35. STELLAR CONSTITUTION (CONSTITUTION DES ÉTOILES)

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I. INTRODUCTION (D. Sugimoto, University of Tokyo)

This report of Commission 35, as in past reports, consists of some details of only a few selected topics. This is necessary because a survey of the entire field of stellar formation, structure, stability, evolution, explosion, and nucleosynthesis for the three year period from mid-1984 to mid-1987 would be excessively long. Our topics here, in order from early to late evolutionary pahses are: Convective Overshooting (N.H. Baker), Mass Loss (I. Appenzeller), Novae (M. Livio), Presupernova Models and SN1987A (K. Nomoto), and Structure of X-Ray Bursting Neutron Stars (M.Y. Fujimoto and D. Sugimoto). In addition, Asteroseismology (H. Shibahashi) is reported briefly as one of the new disciplines now being developed. About two decades ago, Professor Martin Schwarzschild suggested convection, mass loss, and calculation of models through supernova stage as ones of the most important problems to attack. Though great progress has been achieved in these topics, we still have some fundamental questions concerning physical mechanisms involved. This is the reason why these topics are selected for this report.

One of the biggest events of interest of Commission 35 during this period was the occurrence of SN1987A in the Large Magellanic Cloud. This delayed event of nearby supernova from statistical point of view was lucky in the sense that astronomers have been prepared not only with different observational facilities through different wave-length bands even including neutrino detectors but also detailed model calculations through the presupernova stages and some models of explosion into the interstellar space. Nomoto's report herein is somewhat more concentrated on this supernova rather than is exhaustive in the presupernova models in general. Though such a report on the current topics seems premature, it is a topics of urgent concern. Full report could be given in the future.

References are given as their numbers in the Astronomy and Astrophysics Abstracts when possible. In many cases, the conventional references needed to be given because the 1987 volumes are not available at the moment of preparing this report. Because our reports for the preceding or succeeding periods do not necessarily contain the same topics covered here, some essential papers published even before 1984, and some important papers now in press or in preprints are also included.

General interest in stars continues at high level, because the stars are fundamental constituents of the universe and provide a variety of physical phenomena inherent to self-gravitating systems. Some people, or rather onlookers say that interests in astronomy is being shifted from stellar physics to galaxies and cosmology. This is true, in a sense, because the galaxies and observational cosmology are relatively new and expanding fields. Nevertheless, we will be able to see in the following sections that we still have wealth of interesting topics in the field of Stellar Constitution.

During the reporting period seven IAU Symposia and ten IAU Colloquia were held on topics of interest to Commission 35. They are in order of dates: Symposium 116 Luminous Stars and Associations in Galaxies, Porto Heli, Greece, May 26-31, 1985;

Symposium 115 Star Forming Regions, Tokyo, Japan, November 11-15, 1985; Symposium 125 The Origin and Evolution of Neutron Stars, Nanjing, China, May 26-29, 1986; Symposium 122 Circumstellar Matter, Heidelberg, FRG, June 23-27, 1986; Symposium 123 Advances in Helio- and Asteroseismology, Aarhus, Denmark, July 7-11, 1986; Symposium 126 Globular Cluster Systems in Galaxies, Cambridge, MA, USA, August 25-29, 1986; Symposium 131 Planetary Nebulae, Mexico City, October 5-9, 1987; Colloquium 90 Upper Main Sequence Stars with Anomalous Abundances, Crimea, May 14-17, 1985; Colloquium 89 Radiation Hydrodynamics in Stars and Compact Objects, Copenhagen, Denmark, June 11-20, 1985; Colloquium 87 Hydrogen Deficient Stars and Related Objects, Mysore, India, November 10-15, 1985; Colloquium 93 Cataclysmic Variables, Bamberg, FRG, June 18-20, 1986; Colloquium 92 Physics of Be Stars, Boulder CO, USA, August 18-22, 1986; Colloquium 95 Second Conference on Faint Blue Stars, Tucson, AZ, USA, May 31 - June 3, 1987; Colloquium 97 Wide Components in Double and Multiple Stars: Problems of Observation and Interpretation, Brussels, Belgium, June 8-13, 1987; Colloquium 101 Interaction of Supernova Remnants with the Interstellar Medium, Penticton, BC, Canada, June 9-12, 1987; Colloquium 103 The Symbiotic Phenomenon, Torun, Poland, August 18-21, 1987; and Colloquium 108 Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity, Mass Loss and Explosion, Tokyo, Japan, September 1-4, 1987.

II. CONVECTIVE OVERSHOOTING (N.H. Baker, Columbia University)

The structure of stellar convection zones is usually calculated using some form of mixing-length theory, according to which it is postulated that the velocity of convective elements is nonzero only in those regions of the star that are convectively unstable according to a linear stability analysis. (Such a theory is called a "local" theory.) In fact, there is no reason to expect that the velocity should vanish as soon as the acceleration is no longer positive. The true boundaries of a convection zone will thus lie outside the boundaries of the unstable ("superadiabatic") region, and it is this phenomenon that is called "overshooting".

It has long been recognized that this may have detectable consequences for stellar structure and evolution. Energy transport by the overshooting elements may change the structure of the star. In chemically inhomogeneous regions there may be additional mixing of species, which can alter the nuclear processes in subsequent evolution. There may be dynamical effects also, such as momentum transport and wave generation.

The problem that has received most attention is overshooting above the convective cores of massive stars, which may alter the luminosity, the temperature, and even the surface composition of evolving models. In the sun, overshooting from the top of the subsurface convection zone has a strong effect on the velocity fields observed at the surface, and the overshooting region at the bottom may be important for magnetic flux storage. In main-sequence stars overshooting at the bottom of such a zone may have a bearing on the lithium-depletion problem. Mixing by the overshooting elements may be important also in other stars like red giants, novae, and supernovae.

Several approaches to the problem are currently being used. The most realistic are the large two- and three-dimensional simulations now possible on large computers. These are too complex to be used in stellar evolution calculations, and so the search has continued for simpler formulations, usually nonlocal generalizations of mixing-length theory. In evolution studies these are often used, but a purely empirical approach, in which a free parameter is introduced which is proportional to the overshooting distance, has also proved fruitful. In both main-sequence and later stages there are consequences that can be compared with observation.

1. Numerical Simulations

Several types of numerical simulation have been used. Modal expansions with one or two horizontal planforms, as used recently by Massaguer et al. (38.064.041) allow good vertical resolution, but the horizontal structure is distorted by the planform truncation. Two-dimensional simulations like those of Hurlburt et al. (38.065.037 and Ap.J., 311, 563, 1986) also restrict the form of the horizontal flow, but not nearly so severely as the modal approach, and they allow better spatial resolution than is possible in three dimensions. Three-dimensional simulations have also been performed, most with application especially to the solar convection zone: Nordlund (40.080.105), Glatzmeier (39.065.045), Gilman and Miller (Ap.J. Suppl., 61, 585, 1986), and Chan and Sofia (Ap.J., 307, 222, 1986 and Science, 235, 465, 1987) and others have contributed. In most of this work the convective cells are found to extend vertically over a number of pressure scale heights, suggesting that the mixing-length treatment, which postulates a characteristic distance of the order of a scale height, is inapplicable to this type of convection. On the other hand Chan and Sofia (Science, 235, 465, 1987) find a correlation length of the order of one scale height. While there are differences in the results obtained with the various techniques, there are many points of agreement, and certainly we are now beginning to get an idea of what stellar convection zones must really look like.

The work most directly applicable to the overshooting problem is that of Massaguer et al. (38.064.041) (modal) and of Hurlburt et al. (Ap.J., 311, 563, 1986) (two-dimensional). In these papers three polytropic layers are studied, and the mutual interactions of the middle unstable layer and the surrounding stable ones is investigated. Strong pressure fluctuations can counteract the temperature fluctuations and reverse the sign of density fluctuations, leading to a reversal of buoyancy in the upper part of the unstable zone. This produces marked up-down asymmetries in the flow. There is strong penetration into the lower stable region, which induces internal gravity waves. Overshooting into the upper stable zone is much less pronounced, having very little effect on the heat transport there; however, relatively weak velocity fields, which could give rise to mixing, do penetrate to a distance of the order of a scale height. On the whole, the picture appears to be at variance with what any of the mixing-length type theories predict.

The two-dimensional and especially the three-dimensional simulations must be run on rather coarse grids, so only large-scale motions can be explicitly represented. The smaller scales, including the smallest ones in which viscous dissipation occurs, are usually modeled crudely by introducing some kind of eddy diffusivity. In this sense there is a link to the nonlocal mixing-length theories, though the simulations of course take full account of compressibility and have more realistic horizontal structure. The virtues and pitfalls of the simulation approach are summarized in a review of solar and stellar convection by Zahn (in "Solar and Stellar Physics", eds. Schroeter and Schluessler, Springer-Verlag, 1987, in press).

2. Mixing-length Theories

Overshooting is excluded in standard mixing-length theories, but a number of authors have attempted to fix up the mixing-length formalism to take account of penetration. Some authors have used a scheme proposed several years ago by Shaviv and Salpeter, in which the dynamics of the overshooting elements is modeled in a simple way. The method has recently been criticized by Langer (A & A 164, 45, 1986), who finds that the solution is not unique. In any case there are difficulties in matching the overshooting to the solution in the unstable region. Another scheme is that of Roxburgh, which is based on a conservation theorem; this has been criticized by several authors, most recently Baker and Kuhfuss (A & A 1987, in press). Others have used their own recipes. One of the more sophisticated treatments is due to Xiong (40.065.008, 40.065.030), who obtained a nonlocal statistical theory by approximating higher-order correlations, which arise from the nonlinear terms in the equations of motion, with diffusion terms. Mixing of species is also included in a consistent way. Such a theory requires the specification of at least one length scale other than the mixing length, namely some kind of diffusion length. A rather similar approach was discussed by Kuhfuss (A & A, 160, 116, 1986). A much simplified treatment that also invokes diffusion has been proposed by Doom (A & A, 1987, submitted). Another statistical theory, incorporating a length scale partly based on the scale height of potential temperature, has been proposed very recently by Cloutman (Ap.J. 313, 699, 1987). Nonlocal mixing-length theories and other theories have been discussed by Unno et al. (40.064.057, 41.065.007). These authors propose improved ways of constructing stellar models with convection zones.

3. Applications

Unno et al. (40.080.033) applied Xiong's nonlocal mixing-length theory to the solar convection zone. They obtained a rather steep temperature gradient in the overshooting region at the top, in good agreement with empirical data. Photospheric velocities were comparable with those observed in granulations. Schmitt et al. (Ap.J., 282, 316, 1984) applied plume theory (used in atmospheric physics and distantly related to the Shaviv-Salpeter formulation) to the question of overshooting at the bottom of the solar convection zone. They found the overshooting region to be adiabatic, and only a few tenths of a scale height in thickness.

Most of the other applications have been to the evolution of massive stars. A number of papers on this subject are found in the proceedings of IAU Symposium No. 116, "Luminous Stars and Associations in Galaxies" (41.012.079). The evolution of these stars is also affected by mass loss, which is the main subject of a review by Chiosi and Maeder (Ann. Rev. Astron. Astrophys., 24, 329, 1986).

Overshooting from the convective core can be significant in the evolution of stars with initial masses of as little as a few solar masses, and studies have included stars as massive as 120 solar masses and more. The usual technique is to construct sequences of stellar models from which theoretical isochrones can be obtained. These are then the basis of a comparison with observed HR diagrams, especially those of young clusters and associations. (See particularly Stothers (40.065.087) and Mermilliod and Maeder (41.153.005).) Most authors include mass loss (according to an empirical formula) in addition to overshooting, but the effect of overshooting alone can be seen in the paper of Stothers and Chin (39.065.054), who compute tracks with and without mass loss. They model the effect of overshooting by a parameter which is the ratio of the "overshooting distance" to the local pressure scale height at the top of the unstable region, and find the best fit with a parameter equal to 0.35. This is in good general agreement with Maeder and Meynet (A & A, 1987, in press), who use a similar procedure. Another evolution study in which the effect of overshooting alone can be seen is that of Xiong (A & A 167, 239, 1986), who uses his own nonlocal theory, with special attention to details of the overshooting.

Models having a convective core enlarged by overshooting are more luminous at the main-sequence turnoff and have longer H-burning lifetimes than standard models. In general this means that the main-sequence band is wider, which improves greatly the agreement with observational data. The exception to this is that Maeder and Meynet (A & A, 1987, in press) note that their models, including mass loss and overshooting, produce a narrowed main sequence for O-type stars, which they find to be in good agreement with observations for the youngest clusters and associations. Overshooting also limits the extent of the blueward loops in the HR diagram during He burning, thus affecting the statistics of red giants in the diagram. In addition to the works already mentioned, there has been extensive work by other authors, notably by Bertelli et al. (40.065.029, 40,065.107, 41.065.171, 41.065.174), who use an overshooting model something like that of Shaviv & Salpeter, by Doom and collaborators (39.065.004, 41.065.076, 40.065.109), using Roxburgh's overshooting criterion, and by Langer & El Eid (A & A, 167, 265, 1986). It is also to be expected that the effects mentioned will influence mass transfer in close binary systems containing massive stars, the consequences of which have been studied by Sybesma (39.117.033, 41.065.034, A & A 168, 147, 1986). On the whole there seems to be a consensus that models with overshooting produce better agreement with observations, but recently Vanbeveren (A & A, 182, 1987) has questioned this.

In the more massive stars, large convective cores produced by overshooting together with rapid mass loss may lead to the uncovering of nuclear-processed material. This provides the opportunity for confrontation of current ideas of nucleosynthesis with observational data, especially the peculiar abundances seen in various classes of Wolf-Rayet stars. Recent papers that have been especially concerned with such questions are those of Prantzos and collaborators (41.065.099 and Ap.J., 315, 209, 1987), Doom et al. (41.065.076), Langer (A & A 171, L1, 1987), and Maeder & Meynet (A & A, 1987, in press).

4. Future Developments

The stellar evolution studies appear to have given a good idea of the amount of overshooting needed to make contact with observations, and they thus give convection theorists something to aim at. They can be used to calibrate theories having free parameters, but they clearly do not yet provide any sensitive test of the theories. Indeed, the simple parameterizations, which do not pretend to any physical content, seem to be about as good as anything. Evolution studies will surely continue, and may at least help to exclude some of the theories.

In the end, however, one wishes to have a serviceable theory of convection and overshooting, simple enough to be used in stellar evolution calculations and agreeing in at least essential details with more sophisticated models. Possibly the generalized mixing-length theories that are increasingly being developed and applied will be satisfactory; perhaps quite different approaches will have to be tried. One can only be sure that this will continue to be an active field for astrophysical fluid dynamicists. One can also expect that large-scale numerical simulations of compressible convection will become increasingly sophisticated and realistic, providing a body of data which will furnish a guide as well as a challenge to those who wish to devise simpler convection models for use in stellar-structure calculations.

III. MASS LOSS (I. Appenzeller, Landessternwarte, Heidelbrg-Konigstuhl)

1. General Remarks, Meetings, Reviews

During the past decade it became clear that mass loss occurs in practically all stars and at all evolutionary phases and that mass loss may profoundly influence a star's evolution. Hence, the number of papers concerning various aspects of stellar mass loss has been increasing steadily. In this report we shall briefly discuss those new results on stellar mass loss which are directly related to the internal constitution and evolution of stars. Concerning new investigations of the spectroscopic manifestation of stellar mass loss, atmospheric effects and the interaction of stellar mass loss with the interstellar medium we refer to the reports of Commissions 29, 36, and 34.

Among the recent scientific meetings the IAU Symposia Nos. 116 (Luminous Stars and Associations in Galaxies, May 1985, Porto Heli, Greece, 41.12.79) and 122 (Circumstellar Matter, June 1986, Heidelberg, FRG, D. Reidel 1987) and the IAU Colloquia Nos. 89 (Radiation Hydrodynamics, June 1985, Copenhagen, Denmark, 42.12.102) and 92 (Physics of Be Stars, August 1986, Boulder, USA) were to a large part devoted to problems related to stellar mass loss. Many new results concerning cool stars of high and low luminosity were reported at the conference on "Mass Loss from Red Giants" held in June 1984 in Los Angeles (40.12.28) and at the Dunsink Bicentenary Colloquium in 1986 (42.12.24). Mass loss from hot stars was discussed at the NASA-GSFC workshop in June 1984 (39.12.23) and at the workshop on "Instabilities in Luminous Early Type Stars" which took place in April 1986 at Lunteren (Netherlands), honouring C. de Jager. The relation between chromospheric heating and mass loss was the topic of the 1984 "Trieste Workshop" which was held at the Sacramento Peak Observatory, USA (40.12.97). The proceedings of all these meetings contain, in addition to exciting new results, excellent reviews on many details of the mass loss problem. Two other highly useful and comprehensive reviews which must be mentioned here have been published in Volume 24 of the Annual Review of Astronomy and Astrophysics: Chiosi and Maeder (42.65.44) summarized our knowledge about mass loss from hot stars, while Dupree (42.112.43) treated mass loss from cool stars.

2. Mass Loss Rates

An important input parameter of modern stellar evolution computations of massive stars and evolved stars are accurate mass loss rates as a function of a star's position in the HR diagram. Due to more sensitive IR and Radio measurements (for hot stars) and the introduction of molecular microwave data (for cool stars) the accuracy of empirical mass loss rate derivations could be significantly improved during the past few years. New or better mass loss rates of individual hot stars have been reported by Lamers and Waters (38.64.01, 38.64. 06), by Kenyon and Galagher (39.112.73) and by Schmutz and Hamann (42.64.27). De Jager, Nieuwenhuijzen and van der Hucht (41.112.126) compiled a list of 189 individual stellar mass loss derivations taken from the literature and covering spectral types from O to M. For cool stars many new mass loss rates derived from CO observations were publised by Knapp and Morris (39.112.93), Knapp (42.112.86, 42.112.185), and Wannier and Sahai (42.112.69). Valuable new data on mass loss rates derived from UV spectroscopy has been listed in several contributions to the new IUE book ("Exploring the Universe with the IUE Satellite", Kondo et al. eds. D. Reidel 1987).

3. Mechanisms

Although there are still many open questions, the period covered by this report brought real progress in our theoretical understanding of the physical mechanisms leading to stellar mass loss. Greatly improved atmospheric models of hot stars developed by Abbott and Hummer (40.64.06) and by Kudritzki, Pauldrach, and Puls (40.64.03, 42.64.04, A.A. 173, 293, 1987) resulted in much better agreement between theory and observations of radiation-driven winds of O stars. These new results strongly support the basic ideas of the Castor-Abbott-Klein theory. Lamers (41.112. 30., 41.112.127) and Appenzeller (41.65.163) showed that line radiation pressure may also explain the highly non-stationary and extreme mass loss from S Dor and P Cyg stars. Friend and MacGregor (38.64.25) and Uchida (39.64.20) investigated possible magnetic acceleration effects in the wind of hot stars. The stability of line-driven winds was studied by Owocki and Rybicki (38.64.33) and by Lucy (38.64.34). Optically thick radiative wind acceleration at luminosities near or above the Eddington luminosity was modelled by Quinn and Paczynski (39.64.35) and Kato (39.64.55). Stellar pulsations as a mechanism driving mass loss was studied by Dziembowski (39.65.118) and by Willson an Bowen (38.65.65). De Jager further developed his theory of turbulent-pressure driven winds (38.64.16). Mass loss due to radiation pressure on molecules in cool stellar atmospheres was reinvestigated by Stelnitskij et al. (41.64.24). Gail and Sedlmayr (40.64.05, 41.64.37), Drinkwater and Wood (40.65.50) and Yorke (42.64.38) developed new detailed models of the dust-driven mass loss from cool stars. Using better opacities (which included isotopic variants of diatomic molecules) Lucy, Robertson, and Sharp calculated improved models of carbon stars. Compared to earlier results the new evolutionary tracks reach lower effective temperatures and therefore are now consistent with the onset of strong dust-driven mass loss during the evolution of carbon rich stars.

CCD imaging and spectroscopic observations confirmed the highly non-isotropic character of the mass loss from PMS stars (see e.g. 38.121.35, 40.121.55, 41.121.14, 42.121.04). New theoretical models explaining the collimated wind flows were developed by Sakashita, Hanami, and Umemura (39.64.76) and by Pudritz and Norman (41.64.20). Bastian and Mundt (39.121.76) and Croswell, Hartmann, and Avrett (Ap.J. 312, 227,1987) used high resolution spectroscopy to analyse the winds from FU Ori objects. They found very low temperatures in the wind acceleration zones, which rules out a thermal acceleration mechanism and supports the earlier suggestion of a magnetic driving mechanism of PMS stellar mass loss.

4. Evolutionary Computations with Mass Loss

Mitalas and Falk (38.65.33), Pylyser, Doom, and de Loore (40.112.65), Sreenivasan and Wilson (39.65.39, 39.65.58), Bertelli, Bressan, and Chiosi (40.65.29), and Prantzos, Doom, Arnould, and de Loore (41.65.99, 41.65.136, 41.65.137) carried out new theoretical model computations of the structure and evolution of mass-losing stars.

Although differing in various model assumptions and physical details, these new calculations give qualitatively similar results. General discussions of the consequences of mass loss on evolutionary tracks have been presented by Maeder (42.65.15) and by Iben (40.64.26). Maeder also used his evolutionary computations of massive stars with mass loss to study the vibrational stability behaviour during the evolution to the WR stage (39.65.74). Schild and Maeder (38.65.02) compared the results of evolutionary computations with mass loss with the Wolf-Rayet star content of open clusters. In another very interesting comparison of computed theoretical isochrones with observed CM diagrams of 25 galactic clusters, Mermilliod and Maeder (41.153.05) found discrepancies which cannot be explained by the uncertainties of the mass loss rates alone. Brunish, Gallagher, and Truran (41.65.111) re-examined the number ratio of blue and red supergiants as predicted from the evolutionary computations which include mass loss in a self-consitent way. They find satisfactory agreement between the present theory and the observations within the expected errors.

Taken together the improved evolutionary computations show reasonable agreement with the basic observational results. However, in detailed comparisons with galactic clusters there still remain some discrepancies which must be overcome either by even better theoretical models, or perhaps by more accurate empirical mass loss rate derivaitons.

IV. NOVAE (Mario Livio, University of Illinois, Urbana and Technion, Haifa)

1. Introduction

Our understanding of classical novae has benefited in recent years especially from simultaneous multi-frequency observations. In particular, observations in the UV, infra-red, and X-rays have added new dimensions to our coverage of nova energetics. Consequently, much of the present summary of highlights in nova research in the past three years, concentrates on such observations. Some theoretical developments are also outlined. Two books, "Interacting Binary Stars" (39.003.030) and "Interacting Binaries" (1985, Dordrecht: D. Reidel), contain material on novae and related objects. Ritter's fourth edition of the Catalogue of Cataclysmic Binaries, Low Mass X-Ray Binaries and Related Objects (1987, Astron. Ap. Suppl., in press) provides up to date information on nova systems. The most impressive compilation of data on novae and related systems in recent years, is provided by Duerbeck's Reference Catalogue and Atlas of Galactic Novae (1987, Space Science Reviews, 45, 1). The catalogue and atlas contain positions, finding charts, apparent magnitudes, light curve types and principal bibliographical references, and will surely prove immensely useful to all nova researchers.

2. Oxygen-Neon-Magnesium Novae

A recent compilation of abundances observed in nova ejecta revealed the fact that all novae for which reasonable abundance data exist show enrichments in heavy elements or helium or both (Truran and Livio 1986, Ap. J., 308, 721; Truran 40.124.010, Williams 40.124.011, de Freitas Pacheco and Codina 39.124.322). Furthermore, recent abundance determinations established the existence of a class of novae showing enrichment in Oxygen, Neon, and Magnesium (V693 Cr A 1981, Williams et al. 39.124.102, V1370 Aql 1982, Snijders et al. 38.124.201, Nova Vul 1984II, Andrillat and Houzioux 40.124.135, Gehrz et al. 40.124.133). While it has been shown, that breakout of the CNO cycle can yield neon and heavier nuclei (Wiescher et al. 41.065.129), the temperatures required for such a breakout ($T > 4 \times 10^8$ K) are not achieved in nova outbursts. It has therefore been suggested that these enrichments originate from the underlying white dwarf, suggesting the existence of a population of ONeMg white dwarfs in nova systems (Delbourgo-Salvador et al. 40.124.017, Truran and Livio 1986, Ap. J., 308, 721). The white dwarf material is probably brought into the envelope by shear mixing (Fujimoto 1987, Astron. Ap., 176, 53, Livio and Truran 1987, Ap. J., 318, 316) or to some extent by diffusion (Kovetz and Prialnik 39.065.047). It has been shown (Truran and Livio 1986, Ap. J., 308, 721) that selection effects associated with the fact that ONeMg white dwarfs, being more massive, experience their nova outbursts more frequently, act to ensure that the relatively small fraction of the systems in which ONeMg white dwarfs do occur, can account for about one third of the observed outbursts. A simulation of a thermonuclear runaway, when the envelope contains oxygen, neon, and magnesium has been performed by Starrfield et al. (41.065.077), resulting in an extremely violent outburst.

3. X-Ray Observations of Novae

Several EXOSAT X-ray observations of classical novae were reported. First, soft X-rays (0.04-2 keV) were detected from Nova Muscae 1983, about 4×10^7 sec after the outburst maximum (Gelman et al. 38.124.144). This was followed by a second set of observations which revealed that Nova Muscae 1983 continued to emit X-rays at the same intensity in the interval 460-700 days and then started to decay on a timescale of ∿ 300 days (Gelman et al. 40.124.014 and 1987, Astron. Ap., 177, 110). Observations of Nova Vulpeculae 1984I and Nova Vulpeculae 1984II have shown the emission arising from the outburst to about 300 days (Gelman et al. 1987, Astron. Ap., 177, 110). Based on the fact that a decline has been observed in ∿ 2 years in Nova Muscae 1983 (compared to a calculated plasma cooling time of 30-60 years) and on the absence of coronal [Fe XIV] lines, Gelman et al. argued against an interpretation of emission from a shocked circumstellar gas. Instead, they suggested that the observations are consistent with a constant bolometric luminosity model of a hot white dwarf, evolving like the central star of a planetary nebula.

EXOSAT observations of GK Per during its 1983 optical outburst (Bianchini et al. 41.124.162) detected hard X-ray emission showing a strong coherent modulation at 351 seconds, thus identifying the white dwarf as an intermediate polar (Watson et al. 39.124.201). In addition, an aperiodic modulation on a timescale of ∿ 3000 sec has also been detected. Both of these modulations were also identified by high speed photometry (Mazeh et al. 40.124.201). It has been suggested that transition fronts, moving in a small inner disk, may be responsible for the 3000 sec variation (Duschl et al. 40.124.202). Intense soft X-ray emission has also been detected from the recurrent nova RS Oph about two months after its optical outburst. The X-ray flux declined rapidly between 60-90 days (Mason et al. 1986, to be published in "RS Ophiuchi and the Recurrent Nova Phenomenon").

4. Dust in Nova Shells

Considerable progress has been achieved in observations and to a lesser extent in theory of dust formation in nova shells. On the theoretical side, the effects of hydrogen and carbon ionizations on grain growth and destruction have been investigated by Mitchell and Evans (38.124.001). Observations of FH Ser have shown that grain growth occurred at 60-111 days after the outburst, while the grains have undergone a significant reduction in size at 111-129 days. The bolometric luminosity was found to stay constant until 200 days and to decrease as t^{-1} afterwards. In Nova Aquilae 1982, the ejecta was found to contain comparable amounts of gas and dust (Snijders et al. 38.124.201, also Roche et al. 38.124.202, and Catchpole et al. 40.124.008). The general noted trend that slow novae contain larger amounts of dust than fast novae has been confirmed by the finding that five classical novae have counterparts in the IRAS Point Source Catalog (Dinerstein and Robinson 41.124.018).

Somewhat surprisingly perhaps, an excess at 10 micrometers, consistent with the heating of dust, was found for the "dustless" nova V1500 Cyg (Bode and Evans 40.124.163). Even more surprising was the fact that infrared thermal dust emission did not occur (Whitelock et al. 38.124.142) in Nova Mus 1983 (which had a decay rate of ~ 0.06 mag day^{-1}).

5. The "Hibernation" Scenario of Classical Novae

An interesting development in nova theory has been provided by the suggestion of the "hibernation" scenario for classical nova (CN) systems (Shara et al. 1986, Ap. J., 311, 163, Livio and Shara 1987, Ap. J., in press). In this scenario, it is suggested that the mass transfer rate in some CN systems decreases some 50-300 years following the outburst, to values which allow the system to undergo dwarf nova eruptions. The mass transfer rate is then assumed to return slowly to its pre-outburst high value. The cause for a behavior of this type could be an increase in the binary separation as a result of mass loss during the nova outburst, followed by a reduction of the separation due to magnetic braking. The basic motivation for this scenario has been provided by the following facts: (a) The accretion rates deduced from observations (Patterson 37.117.200, Warner 1987, M.N.R.A.S., in press), are too high to produce strong outbursts (Prialnik and Shara 1986, Ap. J., 311, 172, Livio et al. 1987, Ap. J., in press). (b) Observations of the two oldest recovered nova systems CK Vul (1670) and WY Sge (1783) have shown that these systems are in a state of very low mass (Shara et al. 40.124.141, Shara et al. 38.124.181) and RR Pic (1925) was observed to undergo a decrease in its luminosity (Warner, 41.124.221). (c) Some CN systems were observed to undergo dwarf nova eruptions (e.g. Q Cyg, Shugarov 39.124.281, BV Cen, Menzies et al. 41.117.154, V1017 Sgr, Webbink et al. 1987, Ap. J., 131, 493). (d) There exists a known discrepancy between the space density of CNe as deduced from sky surveys and that deduced from conventional nova theory (Patterson 37.117.200).

The most appealing aspect of the hibernation scenario is the fact that it provides a picture of cyclic evolution in which cataclysmic variable systems metamorphose between classical novae and dwarf novae. Some difficulties with this scenario were outlined by Livio (1987, Comments on Astrophysics, in press), as well as crucial observations.

6. Recurrent Novae

Recurrent novae have received much attention in recent years, especially with the outburst of RS Oph in 1985 (39.124.014, 39.124.016, 39.124.018, 39.124.019). The outburst has been observed also in the UV, by Cassatella et al. (40.124.018), in the radio, revealing an unusual radio source (Hjelming et al. 41.124.013) and in X-rays, where intense soft X-ray emission (Mason et al. 1986, to be published in "RS Ophiuchi and the Recurrent Nova Phenomenon") has been detected. New radial velocity measurements for T CrB confirmed that an M3 giant is transferring mass onto a main sequence star in this system (Kenyon and Garcia 41.124.007, also Peel 41.124.007). Observations of U Sco at quiescence revealed He II emission lines on a nearly featureless continuum, no hydrogen lines were detected (Hanes 39.124.004). U Sco was detected in outburst again in 1987, the previous outburst being in 1979 (IAU Cir., 4395-4397, 4399, 4405). In a very comprehensive work, Webbink et al. (1987, Ap. J., 314, 653) examined all of the available observational data on recurrent novae, in an attempt to suggest an appropriate model for each system. They concluded that WZ Sge, VY Aqr, RZ Leo, and V1195 Oph are dwarf novae and V1017 Sgr is a classical nova that has undergone two dwarf nova eruptions. Of the remaining systems, the outbursts of T CrB and RS Oph represent very probably accretion events from a red giant to a main sequence companion (as discussed also by Livio et al. 1986, Ap. J., 308, 736). The X-ray emission in RS Oph is probably caused by high velocity ejecta interacting with a slow moving pre-outburst wind (Bode and Kahn 40.124.001). Webbink et al. (1987, Ap. J., 314, 653) suggested that the outbursts of T Pyx result from thermonuclear runaways (TNR) on a massive accreting white dwarf. Based on a successful simulation of Starrfield et al. (39.124.001), they also suggested that the outbursts of U Sco may be thermonuclear. However, Truran et al. (1987, Ap. J., in press) have shown that if the helium to hydrogen ratio in the accreted material is indeed 2:1 (by number), as suggested by the observations of Hanes (39.124.004), then it is extremely difficult to produce a visually bright nova by a TNR. Remembering in addition, that the time interval between the last two outbursts of U Sco is only eight years, an accretion event interpretation has to be reexamined (Truran et al. 1987, Ap. J., in press).

In an interesting development, recent spectroscopy of V616 Mon has revealed surprisingly large radial velocity variations in the spectrum of the K-star in this system, indicating a massive compact companion (McClintock and Remillard 1986, Ap. J., 308, 110). V616 thus became a very good black hole candidate (Watson 41.117.105)

7. Final Note on Novae as Distance Indicators

Finally, we would like to mention that it has been suggested that the M_V(max) to rate-of-decline relationship is potentially a very powerful tool for the calibration of the extragalactic distance scale (Cohen 39.124.009, van den Bergh and Pritchet 41.161.057).

V. PRESUPERNOVA MODELS AND SN 1987A (Ken'ichi Nomoto, University of Tokyo)

The occurrence of SN 1987A in the Large Magellanic Cloud had a big impact on theoretical works on stellar constitution and a lot of work has been done since then. Spectral observations have shown that SN 1987A is a Type II supernova and thus an explosion of a massive star. Indeed a massive blue supergiant star, Sk-69 202, has been identified as the most likely progenitor of SN 1987A. This is the first identification of a supernova progenitor. The historic observations of neutrino burst from SN 1987A (Hirata et al. Phys. Rev. Lett., 58, 1490, 1987; Bionta et al. Phys. Rev. Lett., 58, 1494, 1987) have confirmed the basic validity of the current theory of Type II supernovae and opened a new era of neutrino astronomy. Further observations in all wave bands are providing us with very interesting materials to test the theory of massive star evolution, nucleosynthesis, and supernova explosion. This opportunity is important because massive stars have been considered to be one of the most important sites of nucleosynthesis, yet their presupernova structure and explosion mechanism still involve considerable uncertainties.

SN 1987A is certainly one of the highlights in the field of stellar constitution, so that I will focus on the problems of presupernova models that is directly related to SN 1987A. Related meetings are Supernova Workshop in Honor of Hans Bethe (Phys. Rep., 1987, ed. G.E. Brown), ESO Workshop on SN 1987A (ESO, 1987, ed. J. Danziger) and IAU Colloquium No. 108, Atmospheric Diagnostics of Stellar Evolution (Lecture Note in Phys., 1987, ed. K. Nomoto). Comprehensive reviews on the current understanding of presupernova evolution are seen in Woosley and Weaver (42.125.057), Nomoto (42.065.126), and Woosley (42.065.136).

1. Evolution of the Progenitor of SN 1987A

Sk-69 202 is the most likely progenitor of SN 1987A (West et al. A&A, 177, L1, 1987; Kirshner et al. Ap.J. , 1987, in press; Gilmozzi et al. Nature, 328, 318, 1987). It is a B3 blue supergiant and its luminosity is estimated to be about 1.3 x 10^5 $L_\odot$ which corresponds to the presupernova luminosity of a helium core of mass about 6 $M_\odot$ (Woosley et al. Ap.J., 318, 664, 1987; Nomoto, Shigeyama, and Hashimoto in SN 1987A, ESO, 1987). Its main-sequence mass is estimated to be M_{ms} = 17 - 20 $M_\odot$ which depends on the helium-core mass to M_{ms} relation and thus on the convective overshooting during hydrogen burning (Hillebrandt et al. Nature, 327, 597, 1987; Maeder in SN 1987A, ESO, 1987).

From the luminosity and the spectral type of Sk-69 202, the progenitor's radius is estimated to be about 3 x 10^{12} cm. The occurrence of a Type II supernova from such a blue supergiant progenitor is not known before. Previously Type II supernovae are subclassified into II-P (plateau) and II-L (linear) according to their light curve shape (Doggett and Branch 40.125.080). Type II-P supernovae are well modeled by the explosions of red supergiants (Woosley and Weaver 42.125.057). The early light curve of SN 1987A reached plateau but its luminosity is about 20 times lower than the typical plateau luminosity of SN II-P. Another important observation is that it took only 3 hr from the neutrino burst to the optical brightening at 6.4 mag. This requires the progenitor's radius of as small as the order of 10^{12} cm in order for the shock wave to propagate through the envelope in sufficiently short time (Shigeyama et al. Nature, 328, 320, 1987). The low luminous plateau is well modeled with a progenitor whose radius is much smaller than that of red supergiants (Arnett Ap.J., 319, 136, 1987; Shigeyama et al. 1987; Woosley, Pinto, and Ensman Ap.J., 1987, in press). All these observations point to the blue supergiant progenitor.

Then the question is why the progenitor of SN 1987A evolved to become a blue supergiant at the explosion. Basically two reasons have been argued. One is the low metallicity of the LMC, which is 1/3 - 1/4 of our Galaxy. With such low metallicity and without mass loss, Hillebrandt et al. (1987) and Arnett (1987) found that their 15 - 20 $M_\odot$ stars remain blue throughout the evolution without becoming red. Woosley, Pinto, and Ensman (1987) found in a similar calculation that 15 - 20 $M_\odot$ stars without mass loss once evolve to the red supergiant and return to the blue if metallicity is low and the Ledoux criterion is applied to convective stability. The other reason is mass loss during the evolution. Maeder (in SN 1987A, ESO, 1987a) argues that mass loss leads to disappearance of the intermediate convective shell and drives the expansion of the star to the red even with low metallicity. The stars more massive than about 20 $M_\odot$ return to the blue when the mass of the hydrogen-rich envelope is reduced below 1 $M_\odot$. Maeder (1987a) and Wood and Faulkner (Proc. Astr. Soc. Australia, 1987, in press) have shown that the low metallicity plays a roll to reduce the mass loss rate by a factor of 2 - 3 so that the return from the red to blue is delayed to the beginning of carbon burning stage and the star ends up as a blue supergiant before evolving to a Wolf-Rayet star. If the low metallicity is essential, the envelope mass could be large, while it is smaller than 1 $M_\odot$ if the latter is the case.

The exact reason for such numerical behavior has not been well analyzed yet. The stellar radius is very sensitive to the temperature and density gradient near the bottom of the hydrogen-rich envelope and thus to the luminosity at the core edge, opacities and the appearance of intermediate convective shell (e.g., Renzini in SN 1987A, ESO, in press). It has been known that stars around 15 - 20 $M_\odot$ show complex evolutionary behavior between blue and red supergiants in the H-R diagram (e.g., Maeder and Meynet A&A, 182, 243, 1987). The low metallicity would affect the structure near the core-envelope boundary through the hydrogen shell burning the opacities.

Because of the complexity of the theoretical models, observational constraints are useful. One is the number ratio of the bright red supergiant to blue supergiant in the SMC, LMC, and Galaxy, which is larger for smaller metallicity (Chiosi and Maeder 42.065.014). Another is the UV observations of SN 1987A that show the existence of circumstellar materials where nitrogen is overabundant relative to carbon and oxygen (Kirshner et al. IAU Cir. 4435). These two facts are consistent with the scenario that the progenitor evolved first to become red and then came back to the blue. Moreover, the progenitor should have undergone significant mass loss during the red supergiant phase to expose the nitrogen-rich layer (Maeder A&A, 173, 247, 1987b). How much hydrogen-rich envelope was left at the explosion may depend on the metallicity and the treatment of convection (Woosley, Pinto, and Ensman 1987).

Another constraint on the mass of the hydrogen-rich envelope, M_{env}, at the explosion has been obtained from the light curve model (Woosley, Pinto, and Ensman 1987; Nomoto, Shigeyama, and Hashimoto 1987). The slow increase of the light curve up to the peak requires a relatively slow expansion of the core which requires the existence of at least 3 $M_{\odot}$ envelope. Whether such constraints are consistent with each other is an open question. This may not be an easy question to answer because it is deeply related to the mass loss and convection that have been long-standing problems.

2. Relation to Other Types of Supernovae

Suppose that uniqueness of SN 1987A is mainly due to the progenitor's mass loss history rather than the low metallicity. Then the relation of SN 1987A to other types of supernovae, namely, Type II-P, II-L, and Ib may be as follows: II-Ps are the explosion of red supergiants, so that their progenitor must have suffered from less mass loss than SN 1987A. This implies that the progenitors of II-P are less massive than 17 - 20 $M_{\odot}$. For II-L, progenitor may either be AGB stars (Wheeler, Harkness, and Cappellaro in 13th Texas Symp., 402, 1987) or stars somewhat more massive than SN 1987A. Because of larger amount of ^{56}Ni production or smaller amount of envelope mass, radioactive decays may dominate the light curve. Type Ib supenovae may be either a kind of accreting white dwarfs (Branch and Nomoto 42.125.014) or Wolf-Rayet stars (Wheeler and Levreault 40.125.261; Begelman and Sarazin 41.125.281; Fillipenko et al. 42.125.223; Gaskel et al. 42.125.028; Wheeler et al. Ap.J., 313, L69, 1987; Schaeffer, Casse, and Cahen, Ap.J., 316, L31, 1987). If the latter is the case, the progenitor of Ib is even more massive than those of II-L and SN 1987A, although the low occurrence frequency of very massive star explosion and too broad a light curve (Woosley 42.065.136) are problems with this Ib model. (The Ib progenitors might be helium stars in close binaries. Even so, the progenitor's main-sequence mass must be larger than SN 1987A because the amount of ^{56}Ni required from the Ib light curve is about 0.15 $M_{\odot}$ (Wheeler and Levreault 40.125.261) which is roughly twice as much as in SN 1987A.) In the above sequence, SN 1987A corresponds to a rather narrow mass range, say, 17 - 20 $M_{\odot}$ which depends on the metallicity (Maeder 1987a). It is interesting to note that the progenitor of Cas A is very likely a WN star (Fesen et al. Ap.J., 1987, in press) and thus might be closely related to SN 1987A.

The idea that the low metallicity is essential in making the presupernova blue might be a good explanation of the fact that Type II supernovae have not been observed in irregular galaxies (Shklovski 38.125.030). In this view, SN 1987A-like supernovae are not rare in metal-poor young galaxies but rare in metal-rich galaxies.

3. Presupernova Core Models and Explosion Mechanism of SN 1987A

The evolution of the core of massive stars is relatively straightforward up to the beginning of the iron core collapse, which is almost independent of the complexity of the envelope. The observation of neutrino burst has dramatically confirmed that the gravitational collapse actually occurred in SN 1987A. Most of the energy released by the collapse has been predicted to be emitted as neutrinos during the proto-neutron star contraction. Because of high density, diffusion of neutrino takes place for over 10 sec (Burrows and Lattimer 42.067.031). The duration of observed neutrino burst over 12 seconds is entirely consistent with this prediction. The total energy of neutrinos emitted from SN 1987A is estimated to be $1 - 3 \times 10^{53}$ erg which corresponds to the binding energy of a neutron star with mass of 1.2 - 1.7 M (Burrows and Lattimer Ap.J., <u>318</u>, L63, 1987; Sato and Suzuki, Phys. Let., 1987 in press). Unless the equation of state is very soft, a black hole formation seems to be unlikely.

One of the central problems in Type II supernova modeling has been to find a mechanism that transforms gravitational collapse into explosion. Two mechanisms have recently demonstrated. One is that the hydrodynamical shock wave ejects overlying materials in a "prompt" manner in mill-seconds. This occurs if the iron core mass is smaller than about 1.6 M and the equation of state is sufficiently soft (Baron, Cooperstein, and Kahana 40.066.123). The other is "delayed" heating of the material behind the stalled shock by neutrinos. The neutrinos are emitted from a hot neutron star that undergoes mass accretion. In a second, the shock wave revives and ejects the material (Wilson et al. 42.065.125). Unfortunately, statistics of neutrinos is too poor to tell us which mechanism did work in SN 1987A.

The hydrodynamical behavior of collapse and explosion depends sensitively on the iron core mass and a density structure in the surrounding heavy element mantle. The major uncertainties in determining the iron core mass include the carbon abundance that is closely related to the treatment of convection. Recent increase in the ^{12}C(α,γ)^{16}O rate by a factor of about three (Fowler 37.061.073) results in the lower carbon abundance (Thielemann and Arnett 40.065.033). Overshooting near the end of core helium burning mixes fresh helium into the central region and decreases carbon abundance (Bertelli, Bressan, and Chiosi 40.065.029; Habets 42.065.032). Moreover, the mass of the evolved core is close to the Chandrasekhar mass, so that the core structure is sensitive to the equation of state of strongly coupled plasmas (Ichimaru Rev. Mod. Phys., <u>54</u>, 1017, 1982) and electron mole number Y_e. For the latter, treatment of silicon burning and associated electron capture involves large uncertainties (Thielemann and Arnett 40.065.033).

In previously published models by Woosley and Weaver (42.125.057), overshooting was included but Coulomb interaction was neglected in the equation of state. For their 25 M star carbon abundance is so small that no convective carbon burning shell forms. The absence of active burning shell results in the formation of an iron core as large as 2.1 M and a relatively high density silicon and oxygen-rich layer. For such a large iron core, the "prompt" mechanism certainly fails to work (Burrows and Lattimer 40.065.132). If overshooting is suppressed, active carbon burning shell forms even with the enhanced ^{12}C(α,γ)^{16}O rate and the resulting iron core masses are as small as 1.4 M for 20 - 25 M stars (Nomoto and Hashimoto Prog. Part. Nucl. Phys. <u>17</u>, 267, 1986); also densities in the heavy element mantle are lower and thus smaller amount of ^{56}Ni would be produced. If this is the case, "prompt" mechanism could operate. Since the progenitor of SN 1987A is about 20 M star, it is interesting whether the observations could provide us with any indication of the deepest core structure.

For stars as small as 13 M, the iron core mass is as small as 1.2 M because inclusions of Coulomb interaction term and electron capture from earlier stages are more effective to reduce the effective Chandrasekhar mass than in more massive stars (Nomoto and Hashimoto, Sci. Rep. Tohoku U. <u>7</u>, 259, 1987). This indicates that presupernova models still have a large uncertainties. Hence, it is still crucial to improve presupernova models in solving the long-standing problem of supernova mechanism.

In SN 1987A, though the mechanism is not yet clear, the shock wave generated at bounce propagated through the star and should have synthesized heavy elements. To find a direct evidence of nucleosynthesis in the deep cores of SN 1987A, we have to wait until emission lines are observed in super-nebula phase (Fransson and Chevalier Ap.J. , 1987, in press). Indirect but good evidence of ^{56}Ni production are seen in the exponential decline of the light curve of SN 1987A, because its decline rate exactly coincides with the ^{56}Co decay rate (Catchpole et al. M.N., 1987, in press; Hamuy et al. Ap.J., 1987, in press). The mass of ^{56}Ni initially synthesized is estimated to be about 0.07 $M_\odot$ (Nomoto, Shigeyama, and Hashimoto 1987). This amount reflects the explosion energy, masses of the resulting neutron star and ejecta, and composition and density structures in the deepest layers.

If the explosion energy is known, it is useful to discriminate the explosion mechanism. For this purpose, quite unique optical light curve of SN 1987A may be useful. From the initial sharp rise, relatively low luminous plateau, and slow increase to the peak, explosion energy of SN 1987A is estimated to be 1 - 1.5 x 10^{51} erg (Woosley, Pinto, Ensman 1987; Nomoto, Shigeyama, and Hashimoto 1987). Consistent calculation of collapse, explosion, nucleosynthesis, and light curve will provide a valuable material to probe the interior of SN 1987A and to test the theory of massive star evolution. In other words, the comparison with the observations of SN 1987A will make it possible to determine some previously unknown quantities and could lead us to deeper understanding of the presupernova configuration, mass loss processes, and convection, which are three major problems in the current stellar evolution theory.

VI. STRUCTURE OF X-RAY BURSTING NEUTRON STARS (M.Y. Fujimoto, Niigata University, and D. Sugimoto, Univeristy of Tokyo)

1. Introduction

X-ray bursts were discovered in 1975. More than thirty X-ray burst sources have been observed to date with a number of satellites. Characteristics of X-ray bursts are: risetime of 1 - 10 sec, decay time of several to several tens of seconds, and duration of 10 - 10^3 sec (Lewin and Joss 34.142.63; Tanaka 41.142.42; Matsuoka 41.142.68). This phenomenon has greatly stimulated theoretical studies on nuclear burnings near the surface of neutron stars. Soon after the discovery, a model of thermonuclear flashes on accreting neutron stars was proposed as a mechanism to produce X-ray bursts (Maraschi and Cavaliere 20.142.63; Woosley and Taam 18.142.64). This model has been studied extensively in these ten years (for the earlier works, see reviews by Taam 39.67.13; Joss and Rappaport 38.117.125). The validity of this model had been generally established. In the reporting years, the X-ray bursts have been studied furthermore as a powerful tool of probing neutron stars. This side is somewhat more stressed in this report rather than the X-ray bursts themselves. Since this topics has never been reported from Commission 35 in the preceeding volumes, we briefly refer also to some former works for easy understanding of the background.

2. Characteristics of Shell Burnings

Properties of the nuclear shell-burnings near the the surface of neutron stars are rather simple and have now been understood fairy well: The pressure of the burning shell is practically indifferent to its thermal state because the thickness of the burning shell is negligible as compared with the radius of the neutron star, and because the nuclear energy release is small as compared with the potential energy of the shell. Therefore, the nature of the shell burning is determined solely by the properties of nuclear reactions. Unless the accretion rate is very low, the accreted hydrogen burns stably, because the rate of CNO cycle is limited by intervening β decays. On the contrary, helium shell-burning, once ignited, grows to a flash and brings about high temperature of the order of 10^9 K where proceeds the formation of heavy elements (Ergma and Tutukov 27.66.511; Taam 29.66.511; Fujimoto et al. 29.66.522). Of particular interest was the nucleosynthesis through successive proton captures and β decays of heavy elements in the hydrogen-rich material, which is termed rp-process (Wallace and Woosley 29.65.105; Hanawa et al. 34.67.81; Wallace and Woosley 39.67.17). On the other hand, Miyaji and Nomoto (40.67.72) discussed the influence of the non-resonant 3α reactions in the low temperature regime on the evolution leading to the shell flash.

In earlier models, only one cycle of thermonuclear flashes were calculated, and only the outer layers were took into computation with the interior replaced by appropriate inner boundary conditions. Models of recurrent shell flashes were constructed later by Woosley and Weaver (39.67.14) with the inner boundary conditions. Hanawa and Fujimoto (38.67.63) computed a recurrence of shell flashes, taking also into account the whole structure of a neutron star and effects of general relativity in spherical symmetry. They demonstrated that a limit-cycle behavior was readily reached after several cycles of flashes because of a small heat capacity of the neutron star envelope.

As for the interaction with the interior of neutron stars, Fujimoto et al. (37.67.70) found that the surface layers and the interior were thermally well decoupled at the shell where heat transports by photon diffusion and by electron conduction are both ineffective during the timescale of accretion. Therefore, the evolution of shell burnings has little to do with the thermal state of the interior for accretion rates of the order as usually observed. For lower accretion rates, however, Hanawa and Fujimoto (41.67.31), and Fujimoto et al. (1987a, Ap.J., 278, 813) discussed a finite effect which could discriminate between different internal thermal states due to possible existence or non-existence of pion condensation, for instance.

One of the interesting findings was the expansion of the envelope and the resulting mass loss from the neutron star during relatively strong X-ray bursts (Hanawa and Sugimoto 31.65.508; Taam 32.66.505; Wallace et al. 32.66.502; Starrfield et al. 32.66.501; Paczynski 33.67.25). They could sound strange because the nuclear energy is much less than the gravitational potential energy. However, there acts the mechanism that concentrates the released nuclear energy into only a small fraction of the accreted surface layer. The expansion is understood as an effect of the decrease of the electron scattering opacity at higher temperatures; more opaque surface layer is pushed out by the photon flux coming from the interior at the rate close to the Eddington luminosity (Hanawa and Sugimoto 31.65.508; Paczynski 33.67.25). Paczynski and Anderson (41.67.33) constructed models of static extended envelope with the general relativity taken into account, and asserted that the effect of general relativity was also crucial to the expansion.

Further expansion leads to the mass loss which was modeled in terms of steady stellar wind (Ebisuzaki, Hanawa, and Sugimoto 33.67.18; Kato 33.67.19). It was elaborated by Melia and Joss (39.67.19), and Quinn and Paczynski (40.64.35), and earlier results were confirmed. Paczynski and Proszynski (41.67.33) also studied the effects of general relativity to observe an influence on the photospheric radius. Helium envelope was assumed in all these models, but the hydrogen-rich layer should be more easily blown off because of higher opacity. Taniguchi and Hanawa (40.67.106) followed the expansion of hydrogen-rich envelope with general relativity included, and Kato (41.67.30) constructed models of mass loss wind from upper hydrogen-rich layer. Observations by Tenma X-ray satellite were interpreted in terms of these mass losses from neutron star (Sugimoto, Ebisuzaki, and Hanawa 38.142.80). The models mentioned above were the stellar wind in steady state. Though Yahel et al. (38.67.93) constructed time-dependent models, they neglected the temperature-dependence of the electron-scattering opacity which was the essential mechnism of driving the mass loss.

3. Problems of Super-Eddington Luminosity

During a burst, the X-ray luminosity and its color change in time, and, accordingly, the star draws a track on a plane similar to the HR diagram. Though this traverse along the track finishes in minutes, it corresponds to the whole evolutionary tracks followed by novae in years. When analyzed peoperly, it provides us with information on the neutron star. Van Paradijs (22.142.5) discussed average radius of neutron stars assuming that the burst peak-flux was equal to the Eddington luminosity. Goldman (26.142.42) and van Paradijs (26.66.517) discussed the general relativistic effects on it.

If the peak-flux is really equal to the Eddington luminosity, the X-ray bursts can play a role of a standard candle. Later, however, this assumption were questioned by the following two independent aruguments. One concerns the temperatures; when the spectra were fitted with the Planckian function, many bursts showed color temperatures much higher than the maximum effective temperature that was shown, from the first principles, to be attained at. The other concerns the flux; for some burst sources, for which independent estimates of their distances were available, the observed luminosity indicated the super-Eddington luminosity for plausible masses of neutron stars.

For the spectra, van Paradijs (31.66.504) suggested a modification of continuous spectra due to suppression of emissivity in the scattering-dominant envelope. Including the Comptonization effect, Czerny and Sztajno (34.67.107), Ebisuzaki, Hanawa, and Sugimoto (38.142.66), and Hoshi (39.67.18) showed that the observed color temperature could be higher than the effective temperature. Self-consistent model atmospheres were constructed by London, Taam, and Howard (38.67.147; 42.67.8), Ebisuzaki and Nomoto (41.67.60), and Ebisuzaki (1987, Publ. Astron. Soc. Japan, 39, 287), who solved the radiative transfer together with the hydrostatic equilibrium in the envelope of neutron star. Foster, Ross, and Fabian (42.67.28) computed also the radiative transfer but not hydrostatic equilibrium. These models gave the relation of the color to the effective temperatures, and enabled detailed comparison of theoretical models with observations.

As to the burst luminosities, no theoretical models produced luminosities appreciably exceeding the Eddington limit. From observational side, there were strong indications for saturation of the flux at a certain level. They were interpreted in relation with expansion of the neutron star envelope which took place at the luminosity very close to the Eddington luminosity. Paczynski (33.67.15) and Ebisuzaki et al. (38.142.66) discussed the expansion of the envelope in relation with observed double peaks in hard X-ray band. Tawara et al. (37.142.9), and Lewin, Vacca, and Basinska (37.142.30) showed that long-lasting bursts with a precursor could also be due to the expansion in much larger scales. Sugimoto et al. (38.142.80) interpreted the observed gap in the peak luminosities in terms of the expansion and mass loss from the distinctly different surface chemical compositions, i.e., from hydrogen-rich envelope and from helium envelope. Though the concept of the Eddington luminosity was essential in these arguments, observations could not give any definite absolute value for the saturation level. Concerning this point, Ebisuzaki et al. (38.142.66) discussed that errors might exist in the estimates of the distance to the burst sources because the Eddington limit was the plausible upper limit for X-ray bursts which proceeded much more slowly as compared with dynamical timescale in the surface layers of the neutron star.

The luminositiy exceeding the Eddington limit may, however, be expected if the the emitting regions deviates from spherical symmetry and the X-ray emission is anisotropic. Lapidus and Sunyaev (40.67.59) argued that the scattering and reflection of photons incident upon the associated accretion disk could distort the angular distribution of the fluxes to produce the super-Eddington luminosity up to by a factor of 1.5 if the source was seen pole on. Melia and Joss (42.142.38) suggested the interaction between the relativistic stellar wind and the accretion disk, but the origin of such high power wind was obscure.

4. Mass and Radius of Neutron Stars

If the observed upper limit to the luminosities is fitted to the Eddington luminosity corresponding to specified chemical compositions, a mass-radius relation results from the observed fluxes and color temperatures where the spectral hardening, i.e., the deviation from the Planckian, is taken into account. This relation is also free from possible anisotropies in the burst fluxes. It was applied to some sources [4U 1636-53 by Fujimoto and Taam (41.67.113); 4U 1636-53 and 4U 1608-52 by Ebisuzaki (1987); 4U 1746-47 by Sztajno et al. (1987, M.N.R.A.S., 226, 39); 4U 1820-30 by van Paradijs and Lewin (1987, A&A, 172, L20); MXB 1728-34 by Foster et al. (42.67.28) and Kaminker et al. (preprint)]. The derived mass-radius relations turn out to be compatible with current models of neutron stars. Some argued that these results could rule out very soft and very hard equations of state. The results, however, depend strongly on the derived color temperatures and the hardening ratios, and thus require further elaborations. In this relation, Jaroszynski (1986, Acta Astron. 36, 335), and Asaoka and Hoshi (1987, Publ. Astron. Soc. Japan, 39, 475) discussed the importance of the effect of rotation and deviation from the Schwarzschild geometry on the distortion of the black body spectra.

For burst sources in globular clusters, the distance estimate is available from optical observations. If we use it, further constraints can be given. Thus, Sztajno et al. (1987) derived a value lower than one solar mass for 4U 1746-37 in NGC 6641 with reservation for the anisotropy, while van Paradijs and Lewin (1987) obtained a mass range for 4U 1820-30 in NGC 6624 which was compatible with those theoretically believed. On the other hand, Horne, Verbunt, and Schneider (41.117.9) suggested a small mass, i.e., 0.6 ± 0.2 $M_\odot$ for 4U 2129+47 (V 1727 Cyg) from spectroscopic observation of emission lines.

An absorption feature was observed in the bursts of 4U 1636-53 and 4U 1608-52 (Waki et al. 38.172.78; Nakamura et al. 1987, Publ. Astron. Soc. Japan, submitted). When it is combined with the mass-radius relation discussed above, the mass and the radius of neutron stars could be determined separately (Fujimoto and Taam 41.67.113; Ebisuzaki 1987). The observed redshift yielded the ratio of the stellar radius to the gravitational radius of R/R_g = 1.6 if the line was identified with Kα line of Fe XXV; it seemed too small when compared with theoretical models of neutron star. If we assigned it with other elements, larger radii were possible (R/R_g = 2.1 and 3.8, respectively, for Cr XXIII and Ti XXI; Waki et al. 38.172.78), but difficulty lies in the origin of these elements. Fujimoto (39.67.122) presented another senario in which the transverse Doppler effect due to rotation of the accreted gas played a role, and gave the value of R/R_g = 2.4 for Fe XXV. This interpretation is, however, subject to a strong condition on the aspect angle of observation. Proper understanding of the absorption feature requires further investigations not only on its identification but also on the line formation in the electron-scattering dominated atmosphere, since an absorption line may suffer from severe smearing due to the Comptonization effect as dissussed by Foster, Ross, and Fabian (1987, M.N.R.A.S., in press).

Additional information can be obtained from the ratio of the persistent flux to the time-averaged burst flux (usually termed as α-value), which is thought to be equal to the ratio of the surface potential to the nuclear energy released in the burst. Lapidus and Sunyaev (40.67.59) pointed out that the α-value was largely affected by the anisotropy both in the burst and persistent emissions. Allowing for the possible anisotropy, Fujimoto (1987b, Ap.J. in press) derived the radius in the range of R/R_g = 2.2 - 3.4 for 4U 1636-53 and EXO 0748-676 from the EXOSAT data (Lewin et al. 1987, Ap.J., 319, 893; Gottwald et al. 1986, Ap.J., 308, 213).

5. Limitations in Spherically Symmetric Models

Most of the models, which were constructed to date, assumed spherical symmetry. Moreover, the accreted material was assumed to pile up layer by layer, successively. On the other hand, there are growing evidences which can hardly be accommodated within such models. Among them are: large variations in the burst properties (such as the peak fluxes, the time-integrated burst fluxes and the recurrence intervals) without any apparent correlations to the accretion rate; too rapid succession of bursts (in less than 10 min) to replenish nuclear fuel by accretion; and absence of burst activity for very bright sources with very high accretion rate.

Various attempts have been continued during the reporting period. Livio and Regev (40.67.10) discussed variability due to the influence of burst emissions to the accretion process. Woosley and Weaver (39.67.14) presented a model of bursts in rapid successions where utilized was residual fuel left unburnt in the preceding shell flash. Nozakura, Ikeuchi, and Fujimoto (38.67.133) studied lateral propagation of the burning front in relation to the rapid succession of bursts due to partial burnings. They were not necessarily granted as successful, and yet assumed the simple accumulation of accreted fuel. Another possible solution was proposed on the basis of detailed analysis of observations. According to EXOSAT data (Lewin et al. 1987), the majority of bursts show much smaller energies and recur at much shorter intervals than predicted by existing models. Fujimoto et al. (1987c, Ap.J. 319, 902) pointed out that an extra mechanism for mixing and heating was necessary to explain them, and suggested hydrodynamical instabilities invoked by the inflow of angular momentum of accreted gas. Fujimoto (1987, A&A, in press) studied the efficiency of elemental mixing and redistribution of angular momentum due to the instabilities, Fujimoto and Hoshi (39.67.121) discussed the effect of dissipative heating on the evolution leading to the ignition of the flashes. Fujimoto et al. (1987c) also argued that this mixing mechanism and the smallnesss of the burst energies could resolve the problem of bursts in rapid succession, since the energy supply was readily explained by the fuel stored only in the upper layers where nuclear burning was inactive.

Effect of magnetic field has so far been ignored or not well explored bacause the magnetic field has been believed to be very weak or even absent in such old neutron stars as the burst sources. However, Kulkarni (42.126.25) asserted, by analysing the nature of optical counterpart of binary pulsar systems, that the decay of the field could be slowed down or might even be stopped when the field strength became of the order of 10^8 G (see van den Heuvel 41.65.158 and references therein). In some models explaining the origin of quasi-periodic oscillations, which were found in some burst sources, the presence of magnetic field of such strength was postulated (Lamb 41.67.159, and references therein). Further studies seem to be necessary to explore the existence of such field and its possible effects on the accreting neutron stars.

VII. ASTEROSEISMOLOGY (H. Shibahashi, University of Tokyo)

Stimulated by the success of helioseismology, a research field called asteroseismology, in which one probes the internal structure of stars by means of observations of their oscillations, is steadily developing. During the past three years, mid 1984 - mid 1987, a couple of conferences whose titles include the term of asteroseismology or its equivalence were held; the NATO Advanced Research Workshop on "Seismology of the Sun and the Distant Stars" in Cambridge in 1985 (41.012.026, ed. D.O. Gough), and the IAU Symposium No.123 on "Advances in Helio- and Asteroseismology" in Aarhus in 1986 (in press by Reidel, ed. J. Christensen-Dalsgaard). The titles of these two conferences are representative of the present status of asteroseismology; the main topics of these conferences were helioseismology, but asteroseismology has been very much activated by the solar oscillation study and is evidently to follow. Some useful theoretical guides have been given and aspiring observations have also been attempted. Good reviews on the subject are available in the proceedings of these conferences (Christensen-Dalsgaard, 41.080.051; Dziembowski and Däppen, in press), and reference may also be made to other reviews by Christensen-Dalsgaard (38.065.129; 42.080.023), de Jager (38.065.130), Dziembowski (39.065.013), and Shibahashi (1986, Proc. Workshop: Hydrodynamic and Magnetohydrodynamic Problems in the Sun and Stars, U. Tokyo, p.195). The following conferences are also somehow related to the subject: the Joint Discussion at the last IAU General Assembly "Solar and Stellar Nonradial Oscillations" (42.012.011, ed. A.N. Cox) and the Los Alamos conference on "Stellar Pulsation" in 1986 (published by Springer 1987, ed. A.N. Cox, W.M. Sparks, and S.G. Starrfield).

1. Solar-like Oscillations

The observable modes in stars in general are limited only to modes with low degrees l, where l denotes the degree of the spherical harmonic function. Since high order p-modes with such low degrees penetrate into the stellar deep interior, they are useful to the seismological approach. By assuming Goldreich and Keeley's (19.080.007) mechanism for the stochastic wave excitation by convective motion in late type stars, Christensen-Dalsgaard and Frandsen (33.065.044) estimated the amplitudes of high order p-modes with low degrees of those stars as $\delta I/I \sim 10^{-5}$. Some aspiring attempts to detect such small amplitude oscillations have been made and two groups (Gelly et al. 42.116.03; Noyes et al. 38.116.024) have so far reported possible detection of them in stars αCen (G2V) and αCMi(F5IV), and εEri (K2V), respectively, and Frandsen (1987, A&Ap., 181, 289) reported an upper limit on p-mode amplitudes in βHyi (G2IV).

The asymptotic theory for high order p-modes with low degree predicts that the eigenfrequencies of p-modes with even and odd l alternate, to first order, with an equal spacing (Tassoul 28.065.044). Since the periodic oscillation is not conspicuous in their raw data, those two groups first calculated the power spectra of the data on the variability and then searched for expected regular patterns on them. By using the frequency spacing thus obtained, we can impose some constraints on the physical parameters of those stars. As for αCMi, the radius thus inferred seems reasonable (Gelly et al.). However, as for αCen, the radius inferred from the oscillation data is inconsistent with that independently determined in terms of the precise measurements of the mass, temperature, and distance of the star (Demarque et al. 41.115.004; Gelly et al. 42.116.03). Guenter and Demarque (41.116.007) compared the calculated oscillation spectrum of models of εEri with the observation by parametrizing the mass, the metallicity, and the mixing length. But the best fit model is so old that the high chromospheric activity and rapid rotation rate of the star seem to contradict with their conclusion. Guenter (1987, Ap.J., 312, 211) discussed this apparent contradiction, and Däppen and Soderblom (1986, IAU Symp. 23) have proposed another possibility of young stellar model.

The quantity of spacing between eigenfrequencies of p-modes with low, even and odd degrees l is, roughly speaking, proportional to the mean density of the star. On the other hand, the small departure from the true equi-distance of the power spectrum is significantly sensitive to physical conditions near the center of the star and then it depends on the evolutionary stage of the star. Christensen-Dalsgaard (38.065.129; 41.080.051; 1986, IAU Symp.123) argues, based on this consideration, that we can distinguish various models differing in masses and ages on a two-dimensional diagram, on which the quantities of the spacing and the departure from the real equal spacing is plotted. Ulrich (42.065.004) argues we can determine the radius and age of isolated stars by means of frequencies of pairs of modes differing by two in the degree l and by one in the radial order n. Precise measurements of eigenfrequencies of p-modes will become a powerful tool to determine these fundamental quantities of stars.

2. Rapidly Oscillating Ap Stars

The rapidly oscillating Ap stars are another group of stars which reveal high order p-mode oscillations with low degrees l. The detailed power spectrum analysis (e.g., Kurtz and Seeman 34.122.052; Matthews et al. 41.122.001) has revealed that some of these stars are pulsating in several modes with uniformly spaced frequencies as theoretically expected for low l high order p-modes (Shibahashi and Saio 40.065.047; Gabriel et al. 39.065.018). The amplitudes of light variation are modulated with the same period and phase as the magnetic strength variation. In order to explain this character, Kurtz (32.122.022) has proposed a model called the oblique pulsator model, in which the observed oscillations are interpreted as very high order p-modes of zonal (m=0) nonradial oscillations of low degree whose symmetry axis is aligned to the magnetic axis but oblique to the rotation axis of the star. This model was generalized by Dziembowski and Goode (40.065.044; 41.065.069), who took account of both the oblique magnetic field and advection to formulate the pulsation as an eigenvalue problem. According to their formula and that of Kurtz and Shibahashi (42.116.081), ($2l$+1)-frequency components are to be observed as a fine structure in the power spectrum even if only a single eigenmode is excited, and their relative amplitudes are not equal each other but dependent on the rotation and the magnetic field of the star. This leads to a possibility of using the fine structure of oscillation frequencies as diagnosis of rotation and the internal magnetic field of Ap stars. In this sense, the observation of the rapidly oscillating Ap stars will open a new aspect of asteroseismology.

A nice review on the observational aspect of these stars was given by Kurtz (41.122.096) in Cambridge, and the theoretical aspect was reviewed by Shibahashi (1987, Stellar Pulsation, p.112).

3. Pulsating White Dwarfs

So far eighteen DA white dwarfs have been found to be pulsating variables, and several pulsating DB white dwarfs and pre-white dwarfs have been discovered. Since the number of modes of an individual pulsating white dwarf is larger than those of other-type pulsating stars but for the Sun, asteroseismology of white dwarf may be the most promising. The oscillations in white dwarfs are regarded as nonradial g-modes. According to the asymptotic theory for high order g-modes with low degrees l, there is a simple relation among the periods, the degree l, and the radial order n of the g-modes (e.g. Tassoul 28.065.044) as in the case of p-modes. Kawaler (1987, Stellar Pulsation, p.367; 1986, IAU Symp.123; 1987, IAU Colloq. 95) applied this relation to get some constraints on individual pulsating white dwarfs.

Cooling rates of white dwarfs are thought to be rapid enough to enable us to detect the resultant period change of pulsations (McGraw et al. 27.126.070; Winget et al. 33.065.063). In fact, such a measurement of period changes has been realized by Winget et al. (39.126.069). Kawaler et al. (40.065.031) showed that the transition from negative to positive dP/dt occurs at nealy 1000 solar luminosity for a wide variety of the planetary nebula nuclei and pre-white dwarf models and that dP/dt is near zero only for a very short time. Measurement of period change will give us some clues to understand the evolutionary stage of pulsating hot pre-white dwarfs.

The eigenfrequencies of g-modes are mainly governed by the Brunt-Väisälä frequency distribution in the star. Therefore, we can, in principle, obtain some information about the Brunt-Väisälä frequency by means of a seismological approach. The mathematical procedure for the inversion to get the Brunt-Väisälä frequency distribution in a white dwraf is outlined by Shibahashi(1986). A comprehensive review on the seismological investigations of compact stars was given by Winget (1986, IAU Symp.123) in Aarhus.