separate a slowly rotating star from a heavier star with a faster central rotation.

Evolution of massive stars (4) and a sequence of evolutionary tracks for medium mass stars (5) have been studied including differential rotation and neglecting non-sphericity effects. For the initial main sequence models various distributions of angular momentum and, during the evolution, conservation of angular momentum in spherical shells have been assumed. Central rotational

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velocities will increase already in the central hydrogen-burning and in secondary contraction phases, and an especially strong increase will be produced immediately after the latter phase. This makes strong surface deformations probable. Effects on the time scale of evolution are less than 10% if the rotation is uniform in the initial main sequence, but increase strongly with increasing non-uniformity of rotation of the initial model. The effects on the form of isochrones are under consideration along with an attempt to apply the results to the brighter stars of the Pleiades cluster.

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Neutron stars

A pseudopolytropic approach to stars has been studied by Guseinov *et al.* (**1**). The equation of state has the following form: $p = c\varrho^{[1+(1/n)]}$ where $c = \text{const}$. This approximation is useful when studying the late stages of evolution.

Amnuel and Guseinov (**2**) investigated accretion of gas on neutron stars having strong magnetic fields. If the star has a magnetic dipole moment then by symmetrical accretion one can obtain the observed radio radiation.

Seidov (**3**) has found in the frame of (general relativity) the crucial value of the jump of energy density in a phase change, resulting to the loss of stability in the point $P_c = P_0$ (P_c – central pressure of the star, P_0 – the pressure in the phase change).

The properties of very dense and degenerated plasma ($\varrho_0 \leqslant \varrho \leqslant 1000\,\varrho_0$ where ϱ_0 – nuclear density) have been investigated by Avakian *et al.* (**4**). The concentration and the threshold of stability for the full spectra have been calculated.

In the frame of Newton's theory of gravity Vandakurov (**5**) investigated the non-radial low-frequency oscillations of a rotating neutron star having a toroidal magnetic field.

Guseinov and Kasumov (**6**) calculated the ejection of an envelope during the collapse of a rotating mass.

Amnuel and Guseinov (**7**) have considered the process of capture of the falling plasma flow by the magnetic dipole of a neutron star in a binary system. The shape of the capture front, originating when plasma stops, has been calculated.

Guseinov and Novruzova (**8**) considered the possibility of the discontinuity of a binary in the case of the collapse of one of the components. They concluded that a neutron star can be at a distance no less than $5 \cdot 10^{12}$ cm from the component and a collapsed star – at a distance no less than 5×10^{11} cm.

Vandakurov (**9**) calculated non-radial oscillation of ideal conducting neutron stars with a magnetic field.

Amnuel and Guseinov (**10**) have studied the influence of various factors on the radiation of a neutron star caused by accretion.

The problem of mass loss for a rotating star during the collapse was considered by Guseinov and Kasumov (**11**). In the assumption that beginning with the start of collapse the specific rotational moment of the star remains constant the rate of maximum loss of mass within collapse only because of rotational instability has been estimated.

Papoian *et al.* (**12**) have determined the structure and integral parameters of uniformly rotating equilibrium models of neutron stars in the ω^4 approximation in the Newton theory of gravity. It was shown that the results obtained differ slightly from those obtained in the ω^2 approximation.

Vartanian *et al.* (**13**) have studied the radial pulsations of rotating cold neutron stars that are

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near the state of stability loss. The effects of the general relativity are taken into account. The integral parameters and frequency of radial pulsations for different equilibrium configurations are calculated.

The frequencies of quasiradial pulsations of rotating white dwarfs and neutron stars within the frame of Newton's theory are calculated by Papoyan *et al.* (**14**). The critical values of the central density in the sense of dynamical instability are obtained.

Guseinov (**15**) has calculated the collapse of hot helium stars with initial conditions $\varrho_0 = 10^9$ g/cm^3, $T_0 = 10^{10}$ K, $3 \cdot 10^{10}$ K.

Schwartzman (**16**, **17**, **18**) made a series of studies of accretion of matter on a neutron star. He has studied various physical processes accompanied by accretion such as ejection of gamma radiation, X-rays, and relativistic electrons and positrons.

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Evolution of stars with a magnetic field

Homogeneous stellar models with a magnetic field were calculated for stars with 4 $M_\odot$ and 32 $M_\odot$. The gradient of the magnetic pressure was included in the equation of equilibrium. The magnetic field H was taken as $H = A\varrho^{2/3}$ where A is a constant and ϱ is the density of the matter. For the 'fossil' magnetic field $A \approx 10^7 (M/M_\odot)^{4/3}$.

Evolutionary tracks for 4 $M_\odot$ and 32 $M_\odot$ stars on the hydrogen-burning stage were obtained for different values of the magnetic field. It has been shown that qualitatively the influence of the magnetic field on stellar models is similar to the influence of rotation and leads to a decrease of the effective mass of the star. G. Ruben and A. Tutukov, *Nauchn. Inf.*, of *A. C. Ac. of Sc. U.S.S.R.* (in press).

The white dwarfs

Eminzade (**1**) estimated the total energy of cool white dwarfs with central densities ($8{\cdot}91 \times 10^7 \leqslant \varrho_c \leqslant 1{\cdot}97 \times 10^{10}$).

Papoyan *et al.* (**2**) have determined the structure and integral parameters of uniformly rotating equilibrium models of white dwarfs in the Ω^4-approximation. They showed that the obtained results slightly differ from those obtained in the Ω^2-approximation. Consequently for a configuration in a critical state with respect to equatorial instability the Ω^2-approximation may be applicable as well as the Ω^4-approximation.

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Using the energy criteria Vartaman and Hovsepian (3) studied evolution and radial pulsations of rotating isotermic white dwarfs. The effects of the general relativity and neutronization are taken into account. Values of the period of pulsation and points of loss of stability for different masses have been found. Sedranian *et al.* (4) have investigated the rotation of white dwarfs using the second-order perturbation analyses. It is shown that the second-order corrections are very small and that the first-order perturbation theory gives good results.

Seidov and Eminzade (5) have found the cooling time for a white dwarf taking into account more correct values of opacities, thermal energy and chemical compositions.

Imshennik and Seidov (6) have investigated periods of pulsation of rotating white dwarfs near Chandrasekhar's limit. They obtained the minimum periods of pulsation and showed that uniform rotation near the possible limit decreases the minimum period of pulsations more than 3 times (from 1·8 s to 0·5 s).

Arutjunijan and Chubaryan (7) have used the Ω^2-approximation for studying small amplitude quasi-radial pulsation of rotating relativistic white dwarfs. When neutronization is taken into account the point of loss of stability is shifted to the smaller central densities as compared with $A/Z = 2$.

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Late stages of stellar evolution

Evolutionary sequences for 16, 32 and 64 $M_\odot$ with initial chemical composition $X = 0{\cdot}602$, $Y = 0{\cdot}354$, $Z = 0{\cdot}044$ ($X_{12} = 0{\cdot}00619$, $X_{16} = 0{\cdot}01847$) have been calculated up to formation of a degenerate core: for 16 $M_\odot$ – to complete core helium exhaustion (1–2), for 32 and – 64 $M_\odot$ – to complete oxygen depletion (3–5). In the course of calculations particular attention was paid to the treatment of semi-convection. Simultaneous calculations were performed using three different stability conditions: *A*) $\nabla_r = \nabla_{ad}$; *B*) $\nabla_r = \nabla_{ad} + \nabla_\mu$; *C*) $\nabla_r > \nabla_{ad} + \nabla_\mu$ (3). The evolution of stars of 32 and 64 $M_\odot$ on the core carbon- and core oxygen-burning stages was calculated taking into account neutrino energy loss.

The results of calculations show that different assumptions of stability conditions in the semi-convective zone do not change the general features of the stellar models at evolutionary stages preceding core helium-burning (3). The main differences appear in the hydrogen profiles being the cause of differences in the late stages of evolution.

In case A the main core helium-burning stage corresponds to the blue supergiant region on the H–R diagram (4), and is followed by the red supergiant stage (5). As for cases B and C, both core helium-burning and succeeding evolution occurs in the red supergiant region (2, 4–5).

Computations of the late stages of evolution of massive stars appear to be very sensitive to the treatment of semi-convection. A more satisfactory agreement with observational data is found for evolution in case A (Schwarzschild' stability criterion).

The age and internal structure of the models of the core carbon- and core oxygen-burning stages change considerably if energy loss by neutrino is taken into account (5).

The problem of partial mixing in the semi-convective zone in massive stars was considered (6), using Kato's idea about vibrational instability layers with $\nabla_a < \nabla_r < \nabla_a + \beta/4 - 3\beta$

The linearized equation of the motion of convective elements in a medium is obtained taking into account radiative heat exchange. A condition for instability was found using the Rause-Gurvitz criterion. It appears that in the semi-convective zone $\nabla - \nabla_{ad} \simeq 10^{-5}$ is maintained during

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the evolution due to enhacement of vibrational motions with a wavelength $\lambda \sim 10^7$cm and their turbulization. This allows one to redefine the problem of semi-convection for massive stars ($M > 10M_\odot$): semi-convection takes place outside the convective core and the stability condition for this zone is $\nabla_r = \nabla_{ad}$. Evolution with this stability condition leads to evolutionary tracks without any loops in the supergiant region on the H–R diagram, as has been shown in (**4**).

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