35. STELLAR CONSTITUTION (CONSTITUTION DES ÉTOILES)

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I. INTRODUCTION

Once again this report consists of detailed discussions of a limited number of topics of current interest, which have not been discussed in recent reports. The subjects are: *Mixing in Stellar Evolution* (A. Maeder); *Supernovae* (J. Craig Wheeler); *Theory of Variable Stars* (J. Cox); *Theoretical Studies of Star Formation* (J. J. Monaghan); *The Age and Helium Content of Globular Clusters* (V. Castellani). Because the first three contributions have been written by different authors there is a small amount of overlap in their contents. I am very grateful to the authors for providing their reports very promptly. The references are in general identified by their number in *Astronomy and Astrophysics Abstracts* but many references are too recent for this to be possible and a few others were not included in *A & A Abstracts*.

Although the study of galaxies and cosmology now excites most popular interest in astronomy, the frequency of IAU sponsored meetings concerned with stars indicates that the structure of stars is still a very active research interest. Since the preparation of the last draft report IAU Symposia and Colloquia of interest to members of Commission No. 35 have been IAU Symposium 85 *Starclusters*, Victoria, B C, Canada, August 1979, IAU Symposium 88, *Close Binary Stars*, Toronto, Canada, August 1979, IAU Symposium 93, *Fundamental Problems in the Theory of Stellar Evolution*, Kyoto, Japan, July 1980, IAU Symposium 95, *Pulsars*, Bonn, FRG, August 1980, IAU Symposium 98, *Be Stars*, Munich, April 1981, IAU Symposium 99, *Wolf Rayet Stars*, Cozumel, Mexico, September 1981, IAU Colloquium 51, *Convection and Turbulence in Stellar Atmospheres*, London, Ontario, Canada, August 1979, IAU Colloquium 53, *White Dwarfs and Variable Degenerate Stars*, Rochester, NY, USA, July-August 1979, IAU Colloquium 58, *Stellar Hydrodynamics*, Los Alamos, New Mexico, USA, August 1980, IAU Colloquium 59, *Effects of Mass Loss on Stellar Evolution*, Trieste, Italy, September 1980, IAU Colloquium 66, *On the Problems of Solar and Stellar Oscillations*, Crimea, USSR, September 1981, IAU Colloquium 69, *Binary and Multiple Stars as Tracers of Stellar Evolution*, Bamberg, FRG, August-September 1981 and IAU Colloquium 70, *The Nature of Symbiotic Stars*, Haute Provence, France, August 1981. There have, of course, been many non-IAU meetings concerned with stellar structure and evolution and some of these are mentioned in the detailed reports below.

Many of the most difficult remaining problems in stellar evolution concern the hydrodynamics of stellar interiors, starting with the process of star formation and ending with stellar death in a supernova explosion. Both of these topics are reviewed below together with a discussion of stellar stability and mixing in stellar interiors. The general topic of mass loss from stars is omitted because it was included in the 1979 draft reports. The topic of The Age and Helium Content of Globular Clusters stands apart from the others, but it seems particularly appropriate because of current developments in cosmology. If Hubble's constant may be of order 100 km s^{-1} Mpc^{-1} , it is increasingly important to know how reliable are estimates of the ages of the oldest known objects in the Galaxy and the helium content needs to be compared with theoretical estimates of primaeval helium production.

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II. MIXING IN STELLAR EVOLUTION (A. Maeder, Geneva Observatory)

a) Introduction

Mixing remains a major source of uncertainty in most stages of stellar evolution (e.g. concluding remarks of *IAU Symp 93* by Tayler). All issues of stellar evolution theory are affected by possible mixing: the lifetimes, the tracks in the HR diagram, the surface abundances and various isotopic ratios, the nucleosynthetic yields, the central conditions, the final stages of evolution, the pulsation properties, the apsidal motion test, the occurrence of some peculiar stars... For 3 quarters of a century Schwarzschild's criterion has been the basic tool for deciding whether or not mixing occurs somewhere in a star. Over recent years there has been a growing number of theoretical and observational papers suggesting sizable divergences from the classical picture. Here we shall mainly focus our attention on these recent developments.

b) Upper Main Sequence stars

The oldest and still most acute problem is that of *rotation and circulation* (see Tassoul, 1978: *Theory of rotating stars*, Princeton Univ. Press). The general idea is that circulation cannot penetrate varying molecular weight barriers, which therefore insulate various regions in a star with respect to their rotation (e.g. Kippenhahn and Thomas, *IAU Symp 93*, 237, 1981). More uncertain remains the evolution of angular velocity distribution in homogeneous regions. Substantial clarifications have been brought by the above authors on the time scale of the Goldreich-Schubert-Fricke instability (which is of the order of the Eddington-Vogt time scale, cf. 28.065.052) and on the non-constancy of the angular velocity distribution ω on equipotential surfaces. Evolutionary models with time-dependent redistribution of angular momentum and composition have been performed by Endal and Sofia (21.065.011), who show in particular that rotating cores develop non-axisymmetric instabilities rather than critical velocities. The instability would prevent their 7 $M_{\odot}$ model from reaching carbon detonation. They have also computed (26.065.007) the expected surface velocities corresponding to various cases of angular momentum redistribution for stars throughout the HR diagram.

Following Zahn's discussion (12.065.143), the mixing associated with *shear flow instabilities* in differentially rotating stars has been considered by several authors in relation with: - mixing in the envelope of early-type stars (Kobayashi 27.064.065), - the diffusion and element stratification in atmospheres (Michaud 27.062.091; Vauclair, S. *A J*, *86*, 513, 1981), - the generation of stellar winds (Sreenivasan, Wilson, preprint 1981), - the $^{12}C/^{13}C$ ratio in giants (cf. Genova and Schatzman 26.065.013). While possibly active in the Sun (see below), diffusion driven by shear flow instabilities has too long a time scale to significantly influence MS evolution for stars in the range $M \simeq 3 - 20\ M_{\odot}$. However, due to the very high radiative viscosity in stars with $M \gtrsim 20\ M_{\odot}$, this mixing process seems to be very efficient in the most massive stars (Maeder, 1981, *A & A* in press), where it may account for the recognised deficiency of MS mass loss in forming WR stars.

A declining importance seems, according to the author's own opinion, to be given now to the role of *semi-convection (SC)* in stellar evolution. There are several reasons for that: 1) After the central H-exhaustion, a fully convective region mixes the previous SC zone. 2) A fine zoning in mass shells leads to an alternating convective and radiative shell structure, a solution which was originally proposed by Tayler in 1954, (cf. 1.065.065). This shell structure moves around so as to maintain a gradient in molecular weight (cf. Schlesinger 14.065.004; Lamb et al. 18.065.010). 3) Mass loss, due to the decrease of the core size, reduces or even suppresses SC (cf. Chiosi et al. 21.065.008; Stothers and Chin 26.065.014), and this influences the C/O yields (Dearborn 25.065.059). 4) The overshooting from convective core appears to reduce or suppress SC (cf. Cloutman and Whitaker 27.065.062 ; Stothers and Chin, *Ap J, 247*, 1063, 1981; Bressan et al. *A & A* in press). 5) Models which simultaneously include mass loss, core overshoot and shear flow mixing (cf. Maeder, *A & A* in press) show that the conditions for SC do not occur during MS evolution.

Schwarzschild's criterion for convection formally indicates the level in a star where the average acceleration of the convective cells vanishes whereas mixing should extend up to the level where the velocity of the convective elements becomes zero (cf. 18.065.004). Various estimates of the distance of *convective overshoot* have been made: either by using a non-local mixing length theory (Shaviv and Salpeter 10.065.018 Maeder 13.065.074; 17.065.018; Bressan et al. 1981, in press), or by accounting for the flux of turbulent energy (Roxburgh 21.065.052) and its finite decay time (Cloutman and Whitaker 27.065.062). Similarly to the debate between the Ledoux and Schwarzschild criteria, the question arises as to how core overshoot penetrates μ-barriers. Models with extended cores show in common a broadening of the MS in the HR diagram (cf. Maeder 17.065.018; Massevitch et al. 25.065.071). A detailed comparison of models and cluster sequences in the HR diagram was made by Maeder and Mermilliod (*A & A, 93*, 136, 1981), who find that in the range of ages from Hyades to Pleiades the stellar cores should include 20-40 % more mass than expected. For large masses ($M > 10\ M_\odot$), the differences appear to be much larger (cf. Meylan and Maeder, *A & A* in press). Stothers and Chin (*Ap J, 247*, 1063, 1981) examine the possible merging between the core and the intermediate fully convective zone, as well as the possible inwards penetration of the outer convective zone in red supergiants. Whether the discrepancies found with the apsidal motion test (cf. Monet 27.120.026) are also related to extended cores remains an open question.

The problem of *tidally driven circulation* in close binaries, which is generally ignored in computations of double star evolution, has been discussed by Smith and Smith (*MNRAS, 184*, 583, 1981).

c) Lower MS stars, Population II stars

The problems of *solar oscillations* and of *solar neutrinos* are two important sources of impetus for studying the solar structure. IAU Coll 66 chaired by D. O. Gough contains the major and most recent references on solar and stellar oscillations. The solar neutrino problem has been reviewed by Iben (1977, 7th Saas-Fee Course), by Bahcall (26.080.027; *Phys Rev Lett, 45*, 945, 1980). Whether these problems are in connection with some kind of mixing is not yet settled.

A lingering mystery remains that of the origin of the *blue straggler stars*, which in some old clusters, like NGC 7789, are far from being a marginal pre-occupation. Wheeler (26.065.040) has illustrated the difficulties in explaining the existence of these stars by non-coeval star formation or by binary mass transfer, a point of view challenged by Meyer-Hofmeister (27.117.079). From computation of partially (and arbitrarily) mixed stars, Saio and Wheeler (28.065.094) find that extensive mixing over a mass fraction 0.4-0.9 is a viable hypothesis for blue stragglers. The mixing mechanism, however, remains to be found.

Models for the spin-down of the Sun have been performed by Endal and Sofia (*Ap J, 243*, 625, 1981) who consider both the transfer of angular momentum as well as *mixing by shear flows*. Schatzman and Maeder (*A & A, 96*, 1, 1981) have also considered solar evolution at the edge of shear flow instability. This mixing produces (cf. also Bienaymé, 1981, thesis Univ. Nice) surface enrichments in ^3He and ^{13}C. A relation between mixing by shear instability and the problems of solar neutrinos and blue stragglers has been proposed (Schatzman and Maeder, *Nature, 290*, 683, 1981).

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The *downward gravitational settling of helium* was considered by Noerdlinger (21.062.037) and Giannone and Rossi (22.065.050). Models of Population II stars with helium settling were made by Noerdlinger and Arigo (27.154.026) who showed that the inferred ages of globular clusters should then be reduced by 22 %. The mixing in horizontal branch stars has been studied by Arimoto (28.065.064), Winget and Cabot (28.065.093). Norris (*Ap J*, *248*, 177, 1981 and ref. therein) has proposed an interpretation of the large range of CN abundances in globular cluster stars in terms of mixing on the Main Sequence. It is clear that the question of mixing remains of major relevance for the cosmological problem of the age of globular clusters.

d) Post-MS evolution

The surface abundances and isotopic ratios of red giants (RG) bear the signature of mixing processes in stellar interiors. As studied in detail by Iben and colleagues, 3 *dredge-up phases* occur; the first is due to the inward penetration of the convective envelope when the star reaches the RG branch (see also Shadick et al., 28.065.002). The second occurs at the beginning of the asymptotic giant branch (AGB) for stars initially more massive than 3-5 $M_\odot$ following the ignition of the He-burning shell. The evolution and surface abundances during this phase have been studied as a function of mass and composition by Becker and Iben (26.065.008; 27.065.040), who also envisage the possible effects of overshooting, semi-convection and circulation (cf. also Becker, *Ap J*, *248*, 298, 1981 for the effects on the second blue loop). The third dredge-up occurs during the AGB: following the He-shell flashes the bottom of the convective envelope penetrates through the H-He discontinuity (for the enhancement in s-process and other elements, see Iben and Truran, 21.065.032). The evolution of surface abundances through all these phases was studied by Renzini and Voli (*A & A*, *94*, 175, 1981). The constraints on mixing during shell flashes from Tc abundances in peculiar red giants have been examined by Scalo and Miller (*Ap J*, *246*, 251, 1981). From the observed luminosity distribution of carbon stars, which, roughly, is shifted towards too low luminosities with respect to theoretical expectations, Iben suggests (*Ap J*, *246*, 278, 1981) the occurrence of mixing during the pulses of AGB stars. The convective effects in the intershell region of red supergiants have been studied by Sackmann (27.065.002; 27.065.005; 28.065.047).

Quite a new insight in AGB evolution has been given by Prialnik, Shaviv and Kovetz (*Ap J*, *247*, 225, 1981). They show that the *diffusion* resulting from encounters of charged particles is fast enough to transport matter between the 2 burning shells of AGB stars. They conclude that a steady state exists which prevents the shell flashes and the third dredge up from occurring; thus these flashes could not be the triggering mechanism of planetary nebulae ejection. Basic questions regarding mixing in *the helium flashes* were asked by Edwards (27.065.013) on mixing induced by gravitational potential fluctuations of convective elements and by Wood (*Ap J*, *248*,311, 1981) concerning the no energy cost of dredge-up mixing. The helium core-flashes were studied in particular by Cole and Deupree (28.065.018; *Ap J*, *247*, 607, 1981; see also Scalo, 25.065.024). Smith and Demarque (28.065.069) show the difficulties in explaining the CH subgiants by mixing during the core flash.

Most relevant for our knowledge of mixing are *the observed CNO, Li abundances and* $^{12}C/^{13}C$ *ratio in red giants and supergiants*. For Hyades giants, the observations are in agreement with the predictions from dredge-up effects, while lower mass giants ($M < 1.3\ M_\odot$) are ^{13}C rich relative to standard predictions, the ^{13}C richness going along with a Li deficiency (Lambert et al. 27.114.006; *Ap J*, *248*, 228, 1981). Lambert and Luck assume (1981, preprint) that Li abundance in red giants is primarily controlled by stellar mass. They support the view that for lower masses some additional mixing occurs in MS stars. Meridional circulation and CNO anomalies in red giants have also been studied by Sweigart and Mengel (25.065.032) while Scalo

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and Miller (22.066.013) suggest that low $^{12}C/^{13}C$ ratios are due to shear instabilities or to mixing during the He-core flash and they rule out mass loss and meridional circulation.

For F-G supergiants and Cepheids, Luck and Lambert (*Ap J, 245*, 1018, 1981) show that ^{12}C underabundance and ^{14}N overabundance are larger than predicted and they also find an unexpected reduction of ^{16}O. They suggest that these results, which show surface evidence of the ON-cycle, are due to some mixing which has occurred during MS evolution. A different and more classical idea is supported by Iben and Renzini (*Ann Rev A A* in press) who assume that some effects in the abundance determinations may mimic the action of the ON-cycle. In order to explain the observations by Luck and Lambert, Becker and A. N. Cox (*Ap J Let* in press) suggest a considerable mixing of material during MS evolution from the core to the near surface region (which, indeed, is in agreement with cluster sequences), this material is then dredged-up into the atmospheres of Cepheids and supergiants.

The study of *pulsation properties* is one of the basic tests on stellar interiors. A. N. Cox and co-workers (cf. A. N. Cox 28.122.102 and ref. therein) have proposed that helium enrichment by a selective wind, which preferentially removes hydrogen, is able to account for the period ratio of double mode Cepheids (Cox et al. 25.122.056) and to predict Cepheid masses consistent with the evolutionary masses. Concerning the pulsation of supergiants and β Ceph variables, Cox and co-workers (1981; *Workshop on pulsating B stars*, Nice Obs.) suggest that the pulsation driving is due to periodic overshooting and mixing of H into convective cores (for β Ceph stars) and convective shells (supergiants). The triggering of the overshoot could occur by non-radial g-mode pulsations, which have large amplitudes in the mode trapping μ-gradient zone.

e) Works on physics of convection and mixing

Some basic problems of *stellar convection* have been considered by Zahn (*IAU Colloq 51*, 1, 1981). Improvements of the classical mixing-length theory regarding the averaging of opacity have been suggested by Deupree (26.065.033), and regarding the value of the mixing-length ratio by Deupree and Varner (27.062.059) and Chan et al. (*Ap J, 243*, 582, 1981). In the third of a series of papers, Latour et al. (*Ap J, 248*, 1081, 1981) have investigated the coupling of the two convection zones in A-type stars by penetrative motions. Convection in spheres and spherical shells of Boussinesq fluids has been thoroughly studied by Marcus (25.062.076; 28.065.030; 28.065.033). The time scale of thermohaline mixing has been estimated by Kippenhahn et al. (28.065.051). Glatzmaier and Gilman (*Ap J Sup, 45*, 335, 351, 381, 1981) have studied compressible convection in rotating spherical shells with an application to the Sun. For the Sun Durney (*Ap J, 244*, 678, 1981 cf. also 26.065.042) has shown that the interaction of rotation and convection results in large pole-equator differences of the flux in the lower part of the convection zone, compatible with a negligible difference at the surface.

The *convective stability of magnetic stars* has been investigated by Simon (28.065.009) who finds a stability condition in the case of poloidal fields. The stability of stars containing mixed poloidal and toroidal fields has been discussed by Tayler (27.062.010). A modification of Schwarzschild's criterion has been proposed in the (too) simple case of net isotropic pressure (Schatten and Sofia, *Ap Let, 21*, 93, 1981). Hubbard and Dearborn have considered mixing driven by magnetic buoyancy in MS stars (28.065.016) and also the converse possibility that strong fields inhibit convection in stellar cores. The interactions between *convection and stellar pulsation* have been considered by Poyet and Spiegel (26.065.048), Gonczi and Osaki (27.062.052; *A & A, 96*, 138, 1981).

An appropriate treatment of the late stages of stellar evolution requires the use of *time-dependent convection* (e.g. Weaver et al. 22.065.033) and most

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authors seem to apply a diffusion treatment. The original suggestion has been made by Epstein (26.125.002) that collapsing cores develop inversion zones with decreasing lepton number per baryon and that such zones are unstable to convection. (The inversion zone is formed as a result of the rapid electron capture rate and the very low neutrino mean free path). The possibility of an associated large scale core overturn (Colgate, Petschek 27.125.032) and its major role in powering a supernova explosion was supported in various papers (e.g. Bruenn et al. 26.065.043; Livio et al. 27.065.089; Smarr *Ap J, 246*, 515, 1981), while according to Lattimer and Mazurek (*Ap J, 246*, 955, 1981) stellar explosions cannot be due to leptonic overturn.

f) Final remark

Although improvements of the convection theory are still badly needed (cf. the case of red supergiants where most of the approximations of the mixing length theory break down), there is now growing evidence that some mixing, in addition to standard convection, plays a role at various evolutionary stages, on the MS and then in later stages. However, so far the respective importance of the various mechanisms mentioned here (shear flow mixing, convective overshoot, meridional circulation, semi-convection, tidal mixing, etc) has not been well established and no standard recipe for the treatment of these effects in evolutionary models has emerged yet. Thus the better knowledge of the mixing mechanisms acting in stars remains a major challenge for the years to come.

III. SUPERNOVAE (J. Craig Wheeler, University of Texas)

Recent review papers have discussed degenerate thermonuclear explosions (Mazurek and Wheeler 27.065.043) pre-supernova evolution (Sugimoto and Nomoto 27.125.031) light curves (Chevalier, *Fund Cosmic Phys, 7*, 1, 1981) and the general status of the subject of supernovae (Wheeler, *Rep Prog Phys, 44*, 85, 1981). These topics and others are explored in more depth in several conference proceedings (Meyerott and Gillespie (eds) 1980, *Supernova Spectra-Atomic and Spectroscopic Data Needs* (La Jolla); Wheeler (ed) 1980, *Proceedings of the Texas Workshop on Type 1 Supernovae* (Austin); Rees et al. (eds) 1982, *Proceedings of the NATO Advanced Study Institute on Supernovae* (Cambridge); the two latter are denoted *T* and *C* in what follows.

Estimates of the lower mass limit for supernovae set by counts of photometric white dwarf candidates in open clusters range from 5 to 7 $M_\odot$ (Anthony-Twarog, *Ap J* in press; Romanishin and Angel 27.153.001). The present studies still allow the possibility that some stars in this mass range undergo degenerate carbon ignition and explode. Current theoretical indications are that a violent but subsonic burning, not a detonation, is involved in such a case (Mazurek and Wheeler 27.065.043; Sugimoto and Nomoto 27.125.031).

Stars with $8 \lesssim M/M_\odot \lesssim 12$ burn carbon in a non-degenerate fashion. Evolution in this mass range is complicated by time-dependent convection, dynamical shell flashes and rapid electron capture and is quite sensitive to mass (Miyaji et al. 28.065.012; Woosley, Weaver, and Taam in *T*). For $M \gtrsim 8\ M_\odot$ the calculations give off-center semi-degenerate carbon ignition which spreads to the center then proceeds in a series of shell burnings. The degenerate core composed of O, Ne and Mg grows to nearly the Chandrasekhar mass. The core undergoes rapid electron capture leading to collapse. Ignition of the oxygen and incineration to nuclear statistical equilibrium occurs via a standing burning wave. Complete collapse of the core to neutron star densities is indicated. For $M \sim 10\ M_\odot$ calculations reveal a complex set of shell burnings which can leave a silicon shell on top of a lighter neon core. Neon shell flashes in this core can be strong enough to eject the H and He layers. These stars are predicted to ultimately develop an iron core

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which collapses due to photodisintegration or perhaps electron capture.

There is a reasonable expectation that stars in the mass range $\sim 8 - 12\ M_\odot$ and somewhat above lead to supernova of Type II. Supernova rates (uncertain though they are) are consistent with Type II coming from this range. With present estimates of the stellar mass function, to omit this mass range and rely on higher mass stars would result in a paucity of events. A possible caveat is that recent indications (eg Bash and Visser, *Ap J, 247*, 488, 1981) suggest that the mass function for O stars may be flatter than previously thought, in which case this argument would need re-evaluation.

Continued study of the proper motions of pulsars has given direct evidence for the lifetime of pulsars against field decay or alignment. Corresponding estimates of the pulsar birthrate, one per 20 - 50 years in the Galaxy (Taylor, Manchester and Lyne, see Lyne in *C*) are consonant with the rate of Type II supernovae. A large contribution of the pulsar birthrate from other than Type II events is not necessary. The detection of X-ray synchrotron nebulae around several pulsars and the failure to see them in a majority of supernova remnants (Helfand 1981, private communication) cautions against premature complaisance in this regard.

Stars of $8 - 12\ M_\odot$ contain very little mass between the collapsing core and the hydrogen envelope so they are not expected to contribute substantially to nucleosynthesis. Nomoto (1981, *Ap J* in press) has proposed that the explosion of an $8\ M_\odot$ star would give a helium rich, metal poor event which he identifies with the Crab Nebula. This is consistent with the carbon abundance deduced from IUE spectra (Davidson et al. 1981, *Ap J* in press) and also with the tentative identification of a dilute hydrogen-rich circumstellar nebula by Murdin and Clark (1981, *Nature* in press).

More massive stars, $\gtrsim 12\ M_\odot$, are predicted to evolve iron cores which collapse through photodisintegration with less of the evolutionary complications which plague the lower mass stars. These stars have thicker shells of heavy elements and some, at least, are expected to explode in order to account for nucleosynthesis of the elements with $12 \lesssim A \lesssim 56$. Whether all stars more massive than $12\ M_\odot$ explode is an open question.

The extensive effort to understand core collapse has focussed on the cores of these massive stars. Electron capture and neutronization are limited by neutrino trapping (Bethe, Brown, Applegate and Lattimer 26.066.131). The result is a relatively low entropy collapse to nuclear density before complete dissociation of nuclei occurs. During collapse a core of $\sim 1\ M_\odot$ with a homologous rather than free fall velocity profile forms (Goldreich and Weber 27.065.088).

When the core reaches nuclear density, the equation of state stiffens and a "bounce" occurs. A shock forms where the infalling matter in the homologous core is moving at the sound speed. Interior to this point, at about $0.2\ M_\odot$, the core is unshocked and remains relatively cool. Exterior matter rains onto the shock and the outstanding question is whether the shock moves out to larger radii sufficiently rapidly to induce an explosion.

Current dynamical calculations show the shock to halt due to the energy lost by dissociation of the infalling core material and to that carried away by neutrinos from densities low enough that they become untrapped. The spherical calculations have to date failed to yield satisfactory explosions. There are some hints that a core of lower initial total mass might be conducive hence exploration of the cores of the $8 - 12\ M_\odot$ stars would be most useful. In the meantime, there may still be beneficial adjustments to the input physics in the present calculations. A thorough summary of the physics of core collapse is given in Brown, Bethe and Baym (1981, preprint).

Some effort has begun to explore the complex behavior of gravitational collapse for which the spherical symmetry is broken. Epstein (26.125.002) and Colgate and Petschek (27.125.032) raised the question of convective instability in which overturn might enhance neutrino flux and hence induce an explosion. Subsequent studies have not borne out this particular possibility since the convection tends to be suppressed by the shock-induced entropy gradient (Smarr et al., *Ap J*, *246*, 515, 1981), but overturn due to an external breaking of the spherical symmetry, as by rotation or magnetic fields may still be possible (Bruenn, Buchler and Livio 26.065.043). Bodenheimer and Woosley are studying the behavior of the layers beyond the iron core to see if rotation creates a centrifugal barrier which may promote a thermonuclear explosion following core collapse. Such a phenomenon might be related to recent evidence for ring-like asymmetries in some supernova remnants (Lasker 27.125.073).

Although fundamental problems still remain, great progress has been made in the last two years, both observationally and theoretically, concerning supernovae of Type I. Oemler and Tinsley (26.125.019) argued that Type I supernovae are not old, but associated with recent star formation. A number of theoretical investigations, particularly that of Axelrod *(PhD California* 1980 and in *T)* have given fresh new evidence that the exponential light tail of Type I events is due to the decay of ^{56}Ni to ^{56}Co and thence to ^{56}Fe.

In early March 1981, a relatively bright Type I was discovered in the spiral galaxy NGC 4536. Excellent optical (Branch et al., *Ap J Let* in press) and UV (Panagia and Wamstecker 1981, private communication) spectra have been obtained. The UV spectra prove that unlike Type II events which are nearly thermal, Type I are severely deficient in the UV even at maximum light. The optical spectra show evidence during peak light for O, Mg, S, Si, Ca and perhaps Na in approximately solar ratios. Iron appears somewhat later in approximately a solar ratio to, e.g. Si. Hydrogen is not seen. There is no evidence for Co at maximum, hence one deduces a blanketing layer of some sort which shields the inner incinerated regions containing the Co and Fe. Solar ratios of the heavy elements suggest a helium envelope, but there is some evidence for a net enhancement of the heavy elements and the presence of O belies a He envelope produced by CNO processing. Whether the observed mix of elements can be produced by partial burning and mixing in the context of a white dwarf model is a subject of current exploration (e.g. Nomoto, *Ap J* in press).

A variety of models for Type I have been proposed. Some stem from recent work on the outcome of accretion at various rates of mass onto carbon/oxygen white dwarfs. Of particular interest are the results of accretion at moderate rates $\sim 4 \times 10^{-9}\ M_{\odot}\ yr^{-1}$ to $10^{-8}\ M_{\odot}\ yr^{-1}$ for which a degenerate layer of helium accumulates and then ignites sending a detonation inward through the C/O core and outward through the helium shell (Woosley, Weaver, and Taam in *T*, Nomoto, *Ap J* in press). This model has some difficulty explaining the observations of Type I events, because it is essentially completely incinerated. Higher or lower accretion rates lead to central carbon deflagration which could leave a shielding layer, and hence perhaps represent a more viable model (Nomoto, *Ap J* in press, Chevalier, *Ap J*, *246*, 267, 1981). Other models invoke not white dwarfs, but stars with extended helium envelopes to provide the shielding layer at maximum light (Weaver, Axelrod and Woosley in *T*; Wheeler in *C*).

The demands of the late-time spectra and of the light curve suggest, but do not yet prove, that so much ^{56}Ni is required that Type I supernova must be totally disrupted and leave no neutron star remnant. This conclusion is consistent with the failure to detect either thermal radiation from cooling neutron stars or synchrotron nebulae from unseen pulsars in the remnants of historical Type I events.

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Branch (*Ap J* in press) has extended an earlier study by Pskovskii (20.125.033) which indicates that there are real variations among the light curves which belie the marked spectral homogeneity. Branch argues that the events with "slower" decaying light curves have higher photospheric velocity and greater peak magnitude than the more rapidly decaying events, counter to simple intuitive models. If such correlations are confirmed they will be a challenge for model builders.

The Einstein X-ray Observatory had a considerable impact on various aspects of supernova research. The high resolution imager experiment allowed remnants to be discovered and studied with unprecedented accuracy. The solid state spectrometer provided the spectral identification of various heavy elements. Cas A showed apparent enhancements of O burning products, S, Si, Ar and Ca (Becker et al. 26.125.045). Similar results were found for the putative Type I remnants of SN 1572 and SN 1604 (Becker et al. 27.125.002, 27.125.076). SN 1006 which is also tentatively assigned Type I status, shows a smooth continuum by contrast (Becker et al. 28.125.030). The Bragg crystal spectrometer showed approximately solar ratios of Fe to O in various remnants (Winkler et al., *Ap J Let, 246*, L27, 1981).

An exciting development was the discovery of radio emission from two recent Type II supernovae after many years of negative results. SN 1979c showed radio emission after one year. SN 1980 K gave a radio signal after only a month (Weiler et al., *Ap J Let, 243*, L151, 1981). This may signal a buried pulsar since either event seems too early to have formed a classical radio remnant or to see a pulsar directly.

There continues to be a discrepancy between the value of Hubble's constant as determined by using a modified Baade method on supernovae and other methods (e.g. Aronson et al. 28.060.107). The event SN 1979c and the recent Type I in NGC 4536 both suggest $H_0 \sim 50$ km s^{-1} M^{-1}pc as have most other supernovae. Wagoner (*Ap J Let* in press) has suggested that electron scattering atmospheres may modify the flux-temperature relation of supernovae in a way to give deceptively low values of H_0. Whether such atmospheres in fact exist for real supernovae remains to be seen.

Finally, in the cosmological vein, Ostriker and Cowie (*Ap J Let, 243*, L127, 1981) have suggested that the chain reactions of primordial supernovae may impose physical length scales on the original post-recombination homogeneity and give rise to clumping on scales of galaxies and clusters of galaxies.

IV. THEORY OF VARIABLE STARS (J. Cox, University of Colorado)

a) Introduction

In this report only certain aspects of the entire field of intrinsic variables will be discussed, and we shall include, for the most part, only work done in 1979 or later. These topics are Recent Books (Sec. b), Solar Oscillations (Sec. c), Long Period Variables (Miras) (Sec. d), R Coronae Borealis Stars (Sec. e), Hot and Cool White Dwarfs (Sec. f), Magnetic Cepheids (Sec. g), Time Dependent Convection (Sec. h), and Modal Selection (Sec. i). Other aspects of pulsating stars, such as Cepheid masses; Cepheid companions; atmospheric data relevant to helium-enrichment in Cepheid atmospheres; Beta Cephei theory; Delta Scuti theory; RR Lyrae and BL Herculis theory; the Blazhko effect; and resonances and bumps; may be found in the Commission 27 Reports.

Perhaps the only item that does not clearly fit into any one of the above categories and yet which should be mentioned is the discovery by D. W. Kurtz (preprint, 1981) of a new type of pulsating star. He has called these new variables *rapidly oscillating Ap stars*, and they have periods in the range 6 to 12 minutes.

Certain abbreviations, to be explained in Sec. b, will be used throughout this report.

b) Recent Books

Two monographs relevant to pulsating stars (primarily on the theory), have been published in the past two or three years. The first of these is *Nonradial Oscillations of Stars* (Tokyo: University of Tokyo Press), by W. Unno, Y. Osaki, H. Ando, and H. Shibahashi, published in 1979. The second is *Theory of Stellar Pulsation* (Princeton: Princeton University Press), by J. Cox, published in 1980. The first book is devoted exclusively to nonradial oscillations, the second to both radial and nonradial oscillations. The Japanese book is more mathematical than the other one.

A book on *An Introduction to Nonlinear Oscillations* (Cambridge: Cambridge University Press, 1980), by R. E. Mickens, has recently been published.

A few conference proceedings which have been published in the past two or three years are relevant: *Current Problems in Stellar Pulsation Instabilities* (eds. D. Fischel, J. R. Lesh, and W. M. Sparks), NASA Technical Memorandum 80625, 1980; *White Dwarfs and Variable Degenerate Stars* (eds. H. M. Van Horn and V. Weidemann), IAU Colloq. No. 53, 1979; *Nonradial and Nonlinear Stellar Pulsation* (eds. H. A. Hill and W. A. Dziembowski) (Berlin, Heidelberg, and New York: Springer -Verlag), 1979; *Stellar Hydrodynamics* (eds. A. N. Cox and D. S. King), IAU Colloq. No. 58, *Sp. Sci. Rev., 27*, 227, 1980; *Changing Trends in Variable Star Research* (eds. F. M. Bateson, J. Smak, and I. H. Urch), IAU Colloq. No. 46, 1979. These last five items will be denoted in the following, respectively, by *CPSPI*, *WDVDS*, *NNSP*, *SH*, and *CTVSR*.

c) Solar Oscillations

The recent discovery of small solar oscillations has generated a large amount of literature, only a fraction of which can be summarized here (see the many references in the review articles to be mentioned below).

Some recent review articles are: Hill, in *SH*, 283; Hill, in *The New Solar Physics*; ed. J. Eddy (Boulder: Westview Press), Chap. 5, 1978; Hill, *NNSP*, 174; Deubner, *Highlights of Astronomy*, ed. M. Stix, *5*, 75, 1980; Hill, *ibid.*, *5*, 449, 1980; Fossat, *Solar Phenomena in Stars and Stellar Systems*, eds. Bonnet and Dupree (Dordrecht: Reidel), 75, 1981. An excellent discussion of the whole situation, mostly from a theoretical standpoint, is provided by Gough, in *NNSP*, 273. Useful background information may be found in *Nonradial Oscillations of Stars*, by Unno et al., Secs. 9 and 32, 1979. Finally, an up-to-date assessment of the status of the field as of late 1981 may be found in Gough's comments in IAU Colloq. 66 (to be published in *Nature*). There now seems little doubt that the oscillations are genuinely solar in origin.

Particularly exciting are the observations carried out by Grec, Fossat, and Pomerantz (28.080.061) at the Earth's South Pole of 5-minute solar oscillations of high order but of low degree (i.e., small ℓ, the latitudinal index of a spherical harmonic). These oscillations, no doubt p modes, have been discussed by Christensen -Dalsgaard and Gough (28.080.062), who conclude that a solar interior of normal helium and metal content is consistent with the observations. They have also been discussed by, among others, Claverie, Isaak, McLeod, and van der Raay (*Nature*, *293*, 443, 1981), who claim to have found rotational splitting of these frequencies. From these splittings the authors infer that the angular rotational velocity of the solar interior is 2 - 9 times larger than the surface value.

A new excitation mechanism, arising from nonlocal effects associated with

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radiative transfer, has been found by Hill and Logan (preprint, 1980; see also Logan and Hill, *SH*, 301). The very interesting prospect of inferring the internal density distribution of the Sun from observations of p-mode, and only a few f- and g-mode, frequencies (helioseismology) has been discussed by Gough (*IAU Colloq. No. 66*, 1981).

d) Long Period Variables (Miras)

The many difficulties involved in these extremely complicated variable stars (to be abbreviated henceforth as LPV's) with greatly distended atmospheres are well described in the review article by Wing, *CPSPI*, 533. A shorter, but more up-to-date, review has been provided by Cahn, *SH*, 457. Still another review article is by Wood, *CTVSR*, 163.

Other review articles that bear on LPV's are by Payne-Gaposchkin (22.122.074); Merrill and Ridgeway (26.114.055); Carbon (26.064.021); Zuckerman (*Ann Rev A A*, *18*, 263, 1981); and Feast, (28.122.097). Also relevant in this context is (although this is not a review article) Celis, (28.122.056).

Observational support for the presence of shock waves in LPV's has been provided by Willson (17.122.034); Hinkle (21.122.017); Pilachowski, Wallerstein, and Willson (*CPSPI*, 577); Hinkle and Barnes (26.122.091); Hall, Hinkle, and Ridgeway (*CTVSR*, 264); and Willson, Wallerstein, and Pilachowski (*MNRAS*, in press, 1981). The theoretical situation regarding shock waves in LPV atmospheres has been discussed by Willson and Hill (*Proc. Los Alamos Solar and Stellar Pulsation Conference*, 1976), Hill and Willson (25.064.049), and Wood (25.122.001). A PhD dissertation bearing on this topic has recently been completed by Pierce (1981).

The question of the evolutionary stage of the LPV's has been discussed by Willson (*Effects of Mass Loss on Stellar Evolution*, eds. Chiosi and Stalio, 353, 1981; *Physical Process in Red Giants* [*PPRG*], eds. Iben and Renzini, 225, 1981; preprint, 1981); Wood and Zarro (*Ap J*, *247*, 247, 1981); Wood (*CTVSR*, 163, 1979; *PPRG*, 205, 1981); and Tuchman, Sack, and Barkat (26.064.035). The effect of pulsation on mass loss has been discussed by Wood (25.122.001; *CPSPI*, 611).

The mode problem (fundamental vs. first overtone) has apparently still not been settled. In contrast to earlier thinking, fundamental mode pulsation has been argued for by Hill and Willson (25.064.049) and Willson (*CTVSR*, 199; 1981, above references), partly on the basis of smaller radii for these stars than had been accepted in the past. Wood (*CTVSR*, 163) argues for first overtone pulsation. The calculations of Wood and Zarro (1981, above reference) were not definitive in this respect. The linear, nonadiabatic pulsation calculations of Fox and Wood (preprint, 1981), are apparently the most complete and definitive to date. They show that nonadiabatic effects reduce the pulsation *constant* Q_0 for the fundamental mode, and increase Q_1 for the first overtone, thus rendering it even more difficult to distinguish observationally between the two modes. These calculations also suggest that the fundamental mode is favoured at the higher luminosities, the first overtone at the lower. On the other hand, the observational results of Robertson and Feast (*MNRAS*, *196*, 111, 1981) suggest exactly the reverse, the higher luminosity LPV's being apparently first overtone pulsators. Some critical comments regarding the Hill-Willson fundamental mode arguments are presented by Wood (*PPRG*, 205).

Finally, arguments are given by Wood, Bessell, and Fox (preprint, 1981) for a division of LPV's in the Magellanic Clouds into asymptotic giant branch stars and core helium burning stars.

e) R Coronae Borealis (R CrB) Stars

Recent review articles on the R coronae Borealis (R CrB) stars are by Feast (*CTVSR*, 246) and King (*SH*, 519) (further references may be found in these articles). King concentrates to a large extent on the three R CrB stars that exhibit Cepheid-like pulsations. The large nonadiabaticity of these pulsations creates mode identification problems, *strange* modes, and other problems, which have been discussed by Cox, King, Cox, Wheeler, Hansen, and Hodson, *SH*, 529.

f) Hot and Cool White Dwarfs

Review papers (primarily observational) on the properties of the recently discovered variable DA white dwarfs, also called the ZZ Ceti stars (cf. McGraw, PhD Thesis, University of Texas at Austin, 1977, which contains a very thorough discussion of these stars), are by McGraw (25.126.017 ; this is not formally a review paper, but is essentially one nevertheless); Nather, 22.126.037; Robinson, *CPSPI*, 423; Robinson, *NNSP*, 444; Robinson, *WDVDS*, 343; and McGraw, *SH*, 601. Excellent theoretical discussions of the oscillatory properties of white dwarfs are by Van Horn, *CPSPI*, 453; Hansen, in *NNSP*, 444; and Dziembowski, *WDVDS*, 359.

The question of the excitation mechanism for the observed (200-1000)s oscillations (which are apparently g modes) of the ZZ Ceti stars is of great interest. Earlier discussions bearing on this question may be found in a number of papers in *WDVDS*.

One of the most exciting recent findings in connection with this question is that the chemical stratification of the outer layers of white dwarfs (discussed in numerous papers in *WDVDS*) seems to play a major role. It has recently been suggested by Winget, Van Horn, and Hansen (*Ap J Let 245*, L33, 1981) that a coincidence between the thickness of the hydrogen layer and the radial wavelength of one of the high-order g modes can *trap* this particular mode. Such a mechanism might explain why only certain modes, and not others, are observed in the ZZ Ceti stars.

Three recent studies show that the basic excitation mechanism for the oscillations of the ZZ Ceti stars is probably the *kappa mechanism* operating in the hydrogen ionization zone in the hydrogen layer of these stars. These studies are: Winget, Van Horn, Tassoul, Hansen, Fontaine, and Carroll (*Ap J Let*, in press); Winget, PhD thesis, Univ. of Rochester, 1981; and Dolez and Vauclair (*A & A*, in press). Somewhat earlier, the driving brought about by the kappa mechanism in the He^+ ionization zone in the helium layer of these stars was studied by Dziembowski and Koester (*A & A*, *97*, 16, 1981). The hydrogen driving was not found by the last authors, presumably because their models were not sufficiently cool. Otherwise the agreement among the above four sets of calculations, which all involved linear, fully nonadiabatic, nonradial oscillation theory, was satisfactory.

g) Magnetic Cepheids

It was suggested by Stothers (26.122.071) that Cepheids might have a tangled magnetic field, which would supply part of the pressure in the envelope. Such a tangled magnetic field is one means by which the mass discrepancy in "bump" and "beat" Cepheids might be resolved (e.g., A. Cox, 28.122.102).

New measurement techniques (Borra, Fletcher, and Poeckert, *Ap J*, *247*, 569, 1981; Borra and Landstreet, 27.116.031) permit values of the longitudinal component of a magnetic field, averaged over the stellar disk, to be determined to within a few tens of gauss. These results are, according to the authors, consistent with the existence of tangled magnetic fields in Cepheids of the strength suggested by

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Stothers.

A recent paper by Stothers, bearing on tangled magnetic fields in pulsating stars, is in *MNRAS, 197*, 351, 1981.

h) Time-Dependent Convection

Some attempts to treat time-dependent convection in a linear theory have been by Baker and Gough (26.122.069); Gonczi and Osaki (27.062.052); Saio (28.065.036); Gonczi (*A & A, 96*, 138, 1981); and Gonczi (preprint, 1981). However, the most definitive calculations which show that convection probably determines the red edge of the Cepheid and RR Lyrae instability strips are probably the nonlinear pulsation calculations of Deupree (27.122.003).

i) Modal Selection

The question of modal selection in pulsating stars, of interest in connection with the vexing problem of double-mode pulsation (for a review, see J. Cox, *SH*, 389), has recently been discussed by Simon (*SH*, 437; *Ap J, 247*, 594, 1981). He has discussed the work integral in connection with the iterative theory. He concludes, among other things, that the manner of treatment of artificial viscosity in numerical calculations might be important. In an earlier discussion, he suggested (25.122.063) that double-mode pulsation in Cepheids may involve a resonance among the fundamental, first, and third overtones. Faulkner and Shobbrook (26.122.011) have suggested that double-mode pulsation may result from a continuous switching back and forth between the fundamental and first overtone. A promising two-time formalism has been applied to the problem by Oded and Buchler (preprint, 1981).

V. THEORETICAL STUDIES OF STAR FORMATION (J. J. Monaghan, Monash University)

No generally acceptable picture of star formation has yet emerged. Notable advances have, however, been made in our ability to give a numerical description of increasingly relevant models. Recent conference proceedings (25.003.008; 20.012.029; 22.131.098; 27.012.010) contain extensive review articles on a wide variety of problems in star formation.

a) Numerical Calculations of Collapse

i) Spherically symmetric models Tscharnuter and Winkler (*Comput Phys Commun, 18*, 171, 1979) have given a comprehensive description of numerical methods for spherical collapse. An improved numerical method has been devised by Winkler and Newman (27.131.019) who also include a better description of radiative transfer. Their calculations confirm Larson's (07.065.077) qualitative results for a $1M_{\odot}$ star. A new feature is that a temperature maximum is produced off centre so that Deuterium burning will start in a shell. The evolution of more massive protostars has been discussed by Larson (07.065.077), Appenzeller and Tscharnuter (11.065.036) and Yorke and Krügel (19.131.028). For $M \gtrsim 50\ M_{\odot}$, radiative effects result in about 2/3 of the mass being ejected. This fraction is likely to be very sensitive to the numerical methods used to describe radiation transport and shock dynamics but the fact that substantial mass loss occurs for $M \gtrsim 10\ M_{\odot}$ should survive improvements in numerical techniques. Several groups are experimenting with simplified and improved versions of Van Leer's (*J Comp Phys, 32*, 101, 1979) numerical method which gives excellent results for shock problems without using explicit artificial viscosity.

ii) Axisymmetric models

1) Initial rotation uniform The initial cloud (assumed spherical) evolves by

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flattening as it collapses. The collapse is highly non-homologous. The calculations of Larson (07.065.076) produced a ring, and this was confirmed by Black and Bodenheimer (17.131.124) using a different numerical method. Tscharnuter (13.065.049) used a method based on Legendre polynomial expansions and found that ring did not occur. It now appears that Tscharnuter's original choice of the azimuthal velocity as one variable leads to a diffusion of angular momentum outwards which suppresses the formation of a ring. Bodenheimer and Tscharnuter (25.065.036) have compared a donor-cell finite difference method with the corrected Legendre polynomial method and found reasonable qualitative agreement. There are, however, large quantitative differences remaining; for example the central density in the two methods can differ by two orders of magnitude. Part of the difficulty with the simulation of these rotating collapses is that the result devolves on the angular momentum transport. Norman et al. (28.062.029) show that ring formation in the central regions of a star may be due to spurious angular momentum transport inward. They identify strong diffusion terms in the original donor cell scheme of Black and Bodenheimer and show that, if these are removed, the collapse produces a dense disk. However, rings which form far from the centre are less susceptible to this effect (this is the case for the rings found in the Bodenheimer Tscharnuter comparison), and may be considered genuine. Tohline (27.131.015) showed that ring formation may be simulated by independent particles moving in a potential well. The rings appear as density concentrations as particles bounce out from the central regions. Norman (*PhD California* 1980) has given a comprehensive description of collapse during the isothermal stage. His work includes the construction of equilibrium configurations that generalize the Bonnor-Ebert spheres. These rotating configurations can contain a mass very much greater than that in the critical Bonnor-Ebert sphere, though it is possible that these configurations are not stable to non axisymmetric perturbations.

2) Initial rotation differential Norman (*PhD California* 1980) and Gingold and Monaghan (*MNRAS* in press) have examined the effect of allowing the initial rotation to be differential. These calculations show that ring formation is promoted if the angular velocity decreases outwards. In Norman's work an analysis of the effect of differential rotation is attempted by assuming the cloud collapses to an equilibrium disk which becomes unstable. He concludes that the case of initial uniform rotation is a critical case for ring formation. Since an equilibrium disk is not formed during the collapse it is difficult to see how relevant this analysis can be. Gingold and Monaghan make use of Hunter's equation to show that differential rotation with angular velocity decreasing outwards produces a ring by a kinematic effect.

These calculations show that models with uniform rotation give too restricted a picture of the development of a collapsing axisymmetric cloud, and models with the same initial thermal, gravitational and rotational energies can differ greatly in their evolution if they differ in their angular momentum distribution.

3) Magnetic Fields Mouschovias (17.062.036; 18.062.006) has calculated a sequence of equilibrium clouds with a poloidal field linking the cloud of interest to an external conducting medium. His results have been confirmed by Scott and Black (28.131.033). Magnetic braking (Mouschovias 25.131.095; 27.313.133, Gillis et al. 25.131.063, Mestel and Paris 25.131.064) has been analysed in detail and found to be an effective way to remove angular momentum. It would be premature to be guided too strictly by these results since they may be very sensitive to the assumptions of strict axial symmetry and a magnetic field with simple topology.

iii) Non Axisymmetric Models Calculations have been made using a variety of numerical methods (Tohline 27.062.004, Boss 27.131.153, Lucy 20.065.081, Gingold and Monaghan 20.062.017 and *MNRAS, 197*, 467, 1981, Wood *MNRAS, 194*, 201, 1981, Rozyczka et al. 27.131.057) to follow the evolution of isothermal clouds. None of these methods achieve the resolution that is incorporated in the best axially symmetric models and for this, or other reasons, there is great disagreement about the results. Bodenheimer et al. (28.131.029) have extended Tohline's (27.062.004) calculations of fragmentation in clouds which initially rotate uniformly. They introduce non spherical m = 2 perturbations (magnitude ⩾ 10%) and study the evolution as a function of thermal, rotational and gravitational energy. Their general result is that if the thermal energy >.3|gravitational energy|an axisymmetric ring forms then fragments, whereas with the inequality reversed the system evolves immediately to a binary within a flattened cloud. Tohline had found that 10% perturbations were always pressure damped, but this appears to be due to the smaller number of models he examined. The results of Bodenheimer et al. are in general agreement with the calculations of Boss (27.131.153) who used a similar donor-cell method. However, Boss found that very small (10^{-14}) perturbations can grow into a significant fragment. The comparison of the Boss and Tohline donor-cell schemes by Boss and Bodenheimer (27.131.117) for a spherical cloud with a large (50%) perturbation shows that the two methods are in qualitative agreement. When interpreting these results account should be taken of the fact that the resolution of a fragment is very coarse, often only three azimuthal cells contain the entire fragment, and the first order diffusion terms may swamp the calculation locally. The restriction of the potential field to spherical harmonics with $\ell \leqslant 4$ may also introduce large errors in the long term motion since the gravitational field of the highly flattened cloud is then only crudely represented.

The calculations of Rozyczka et al. (27.062.007) are based on an extension of Tscharnuter's spherical harmonic method. They have examined the growth of m = 2 and m = 4 perturbations on models derived from the system considered in the joint calculation of Bodenheimer and Tscharnuter. The m = 2 perturbations always grow if the perturbation is very large (40%) but in some cases fail to grow if smaller (20%). It seems doubtful if a method based on spherical harmonics is adequate for highly flattened systems since a very large number of spherical harmonics may be needed to resolve a fragment far from the centre of the coordinate system. Rozyczka et al. use spherical harmonics up to $\ell = 5$.

Gingold and Monaghan (*MNRAS, 197*, 467, 1981) used a particle method to simulate the collapse considered by Boss and Bodenheimer. Their results agree qualitatively with those of Boss and Bodenheimer up to ∿ 1.7 initial free fall times, but disagree about the subsequent evolution. Using related particle methods Lucy and Wood found that clouds can fragment into two and three body systems. These particle methods have substantial advantages over finite difference methods of the donor cell type, but they have the disadvantage that the motion of the particles can become disordered during the collapse.

It is clear that a great deal of further work is needed before the results of non axisymmetric computations can be considered reliable. Nevertheless they do make it clear that models with high symmetry cannot provide a basis for theories of star formation. There is, for example, general agreement that fragmentation occurs producing fragments with less angular momentum per unit mass than that in the original cloud.

b) Application to Star Formation

Bodenheimer (22.131.022) has examined the fragmentation of a cloud of 10^4 $M_\odot$ using a numerical method which assumes the system is axisymmetric. The ring which forms is assumed to break into two equal, spherical uniformly rotating clouds. The evolution of these clouds through further stages of ring formation and fragmentation was followed. The calculations show that the final fragments have an angular momentum distribution which is consistent with observations. The results can only be considered suggestive because the assumptions about the fragmentation process are very crude, and the initial conditions differ greatly from those that might be expected in molecular clouds.

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Tohline (27.162.056) has re-discussed the growth of perturbations in a spherical collapsing cloud. His results may be interpreted as showing that the evolution is sensitive to the initial conditions. This underlies once again that a fundamental problem in star formation is that we do not know the correct initial conditions for numerical models.

c) Turbulence

The importance of turbulence was early emphasized by Weizäcker who made it the basis of his cosmogonical theory. Observations by Courtes (*IAU Symp 2*, 131, 1953) suggested that the spectrum of turbulence was roughly Kolmogorov. Recently, interest in the effects of turbulence has been revived largely because observations of molecular clouds indicate that the motion is disordered and often supersonic. Larson (*MNRAS, 194*, 109, 1981) has correlated numerous observations and concluded that the spectrum of the disordered motion is close to the Kolmogorov spectrum. Even if the details of Larson's work are incorrect it appears that models of star formation will have to include the effects of disordered motion.

Since collapse at a rate faster than the viscous dissipation time scale will amplify vorticity, these effects will become greater as the collapse proceeds. The major result will be changes in the effective transport coefficients which will alter the angular momentum distribution and the structure of shocks in the main flow.

Rozcyzka et al. (27.062.007) have examined a pseudo turbulence which has a correlation length close to the cell length scale. This model is too crude to stimulate real turbulence though it does indicate how a disordered velocity field stimulates fragmentation. These results suggest that a velocity field based on the Kolmogorov spectrum will provide a more realistic field of density perturbations than the current approach based on spherical harmonic perturbations. Tscharnuter (*IAU Symp 93*, 105, 1981) has shown that turbulence can have an important influence on the late stages of stellar evolution through its ability to transport angular momentum. The calculations are not, however, self consistent because they do not include the effect of rapid rotation on the turbulence.

VI. THE AGE AND HELIUM CONTENT OF GLOBULAR CLUSTERS (V. Castellani, Frascati)

In past years, both the ages (t) and the original helium content (Y) of globular cluster stars have received an increasing attention, largely as a result of the increasing output of observational data and of the consequent increasing popularity of the theoretical framework regarding Population II stars.

As is well known, from knowledge of Y and t one expects to derive information about important quantities such as Hubble's constant, big-bang nucleosynthesis and (hopefully) the density of the present universe, the early evolution of the galactic halo, etc.

Different ways can be (and have been) used in order to reach conclusions about the actual values of the quoted parameters in different clusters: in all cases the general background is that the location of evolving stars in the HR diagram is a function of the time plus the original chemical composition, so that theoretical constraints may be derived and compared with observations.

A firm knowledge of Y and t is probably difficult to achieve, as will be sketched in the following sections where recent investigations on the matter and the related problems are shortly reported. As a general background, one has to remember that a large factor of indeterminacy comes from the actual tantalizing

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situation regarding the real metallicity of (metal-rich) clusters: high dispersion spectra (see e.g. Cohen 28.154.025; Pilachowski et al. 27.154.001) give values of [Fe/H] largely conflicting with other metal-indicators, and an agreement on the argument seems difficult to achieve. Also largely indeterminate is the amount of the often suggested variation of Z_{CNO}/Z.

a) Helium content

The helium content can be directly derived from the absolute magnitude of Main Sequence stars or, more indirectly, from more sophisticated evolutionary constraints, like the photometric and/or pulsational properties of HB stars.

Globular Cluster Main Sequences are, on the contrary, used to reach indications on the distance modulus of the clusters, by simply assuming a Y-value or, with perhaps a more physical approach, by fitting GC to the field subdwarfs, assuming in this way a constant Y among the galactic globular clusters and between globular clusters and halo subdwarfs. One has to note that, in this framework, Carney (26.126.021) finds the halo subdwarfs fitting the MS with Y = 0.20.

Several authors (Caputo et al. 27.154.011), Arimoto and Simoda(*Astr Sp Sci*, *76*, 73, 1981) have devoted their attention to the observational value of the parameter $R = N_{HB}/N_{RG}$, the ratio between the number of HB stars and the number of RG stars more luminous than the HB level. As has been shown by Iben and Rood (2.154.019), this ratio is expected to be a sensitive function of the Y content only.

The Y values derived have rather reasonable values, ranging largely in the interval $Y \gtrsim 0.20$ to 0.30. Unfortunately the theoretical calibration of R is dependent on assumptions about the efficiency of semiconvection or the possible occurrence of a dramatic He-flash (Cole and Deupree *Ap J*, *247*, 607, 1981. Neither the observed variations in R can be assumed as a "bona fide" indicator of variations in Y, because the observations have shown the existence of some unusual features ("gaps") in HB distributions of NGC 6752 (Cannon and Lee 1973 private communication) and M15 (Bonanno et al. in preparation), so that it looks quite hazardous to derive conclusions before reaching a clear theoretical knowledge of actual HB's.

Theoretical investigations on the width of the instability strip (Deupree, 19.122.114) suggest that this parameter is strongly dependent on the amount of helium in the envelope of the stars. By literally adopting Deupree's results one cannot escape the conclusion that He content in RR-Lyrae rich globular clusters as high as $Y \sim 0.30$, because for lower Y (~ 0.20) the strip practically vanishes. Such a conclusion, which is based on rather sophisticated physics of stellar envelopes is challenged at least by two different approaches, namely:
1) Vandenberg (*Proc IAU Colloq 68* in press) by fitting the shapes of the observed H-burning phases, finds that the best fit is achieved when $Y \sim 0.20$.
2) Castellani and Tornambè (*A & A*, *96*, 207, 1981) by constructing synthetic HB were not able to fit the observed Oosterhoff II type clusters, unless $Y \sim 0.23$ plus some modifications to the current theoretical evolutionary framework. Of these two approaches, the second is based on physics (topology of the instability strip and so on) at least as sophisticated (and debated) as the Deupree procedure. Vandenberg's results are, on the contrary, a straightforward approach to the problem, so that the situation is far from being clear.

Very recently Caputo and Cayrel (*Proc IAU Colloq 68* in press) adopted as Y - indicator the difference in magnitude between the HB and the MS at a given colour. This is a modification, suggested by the improvement in observational data, of the old idea by Rood and Iben (*Ap J*, *154*, 215, 1968) to use the *relative* luminosity of different evolutionary phases. The preliminary results are suggestive of a correlation between Y and Z, in the sense that increasing Z (from 10^{-4} to 10^{-3})

corresponds to Y increasing between 0.20 to 0.30. This approach looks straight-forward enough to be not easily challenged, as long as the *canonical* evolution holds.

In this context, one has to notice the exemplary analysis by Sandage (*Ap J, 248*, 161, 1981) of the pulsational properties of RR Lyrae stars in the clusters M3 and M15.

On the basis of observations, Sandage reached the conclusion that RR Lyraes in the metal-poor Oosterhoff II globular cluster M15 have, at the same effective temperature, periods longer by $\Delta \log P \cong 0.06$ with respect to M3 pulsators. If we adopt a canonical evolutionary frame, one cannot escape the conclusion (based on a complete analysis of the whole evolutionary and pulsational frame) that Y is now *anticorrelated* with Z, as low-Z clusters like M15 are more helium abundant by $\Delta Y = 0.05$ with respect to intermediate-Z clusters like M3.

The only way to escape this (odd) conclusion is to challenge the temperature scale adopted by Sandage or, again, the canonical evolutionary frame. One has finally to notice that Cox (*Proc IAU Colloq 68* in press) recently analysed double-mode pulsators in M15, reaching valuable information on the masses of actual pulsators and on the observational topology of the instability strip. As a whole, it looks as if the Y-problem is largely undetermined, though with some indications that in the next years it will probably receive firmer conclusions.

b) Globular-Cluster Ages

Fortunately enough the indeterminacy of the helium content does not strongly reflect on the evaluation of ages. Unfortunately enough ages are still an open problem.

As a matter of fact, evaluations of ages have to be based on the dependence of Turn-Off luminosities or temperatures on time. It turns out that, in both cases, ages are strongly dependent on the assumed metallicity Z, in the sense that if one cluster is assumed more metallic than in reality, it will be found also to be younger. So one is driven to wonder how far the relations t(Z) carefully reported in the literature (Carney 27.154.070; Demarque 27.154.030) are just reflecting the bewildering indeterminacy in the Z-values of metal-rich clusters. Perhaps the only real thing we can say at present is that galactic globular clusters have a mean age of about 15 ± 5 billion years.

More detailed investigations (Sandage *Ap J* in press) failed in detecting age differences among galactic globular clusters. This is at least in part coming from the indeterminacy of the TO luminosity by about ± 0.25 mag, which means ± 3 billion years.

Ages from integrated UV spectra have been recently proposed (van Albada et al. *MNRAS, 196*, 823, 1981; Nesci in preparation). Such a procedure looks as a very promising one, provided that the contribution to UV fluxes by HB and subgiant stars are carefully subtracted from the observed distribution.

In conclusion, although most quoted globular cluster ages are in conflict with the standard hot big bang cosmological theory if H_o turns out to be as large as 100 km s^{-1} Mpc^{-1}, it is not yet possible to be certain that they are really incompatible with the theory and such a value of H_o.

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VII. PHYSICS AND EVOLUTION OF STARS (A. V. Tutukov, Moscow)

In addition to the above reviews of special topics, Dr Tutukov has supplied a brief account of work carried out in the USSR in 1979-81, which follows.

The study of stellar evolution is of great interest to astrophysicists of the USSR due to the diversity of physical processes manifested in it. The rapid growth in the quantity and quality of observations in radio-, IR-, optical-, UV- and gamma-regions makes it necessary to interpret the obtained results at a rather high quantitative level. Therefore the numerical study of stellar evolution is one of the topical problems in theoretical astrophysics of today.

Zeldovich, Blinnikov and Shakura (*Physical grounds of theory of stellar evolution*, Moscow, 1981) summarise the physical fundamentals of the present-day stellar evolution theory. Imshennik and Morozov (*Radiative relativistic gas dynamics of high temperature objects*, Moscow, 1981) sum up their work on the problem of relativistic gas dynamics. The use of the general principles developed in this monograph has made it possible to continue the study of neutrino transfer in conditions of collapsing stellar cores: equations of neutrino gas dynamics have been derived taking into account both the absorption and scattering of neutrinos (electron and muon) in two approximations - that of neutrino thermal conductivity and of "comptonized" neutrinos (25.062.110).

a) Early Stages of Stellar Evolution

Avedisova (in press) has compiled a catalogue of star formation regions including 480 objects. The catalogue systematizes observational data on the radiation of star formation regions in radio-, IR- and optical spectral regions. Shustov (25.064.091) has numerically studied the evolution of spherically-symmetric gas-dust envelopes around young massive stars for models with total masses of the star and envelope: 2, 10, 50 and 300 $M_\odot$. Yorke and Shustov (*A & A*, *98*, 125, 1981) have studied the dependence between the IR-spectrum of young stars with gas-dust envelopes and the dust distribution. Tutukov and Shustov (*Astr Zh*, *58*, 109, 1981) have investigated the evolution of the radiation spectrum of a young massive star from its formation to envelope scattering, and found a good agreement between theoretical and observational spectra. Avedisova (26.155.058) has estimated the modern rate of star formation in our Galaxy on the basis of observed thermal radio-frequency radiation: $\sim 6\ M_\odot$/yr.

Fedorova (*Astr Zh* in press) has studied the dependence between the minimum mass of stars in which hydrogen burning is possible and the rotational velocity, magnetic field strength, and accretion rate. It has been found that rotation and magnetic fields with an energy of about 10 per cent of the gravitational energy can increase the minimum mass of a main-sequence star by a factor 1.5 to 2. Accretion onto dwarfs with an initial mass of $\sim 0.01\ M_\odot$ considerably increases the cooling rate of a star. Bisnovatyi-Kogan et al. (26.065.006) have studied the contraction of rapidly rotating stars to the main sequence and arrived at the conclusion that rotation can considerably slow down the contraction. Bisnovatyi-Kogan and Lamzin (27.121.018) have studied corona models of RU Lupi (a T Tau-type star) and have calculated X-radiation of these stars on the basis of the observed UV-radiation of this star. Tutukov (27.153.086) has proposed a scenario of O-association formation. O-associations may be the product of a star formation process in molecular clouds with the mass of $\sim 10^5 - 10^6\ M_\odot$, which consists in successive formation of stellar clusters and their dissociation after the loss of a gaseous component.

Massevitch et al. (25.065.071) have studied the evolution of single massive stars at the hydrogen burning stage with regard for mass loss and additional mixing. Mass loss at the observed rate has been established to be insufficient for stripping the helium core of a star and for the formation of a single Wolf-Rayet star.

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Additional mixing makes it possible to explain some effects usually ascribed to mass loss.

b) Evolution of Close Binary Stars

Tutukov and Yungelson (*Nauchn Inf, 49*, 3, 1980) have proposed a scenario for evolution of close binary stars with moderate masses. This scenario makes it possible to trace the evolution of close binaries from two stars on the main sequence to the formation of two degenerate dwarfs. Tutukov and Yungelson (28.065.014) having studied evolution of stars with $M \gtrsim 50\ M_{\odot}$ arrived at a conclusion: most massive stars of our Galaxy may be former secondary components of close binary stars after mass exchange and have relativistic satellites, and most massive yellow supergiants may have a double core. Lozinskaya and Tutukov (*Nauchn Inf, 49*, 21, 1980) have analysed the observed properties of *single* nitrogen stars of the Wolf-Rayet type with nebulae in order to explain their origin. These stars have been established to be evolutionary products of massive close binaries arising after the loss of a hydrogen envelope during the second exchange in the system. The established duplicity of some of these stars supports the proposed scenario.

Tutukov and Yungelson (28.068.088) have obtained thermal-equilibrium models of massive stars for a number of evolutionarily conditioned radial distributions of hydrogen. These models make it possible to understand what causes the dependence between evolution of massive binary components and the stability criterion in the area of variable molecular weight. Ergma and Tutukov (25.066.505; 26.064.030) have developed an analytical method for studying the thermal evolution of a degenerate envelope of an accreting degenerate dwarf or neutron star. Dependence between the frequency of nova outbursts and X-ray burster flashes and the accretion rate and mass of an accreting star has been established.

Bisnovatyi-Kogan and Blinnikov (25.062.019; 25.062.061) have considered wave propagation in matter with high radiative pressure as applied to accretion discs and supermassive stars. It is established that wave damping in these media may be important for the interpretation of variability of accreting relativistic stars. In (27.142.139) it is shown that taking account of the heating of matter accreted by a star does not change the value of the Eddington limit on accretion rate. Paczyński and Bisnovatyi-Kogan (*Acta Astr* in press) have obtained the model of an accretion disc around an accreting black hole.

Tutukov and Yungelson (27.117.026) have investigated the effect of gravitational waves on the evolution of dwarf binary stars consisting of main-sequence stars and degenerate dwarfs. Ergma et al. (27.126.002) have shown that the envelope of an accreting degenerate dwarf can be enriched with carbon and oxygen. This enrichment is necessary to explain nova outbursts. Ergma and Kudryashov (28.066.523; 28.066.530) have studied the kinetics of hydrogen and helium burning in neutron star envelopes as applied to X-ray bursters. Bisnovatyi-Kogan et al. (*Astr Zh, 58*, 136, 1981) have obtained a model of SS 433.

Fadeyev and Tutukov (*MNRAS* in press) have studied the development of pulsation instability of an FG Sge model. It is established that pulsation instability leads to the formation of an extended envelope around a star and evidently to mass loss by the envelope.

c) Late Stages of Evolution and Supernova Outbursts

The result of the carbon-oxygen core outburst is to a great extent dependent on the temperature distribution in central regions of the core right at the time the hydrodynamic phase starts. Ergma et al (26.065.046) and Kudryashov (*Nauchn Inf* in press) have studied the effect of convection on the temperature distribution in a degenerate carbon-oxygen core. Imshennik and Nadyozhin have written a general

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review on the problem of supernova outbursts (in *Soviet Science Reviews*, *2*, 1980). The work by Chechetkin et al. (27.065.015) is devoted to a detailed description of a hypothesis on the nature of two known supernova types SN I and SN II proposed on the basis of numerical studies. Neutrino ignition is considered as one of the most important mechanisms of thermonuclear burning propagation in the degenerate carbon core of a star. Matter neutronization and neutrino energy losses are self-consistently taken into account.

Problems of gravitational collapse hydrodynamics and questions of supernova outburst theory have been considered in a number of works. Nadyozhin (27.066.028) has shown that even in the absence of the visible supernova outburst, due to partial mass loss by neutrino radiation, gravitational collapse can be accompanied by phenomena accessible to present-day observational astronomy (formation of peculiar nebulae, initiation of intensive stellar pulsations). Formation of type-I supernova envelopes with velocity gradients and some aspects of the general picture of SN I outburst have been considered by Imshennik et al. (*Astr Space Sci* in press). Utrobin and Chugai (26.125.059) have studied the conditions of formation of some typical SN I spectral lines. The paper by Nadyozhin (preprint *ITEF - 1*) is devoted to peculiarities in the initial phase of interaction between a receding stellar envelope and surrounding medium.

Works on the magnetorotational explosion have been continued. Within a cylindrical model a calculation is made for small $\alpha = E_H/E_\omega$ corresponding to actual $B \gtrsim 10^{13}$ G fields on the surface of neutron stars. The explosion effectiveness is shown to be almost independent of B (26.125.61; Bisnovatyi-Kogan, *Ann New York Acad Sci*, *336*, 389, 1980). Ivanova and Chechetkin (*Astr Zh* in press) consider a supernova model based on loss of stability in degenerate iron cores of stars. A white dwarf has been obtained as the compact remnant. Work on the problem of nucleosynthesis at a supernova outburst has been carried on. It is established that taking account of interaction between neutrinos and the carbon layer of the stellar core can explain the observed high concentration of the ^{11}B isotope relative to ^{10}B (27.061.047). Neutrino radiation may also be responsible for the formation of a radioactive isotope ^{26}Al in pre-planetary matter (27.061.033).

The spectrum of electron neutrinos and antineutrinos emitted upon the formation of a neutron star has been calculated (27.066.505). Simple formulae are obtained for the rate of electron and positron capture by atomic cores in astrophysical conditions by Gavrichenko and Nadyozhin (preprint *ITEF - 123*). Processes of dense and hot matter relaxation to the state of quasi-equilibrium and of complete nuclear statistical equilibrium have been studied. Characteristic relaxation times are calculated. Relaxation to quasi-equilibrium is shown to be independent of density over a wide range of densities (*Pisma Astr Zh*, *8*, 1981).

Bisnovatyi-Kogan and Chechetkin (*Astr Zh*, *58*, 561, 1981) have proposed a model of γ-bursts as a manifestation of the activity of a neutron star nonequilibrium layer. The theory of the nonequilibrium layer of neutron stars is described in a review by Bisnovatyi-Kogan and Chechetkin (*Usp Fis Nauk*, *127*, 263, 1979). Ptitsyn and Chechetkin (27.125.066) have numerically studied the distribution of elements in the region of the iron peak on the basis of a deflagration model of the supernova outburst. It is established that since iron is mostly formed as ^{56}Ni, the decay $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ can noticeably contribute to the observed light curve of supernovae.

VIII. CONCLUDING REMARKS

As was mentioned in the introduction and as has become clear from the individual contributions, there are many problems in non-linear hydrodynamics which must be

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solved before our understanding of stellar structure and evolution can be considered satisfactory. It is also clear that, if the full complexity of a real physical situation is included, even modern large computers may be incapable of providing a clear solution to a problem. If substantial progress is to be made, there must be a strong interplay between results of complex calculations and physical intuition so as to determine which factors are crucial and determine qualitative behaviour and which merely serve to modify numerical results.

R. J. TAYLER
President of the Commission

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