35. STELLAR CONSTITUTION (CONSTITUTION DES ÉTOILES)

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1. INTRODUCTION

Following the example set by the previous President of the Commission (L. Mestel), we have arranged for this report to consist of detailed reports on a limited number of topics of current interest. The subjects discussed are: (1) Developments in the Theory of Evolution of Single Stars (Dr. Ergma); (2) Close Binary Stars (Drs. Bath and Pringle); (3) Effects of Opacity and Composition on Stellar Evolution (Dr. Cox); (4) Effects of Mass Loss on Stellar Evolution (Drs. Dearborn and Schramm). Because these reports have been produced on a tight schedule by authors from different countries, there is some unavoidable overlap in their contents. We are grateful to the authors for providing the reports.

Study of the evolution of stars continues to be central to astrophysics although research in galaxies and cosmology may have appeared a more glamorous subject in the recent past. To some extent this is because the subject of stellar evolution has come of age and most of the easy and straightforward problems have been solved. There is now reduced emphasis on the study of single spherical stars in quasi-static stages of evolution. Instead there is much work on the more difficult problems of non-spherical stars, either single or interacting, and of mass loss from stars, either steady or explosive. Many of these problems are too complicated to be solved exactly with the present generation of computers even if the physical processes involved are fully understood. One particular problem in which uncertainties in the laws of physics, departures from spherical symmetry and extremely short timescales are probably all involved is the explosion of a supernova and it is perhaps not surprising there is not agreement on what causes a supernova explosion. In saying this it must not be forgotten that there are still uncertainties in the structure of single spherical stars. The solar neutrino discrepancy is still not resolved, there are disagreements about the form of stellar opacity, the maximum mass of a neutron star is not settled and further resonances may yet be found in nuclear reactions which are important in nucleosynthesis.

Since the 1978 Grenoble General Assembly and the symposia and colloquia associated with that General Assembly, meetings of interest to members of Commission No. 35 have included IAU Symposium 76 "Planetary Nebulae", Ithaca, U.S.A.,June 1977, IAU Symposium 80 "The HR Diagram. The 100th Anniversary of Henry Norris Russell", Washington, D.C.,U.S.A., November 1977, IAU Symposium 83 "Mass Loss and Evolution of O-type Stars", Vancouver Island, Canada, June 1978, IAU Colloquium 42 "The Interaction of Variable Stars with Their Environment", Bamberg, G.F.R., September 1977 and IAU Colloquium 52 "Protostars and Planets", Tucson, U.S.A., January 1978. Meetings planned in conjunction withthe General Assembly are IAU Symposium 85, "Star Clusters", Victoria, B.C.,Canada, August 1979, IAU Symposium 88, "Close Binary Stars", Toronto, Canada, August 1979 and IAU Colloquium 51 "Convection and Turbulence in Stellar Atmospheres", London, Ontario, Canada, August 1979.

2. DEVELOPMENTS IN THE THEORY OF EVOLUTION OF SINGLE STARS (E. V. Ergma)

1. General Problems

Evolution of massive stars with mass loss have recently been considered in

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several countries. [C de Loore et al. (17), Chiosi et al. (2), Massevitch et al. (3), Sreenivasan and Wilson (4)]. It was shown that the effect of mass loss causes a broadening of the hydrogen core burning phase in the H-R diagram. It was pointed out by Chiosi et al. (2) that the core He burning phase is rather sensitive not only to mass loss in the acoustic-flux regime (in the red giant stage) but also to mass loss occurring in the core H-burning phase. To explain an evolutionary scenario from O-B stars to W-R stars a very large mass loss is required $\dot{M}>10^{-4}M_\odot\ yr^{-1}$). A mass loss rate $\dot{M}\geqslant 4x10^{-6}M_\odot\ yr^{-1}$ may lead to a decrease of the luminosity and to the production of an OBN star near the main sequence (5).

Besides the mass loss mechanism the observed widening of the upper part of the M-S may be explained by two other mechanisms: Firstly there can be an increase of the convective core by convective overshooting. Such an increase may lead to a widening of the M-S band so that not only blue and yellow giants but also more massive red giants remain in the phase of hydrogen core burning. The time of H-burning in the core also increases (3). The second mechanism of the widening of the upper M-S band is connected with the new Carson opacities. Stothers and Chin (6) have found that a pronounced difference exists between evolutionary tracks calculated with Cox-Stewart's and with Carson's opacities. It is to be regretted that Carson's opacity tables are still not available to the astronomical community.

The physical picture in Cas A has been analyzed by S. Lamb (7) with the result that the progenitor of Cas A could be a massive star that has lost considerable part of its envelope during the early supergiant phase.

The special evolutionary code proposed by B. Paczyński has been developed by Rozyczka (8,9) by a replacement of the Lagrangian coordinates by Eulerian coordinates which significantly reduces the computing time when investigating the helium and carbon flashes or accretion processes on to white dwarfs. With the help of this program the position of the helium flash as a function of rotation,chemical composition and screening factor has been investigated.

Calculations for 46 stars have been performed from the subgiant branch to the onset of helium burning ($0.10\leqslant Y\leqslant 0.4$, $0.7\leqslant M/M_\odot\leqslant 2.20$, $10^{-5}\leqslant Z\leqslant 0.04$). The tracks are particularly sensitive to changes in the heavy-element abundances (10).

The effect of heavy-element abundance on stellar evolution has been investigated by Alcock and Paczyński (11) with the result that in a 7 $M_\odot$ star carbon is consumed non-violently if $Z = 4.10^{-4}$ but is ignited in a highly degenerate core for $Z = 0.03$. This indicates a possible different behaviour for massive Population 2 and Population 1 Stars.

Evolutionary calculations for small super-metal-rich stellar masses ($0.6\leqslant M/M_\odot\leqslant 1.5$, $Z = 0.10$) have shown that Z values as large as 0.10 could account for gaps in evolutionary tracks near the main sequence as large as $\Delta M_b \sim 0^m5$ independent of the He content (12). Evolution of extremely metal-poor stars remains sensitive to initial heavy element abundance and evolution is significantly faster than that of pop I stars. Core helium ignition takes place prior to reaching the red giant branch (13). Evolution of massive helium stars with the new opacities given by Carson has been followed by Stothers and Chin (14). If neutrino losses are neglected, the phase of carbon burning in the core occurs in the red-supergiant region but with neutrino losses carbon burns near to the He M-S.

Several authors (15, 16) have studied advanced evolution of massive stars. According to Arnett (15), helium stars more massive than 12 $M_\odot$ avoid the silicon flash. For M_α about 6-8 $M_\odot$ there is a mild silicon flash. For less massive helium stars silicon starts burning in highly degenerate conditions.

Ergma and Vilhu (16) have found that for $9M_\odot$ stars carbon starts burning at some distance from the centre, so that the flash moves inwards removing finally the degeneracy. No mixing has been found.

The problem of occurrence of loops (one or two) in the H-R diagram is still being discussed by several authors. The factors that affect the length of the first loop are as follows: the mass fraction in the helium core, the opacity in the radiative envelope, the location of the hydrogen-burning shell at core helium ignition, the location of the outer boundary of the zero-age M-S convective core, the depth of convective mixing at the peak of the giant branch (if deep mixing occurs), the duration of core helium burning, the fraction of the energy produced by the hydrogen burning shell and the extent of intermediate convective mixing (17). The behavior of the second loop in the H-R diagram has been studied by Höppner et al. (18).

Evolution of rotating stars with $7M_\odot$ and $10M_\odot$ has been followed by Endal and Sofia (19). They found that evolved stellar cores develop nonaxysymmetric instabilities corresponding to the bifurcation of the Maclaurin sequence before they reach critical (Keplerian) rotational velocities. For $7M_\odot$ the instability point is reached prior to carbon ignition, indicating that catastrophic carbon detonation may be avoided by rotating stars.

2. Chemical evolution

A most interesting problem is the variation of surface chemical abundances caused by the evolution of stars. In this field most promising investigations are connected with s-process elements in the helium burning shells and consequent mixing.

Paczyński (20) has studied helium shell flashes in models of Pop I stars with $M_{co}=0.8\ M_\odot$ for $M_{tot} = 8\ M_\odot$ and $3M_\odot$. If no over-shooting occurs at the base of the convective envelope, the features of the helium shell flashes do not depend on the mass of the envelope. If convective overshooting is taken into account, then following the peak of the helium flash the massive envelope penetrates the core and mixing occurs. Several papers by Iben and Truran (21, 22) and Iben (23) are devoted to the s-process nucleo-synthesis in thermally pulsating stars, based on Iben's mechanism for the production of neutrons $^{14}N(\alpha,\gamma)^{18}F(,\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$. The main results of these studies are: 1) significant enhancement of s-process elements does not occur for luminosities less than $M_B \sim -6$. 2). For stars of a given initial composition the surface abundance of ^{12}C exceeds that of ^{16}O at roughly the same surface temperature independent of mass. 3) $M<1.5M_\odot$ stars do not as a consequence of thermal pulses produce $^{12}C/^{16}O>1$. 4) $M<2.5\ M_\odot$ stars do not achieve convective shell temperatures sufficiently high for the production of s-process elements. 5) For $M>3M_\odot$ the surface enhancement of s-process elements ~2-20, maximum $M \sim 5M_\odot$. 6) stars with $3 \lesssim M/M_\odot \lesssim 8$ are the major sources of s-process elements in the galaxy.

The distinguishing feature of the ^{22}Ne neutron source studied in (21) is that, under a wide variety of conditions in the convective helium shells, s-process elements ($70 \leqslant A \leqslant 204$) are invariably produced in solar system proportions. This neutron source fails to produce in solar proportions elements in the range $60 \leqslant A \leqslant 70$ and the heavy lead isotopes.

Neutron capture nucleosynthesis in the helium-burning cores of massive stars studied by Lamb et al. (24) showed that: 1) a significant amount of elements ^{25}Mg, ^{26}Mg, ^{36}S, ^{37}Cl, ^{40}Ar, ^{40}K, ^{58}Fe are produced in stars with $M \geqslant 15M_\odot$. 2) Nuclei in the mass range $60 \leqslant A \leqslant 70$ are built in stars more massive than $15M_\odot$. 3) The helium cores of massive stars cannot be the major source for formation of the heavier ($A>90$) s-process nuclei. For the explanation of the origin of CH and carbon stars, the core helium flash (off-center) has been proposed (25). It was shown that the amount of carbon produced during the flash increases with the mass fraction of the off-center core helium flash and at least some R-type carbon stars may be explained by this effect.

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Fujimoto (26, 27) studied the possibility of hydrogen mixing during helium flicker and concluded that the helium convective zone grows extensive enough to trigger the Schwarzschild mechanism $^{12}C(p,\gamma)^{13}N(,\beta^{+}+\nu)^{13}C(\alpha,n)^{16}O$ for two cases: 1) when the mass fraction of the hydrogen-rich envelope is very small; 2) when the helium burning luminosity L_{He} grows larger than $10^8 L_{\odot}$.

Hot-bottom convective neutron and s-process element production has been studied by Despain (28).

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3. THEORETICAL PROBLEMS IN CATACLYSMIC BINARIES AND RELATED OBJECTS (G. T. Bath and J. E. Pringle)

The cataclysmic variables (dwarf novae, nova-like variables, and AM Her-type objects) provide a testing ground for theoretical studies of mass transfer and accretion processes in close binaries. Recognition of this in the period prior to this report (IAU Symposium 73, Eggleton et al. 1976) has led to many theoretical developments in the subject.

The presence of a disc around the white dwarf component is well established. The optical luminosity of a steady-state accretion disc depends primarily on the mass transfer rate through it, and the temperature distribution over the surface. The temperature distribution may be estimated assuming black body emission, since

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for any viscosity likely to be generated by subsonic turbulence the disc is optically thick, at least in the brightest inner region. Tylenda (1977, Acta Astron. 27, p.235) compares the theoretical spectrum of a steady state disc from the soft x-ray to the infra-red region with the observed spectrum of SS Cygni at outburst. The fit is good for an accretion rate 6 x 10^{17} g s^{-1}. Agreement with the UV spectral distribution of two old novae, V603 Aql and RR Pic, is satisfactory for accretion rates 8 x 10^{17} g s^{-1} and 4 x 10^{18} g s^{-1} respectively, confirming the widespread suspicion that old novae are similar to the outburst state of dwarf novae, but 'stuck' permanently at a higher accretion rate.

A more accurate flux distribution is needed to calculate colours. Schwarzenberg-Czerny and Rozyczka (1977, Acta Astron. 27, p.429) fit steady-state discs with a grid of normal stellar atmospheres but ignore the important contributions of the 'hot- spot' and emission lines from optically thin regions. They find the observational agreement in the two colour diagram is poor. Not surprisingly, only the brightest systems with highest accretion rates and disc temperatures show reasonable agreement. Rather than interpolating over a grid of published stellar atmospheres, as in the previous study, Mayo (Ph.D. Thesis, Cambridge, 1978) has constructed models covering the correct range of g and T_e, including absorption line formation, and finds good agreement with the outburst spectrum of SS Cygni, but the quiescent state is less well fitted.

Two sources of soft x-ray emission in dwarf novae have been proposed - non-thermal radiation from the shocked 'hot-spot' region and thermal radiation from the boundary layer region of the disc/white dwarf interface, where about half the accretion energy is liberated where the disc grazes the stellar surface. Pringle (1976, Monthly Notices Roy. Astron. Soc. 178, p.195) concludes that the thickness of the shocked region in the 'hot-spot' is very much less than the radius of the incoming stream, and the spot cannot be optically thin to soft x-ray photons; whereas much of the boundary layer energy can be emitted as soft x-rays (0.15>KeV) if the boundary layer is optically thick. These conclusions receive support from the recent observation of a 9 sec periodicity at outburst in SS Cyg at both soft x-ray (Cordova et al., 1978, IAU Circ. 3235) and optical wavelengths (Patterson et al.Astrophys.J. Letters in press) clearly produced close to the boundary layer region. A further, and more detailed, study by Pringle and Savonije (Monthly Notices Roy. Astron. Soc., in press) has shown that for low accretion rates ($\lesssim 10^{16}$ g s^{-1}) the boundary layer can be optically thin and emit x-rays with energies up to about 20 KeV. The recent discovery of hard x-ray emission in SS Cyg in the inter-outburst state (Ricketts, King and Raine, Monthly Notices Roy. Astron. Soc., in press) indicates strong non-thermal radiation can be important in the quiescent state.

Of direct relevance to the discovery of x-ray emission from cataclysmic variables have been a number of studies of the x-ray emission processes associated with accreting white dwarfs. Katz (1977, Astrophys. J. 215, p.265) has calculated the emitted spectrum of radially infalling material under the assumption that the outward flux does not interact with the accreting gas. Fabian, Pringle and Rees (1976, Monthly Notices Roy. Astron. Soc. 175, p.43) estimated the importance of absorption in the accreting gas and argued that this leads to an upper limit to the luminosity of about 10^{36}erg s^{-1}. This is confirmed by Kylafis (Ph.D. thesis, Illinois, 1978). When radial infall takes place along magnetic field lines, cyclotron cooling can be important. The effects of this have been estimated by Masters et al. (1977, Monthly Notices Roy. Astron. Soc. 178, p.501). Because of the importance of this process in AM Her variables more detailed calculations of this process have been undertaken (see Tuohy et al.:1978, Astrophys. J. Lett. 226, p.L17 and references therein).

The cause of bursting flows through the disc in dwarf novae during eruptions remains the most speculative and uncertain area in the subject. Madej and Paczyński (IAU Colloquium 42, p.313, Kippenhahn et al.) following the suggestion of Osaki, argue that the optical brightness of the 'hot-spot' in U Gem favours a disc storage mechanism, and construct a model with the incoming stream forming a torus with constant angular momentum per unit mass and vanishingly small viscosity. They suggest eruptions are due to an ad hoc increase in viscosity leading to sudden accretion. The cause of the sudden viscosity increase and the factors which determine a repetition timescale of ~30 days remain unknown. Sunyaev and Shakura (1977, Soviet Astron. Letters 3, p.138) discuss the formation of disc reservoirs around a magnetised central star. If the magnetosphere exceeds the corotation radius, matter storage may occur in circumstances which would otherwise lead to steady accretion.

The alternative outburst scheme for dwarf novae associates enhanced accretion with bursting mass transfer by the companion. Webbink (1977, Astrophys. J. 211, p.486; 1977, Astrophys. J. 211, p.881) finds that main sequence stars going through case A evolution can experience 'dynamical' phases of transfer, a result confirmed by other workers. Dynamical instabilities can only be properly studied with a full hydrodynamic code. A non-linear hydrodynamic code, which includes time-dependent convection using a mixing length formulation, has been developed by Wood (1977, Astrophys. J. 217, p.530). He confirms the existence of dynamical instability in some models, and shows, as in earlier work, that this can produce bursting mass transfer. Mass transfer rates and repetition times fit those required in dwarf novae, but Wood confirms earlier results that the existence of the instability is sensitive to the treatment of convection. Given the complexity of the geometry near the Lagrangian point, the lack of a realistic theory of convection, and uncertainties about the correct value of the mixing length to scale height ratio in the theory which is available, the existence of instabilities remains unclear. Detection of hard (>2 KeV) x-ray emission from SS Cyg throughout the quiescent phase (Ricketts, King and Raine, Monthly Notices Roy. Astron. Soc., in press) argues in favour of continuing accretion and against a simple disc storage mechanism.

Further work has been done on investigating the conditions needed for an equilibrium (time-independent) accretion disc to be stable. Shakura and Sunyaev (1976, Monthly Notices Roy. Astron. Soc., 175, p.613) have made a detailed study of the inter-relationship of secular and thermal instabilities, showing that in general both are present (if not all) and that the fastest growing mode is the thermal one. Pringle (1976, Monthly Notices Roy. Astron. Soc. 177, p.65) demonstrated how a simplified instability criterion could be obtained by considering just the thermal mode. Piran (1978, Astrophys. J. 221, p.652) has generalized previous work to consider arbitrary viscosity laws and cooling mechanisms.

An understanding has been reached of what happens to the angular momentum of matter that is transferred in a binary system in which an accretion disc is formed. Numerical experiments had earlier showed that almost all the transferred material is accreted and the disc more or less extends out to fill the Roche lobe of the accreting star in an equilibrium situation. Investigations by Paczyński (1977, Astrophys. J. 216, p.822), Papaloizou and Pringle (1977, Monthly Notices Roy.Astron. Soc. 181, p441) and Weber (Ph. D. Thesis, Berkeley, 1978) have shown that the outer edge of the disc is curtailed by tidal processes which remove angular momentum from the transferred material and return it directly to orbital angular momentum. In this way the excess angular momentum of the transferred material is removed, allowing essentially all the transferred matter to be accreted.

Both Ritter (1976, Monthly Notices Roy. Astron. Soc. 175, p.278) and Robinson (1976, Astrophys. J. 203, p.485) have determined component masses for cataclysmic binaries assuming the secondary obeys a main-sequence mass-radius relation and fills its Roche lobe. A method based on particle trajectories and the position of the 'hot-spot' has been used by Smak (1977, Acta Astron. 26, p.271). The difficulty with the last method lies in determining the size of the disc, whilst the first method relies on the assumption of a normal main-sequence structure for the companion.Despite these difficulties, the methods are sufficiently accurate to show that early suggestions that the white dwarf mass is close to 1.2 $M_\odot$ in almost all systems are incorrect.

Further observations have been made of coherent short period oscillations seen in cataclysmic variables during outburst. These oscillations are highly variable and lie in the range of 8-50 seconds. The more recent observationsl results can be found in papers by Patterson, Robinson, and Nather (1977, Astrophys. J. 214, p.144) Warner and Brickhill (1978, Monthly Notices Roy. Astron. Soc. 182, p.777) and Nevo and Sadeh (1978, Monthly Notices Roy. Astron. Soc. 182, p.595) and references therein. Robinson and Nather (Astrophys. J., in press) have recognised a new phenomenon of quasi-periodic oscillations which can be seen in the light curve but which have sufficient phase-jitter that they do not show up well in power spectrum analyses.

Theoretical work by Papaloizou and Pringle (1978, Monthly Notices Roy. Astron. Soc. 182, p.423) suggests that much of what is observed can be interpreted as non-radial oscillations of a rapidly rotating white dwarf, whose rotation period is comparable to the period of the observed oscillations. They argue that the amount of mass involved in the oscillation is exceedingly small (around 10^{-8} to $10^{-10}M_{\odot}$).

One of the most startling recent discoveries has been the AM Her-variables (at present AM Her, AN UMa, and VV Pup). These stars are characterized by displaying strong circular and linear polarization which varies in a regular manner with periods of 2-3 hours. The best studied of these, AM Her itself, has been known for decades as a semi-regular variable. It is now known to vary with a 3.09 hr period, both photometrically, in all regions of the spectrum up to 60 KeV, and spectroscopically. The nature and relative phasing of these variations are highly unusual. A large body of observational data has now been published, most of which can be traced through papers by Priedhorsky and Krzeminski (1978, Astrophys. J. 219, p.597), Chanmugam and Wagner (1978, Astrophys. J. 222, p.641) and Liebert et al.(1978, Astrophys. J. 225, p.201). From these papers emerges a plausible theoretical model in terms of a close binary system consisting of a lobe-filling red dwarf and a strongly magnetic (10^8 gauss), accreting white dwarf. The strong field ensures that the white dwarf is phase locked to the red companion, and so rotates with the binary period. It also ensures that accretion takes place only on to the magnetic pole(s) of the white dwarf, giving rise to the x-ray emission as well as the strong optical polarization. The relative positions of the polar axis and of the gas stream of the accreting matter can be adjusted to obtain reasonable agreement with observations.

The origin of cataclysmic variables remains problematic. The presence of a white dwarf in a system with an unevolved companion and a separation of a few solar radii indicates extensive angular momentum loss. In particular the specific angular momentum of cataclysmic binaries is so low that, during an earlier, more widely separated phase, an efficient mechanism must have existed for transferring angular momentum from the stellar core(s) of the stars to outer envelope material which is finally lost. Ritter (1976, Monthly Notices Roy. Astron. Soc. 175, p.278) discusses anevolutionary scheme involving case B or C mass transfer combined with extensive mass and angular momentum loss, but does not consider the problem of angular momentum exchange between the stellar core and the envelope. Lin (1977, Monthly Notices Roy. Astron. Soc. 179, p.265), Flannery and Ulrich (1977, Astrophys. J. 212, p.533) and Nariai and Sugimoto (1976, Publ. Astron. Soc. Japan 28, p.593) have studied various aspects of binary stability and evolution with mass and angular momentum loss, but the use of the outer, L_2, Lagrangian point to define a critical surface, analogous to the inner critical surface, is open to criticism since corotation is unlikely to be maintained.

The evolution of close binaries with a common envelope, in which a compact component is embedded in the extended envelope of the companion, have been examined with a variety of assumptions about dissipation and angular momentum transfer between the components. Alexander et al. (1976, Astrophys. J. 204, p.879) discuss the evolution of the orbital elements including gravitational drag, for the case of a compact object orbiting through a constant velocity outflowing wind, and suggest that symbiotic stars may be experiencing orbital decay as a result of accretion by the compact component. Taam et al. (1978, Astrophys. J. 222, p.269) follow the evolution of a 16 $M_\odot$ supergiant as a 1 $M_\odot$ neutron star spirals in, through turbulent dissipation and frictional drag. Either of two outcomes results: hydrodynamic expulsion of the envelope, or coalescence of the two cores with no ejection. Mass ejection requires a more extended envelope in which the lower binding energy, and inefficient convective energy transport, both aid expulsion. Tutukov and Yungelson (IAU Symp. 83, "Mass Loss and Evolution of O-type stars") have also examined the conditions required for expulsion of the envelope. Meyer and Meyer-Hofmeister (Astron. Astrophys. in press) have studied the evolution of a 5 $M_\odot$ red giant and a 1 $M_\odot$ main sequence star through a common envelope phase, aimed particularly at accounting for the existence of cataclysmic binaries. Transfer of angular momentum between the inner, tidally dominated region of the common envelope, and the outer region, due to a form of turbulent velocity, is the crucial feature of their model.

Symbiotic stars may be related to earlier stages in the formation of cataclysmic binaries. Bath (1977, Monthly Notices Roy Astron. Soc. 178, p.203) emphasises the role of accretion in symbiotic binaries. He developes a model based on super critical accretion by either a white dwarf or a main-sequence star, with nuclear burning only able to contribute in the former case. Variability, observed in systems like Z And, is due to variable mass loss by the giant companion. Yungelson and Tutukov (Astrofizika, 1976, 12, 521) discuss the structure and evolution of symbiotic stars assuming that the hot components are generating energy primarily by nuclear burning rather than accretion. Paczyński and Rudak (Astron. Astrophys., in press) suggest a model for two classes of symbiotic star. With the accretion rate between two critical values a stably-burning hydrogen shell is the energy source, with variability produced by variable accretion. In the second class the accretion rate is below a lower critical value and hydrogen burning proceeds through a series of shell flashes.

The relative importance of nuclear burning and accretion energy in symbiotic stars has yet to be established. Many of the arguments put forward in discussion of dwarf novae and classical novae are likely to raise their hoary heads again here. If accretion is dominant then some systems should be found in which the accreting star is too massive to be a white dwarf, and is a main sequence star in which surface nuclear burning is impossible. If these systems exist, then they would be the most likely progenitors for cataclysmic binaries.

4. EFFECTS OF OPACITY AND COMPOSITION ON STELLAR EVOLUTION TRACKS IN THE H-R DIAGRAM (Arthur N. Cox)

1. Introduction

A review such as this which attempts to discuss the accuracy of stellar evolution tracks in the H-R diagram, and especially the effects of opacity, is necessarily incomplete. There are some recent results where the opacity or composition has been changed systematically. These are what will be discussed in some detail. Composition changes can be interpreted in terms of opacity changes in the most simplified case, but they obviously are not interchangable because each element has its unique pattern of absorption while opacity errors can be of any size and at any temperature and density. This review will discuss results published mostly after 1975 and before 1979.

There are many other uncertainties in the calculation of stellar evolution tracks besides opacities and compositions. Thermonuclear energy sources, especially those at high temperatures, but even the basic pp reactions, may not be known accurately and energy source representations may differ from one set of calculations to another. One example of this difficulty can be found in studies with and without the reaction $N^{14}(\alpha,\gamma)F^{18}$ by Durand, Eoll, and Schlesinger (1976, Monthly Notices Roy.

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Astron. Soc. 174, p.671). Neglect of this reaction supresses the Cepheid blue loops in evolution tracks for 8 and 10 $M_\odot$ stars.

The changing composition due to nuclear burning (nucleosynthesis) is always considered in stellar evolution calculations, but just how these changes are considered in calculating the equation of state, opacity and energy generation is usually obscure. Lamb, Iben, and Howard (1976, Astrophys. J. 207, p.209) and Weaver, Zimmerman, and Woosley (1978, Astrophys. J. 225, p.1021) have shown how these composition changes develop and have followed the changes in material properties correctly by using formulas for them.

The loss of mass during evolution of stars of mass greater than 10 $M_\odot$, a new research area, produces tremendous changes in evolution tracks. The small effects of all other uncertainties are overwhelmed. Examples of this research for massive stars are Dearborn, Blake, Hainbach, and Schramm (1978, Astrophys. J. 223, p.552), Sreenivasan and Wilson (1978, Astrophys. Space Sci. 53, p.193), de Loore, de Greve, and Lamers (1977, Astron. Astrophys. 61, p.251), Chiosi, Nasi, and Sreenivasan (1978, Astron. Astrophys. 63, p.103) and Stothers and Chin (1978, Astrophys. J. 226,p.231). This latter paper shows that the blue supergiants brighterthan 3×10^4 $L_\odot$ at a range of T_e can be explained by either mass loss or opacity effects making it important to know the opacity accurately at temperatures near 10^6 K.

Mengel (1976, Astron. Astrophys. 48, p.83) shows the effects of mass loss for population II stars as they evolve with double shell sources off the horizontal branch to carbon ignition.

Another effect on evolution tracks for stars at 10 $M_\odot$ and above is the semi-convection and convective overshooting which can mix hydrogen into the thermonuclear burning core and prolong the star's life near the main sequence. Opacity effects in the million degree range are important for determining the thickness of this marginally convective region as well as for the outer envelope structure and the surface conditions. Maeder (1976, Astron. Astrophys. 47, p.389) has artifically inserted several versions of this overshooting in his calculations to produce evolution tracks and isochrones that match the cluster color magnitude diagrams very well. However, he has not changed the opacity to see how the arguments might be affected with different opacities. Helium abundance changes at Z = 0.1 can also produce large observed gaps according to Castellani and Tornambe (1977, Astrophys. Space Sci. 46, p.195).

In the later evolution core helium burning stages there are more features that can obscure or mitigate the importance of opacities. Blue loops seem to depend on the exact profile of the hydrogen content in the outer layers down to perhaps 10^6 K. In 1972 Robertson investigated several input parameters and found that the envelope opacities were important in order to predict Cepheid blue loops. However, the existence of the blue loops seems to depend on the red giant mass loss, nuclear reactions, and even the ratio of mixing length to scale height in convection zones, preventing any opacity measurement. The second blue loop, when models of 7 - 9 $M_\odot$ have two shell sources, has been considered by Höppner, Kähler, and Weigert (1978, Astron. Astrophys. 63, p.391).

Rotation is another parameter that is usually ignored, but it can influence stellar evolution tracks as discussed by Endal and Sofia (1976, Astrophys. J. 210, p.184 and 1978, Astrophys. J. 220, p.279). At 7 $M_\odot$ the dwarf-stage seems to be slightly less luminous and the giant stage slightly more luminous when rotation is included in several possible ways. Similar effects are seen by Mengel and Gross (1976, Astrophys. Space Sci. 41, p.407) for population II 0.85 $M_\odot$ evolution.

This review does not consider the late evolution stages for population I or II stars after the blue loops, that is, for the stages of helium shell flashes (Paczyński, 1977, Astrophys. J. 214, p.812; Iben, 1977, Astrophys. J. 217, p.788) and other core thermal oscillations during carbon burning (Iben, 1978, Astrophys. J., in press). Also, evolution track calculations for mass transfer in binary systems (see Massevich, Tutukov, and Yungleson, 1977, Astrophys. Space Sci. 40, p.115), done actually for single stars in spherical geometry anyway, will also not be discussed because the opacity and composition effects can all be seen without the complicating problems of mass addition or loss.

2. Opacity Calculations

Opacity data used for all stellar evolution calculations are based on either the Los Alamos data or the new unpublished Carson results. A tabulation of opacities for 40 mixtures of interest for stellar evolution has been given by Cox and Tabor (1976, Astrophys. J. Suppl. 31, p.271). Newer tables can be obtained from the Astrophysical Opacity Library of Huebner, Merts, Magee, and Argo (1977, LA-6760-M Los Alamos) which became available in December 1977. The library consisting of magnetic tapes for each of 20 elements has been sent out to about 10 institutions in the United States and Europe. Updates of the library will be available periodically. These Los Alamos tables, or quite frequently fits to them, in evolution programs by Demarque, Iben, Paczynski, Eggleton, Stothers, etc. or, for pulsation calculations, fits by Stellingwerf (1975, Astrophys. J. 195, p.441 and 1975, Astrophys. J. 199, p.705) are used in all calculations except a few by Carson and Stothers (1976, Astrophys. J. 204, p.472; 1977, Astrophys. J. 211, p.189; 1977, Astrophys. J. 216, p.61; 1978, Astrophys. J. 226, p.231) and by Stothers (1976, Astrophys. J. 210, p.484).

Additional mixtures have been calculated at Los Alamos. Huebner in the Proceedings of an informal conference on the status of solar neutrino research (1978, BNL 50879 1, 107. Brookhaven) discussed several mixtures. He has considered a total of 20 with compositions of C, N, O, Ne, Mg, Fe varying by 25% to see what effects there could be on the solar structure and predicted solar neutrinos. Seven more mixtures are given by Cox, King, and Hodson (1979, Astrophys. J., in press) in dwarf Cepheid studies. Finally, opacities using the same program used for the 1969 publications in the Astrophysical Journal Supplement for 16 mixtures have been used by Demarque for studies of evolution tracks with enhanced carbon and nitrogen abundances.

Detailed tables since the 1976 publication (same mentioned above) are

Older Version of Computer Program

Demarque Mix	X	Y	Z
20	0.800	0.194336	.005664
21	.500	.494336	.005664
22	.200	.794336	.005664
23	.000	.994336	.005664
24	.800	.196	.004
25	.500	.496	.004
26	.200	.796	.004
27	.000	.996	.004
28	.800	.190934	.009066
29	.500	.490934	.009066
30	.200	.790934	.009066
31	.000	.990934	.009066
32	.800	.196	.004
33	.500	.496	.004
34	.200	.796	.004
35	0.000	0.996	0.004
		New Opacities	
Cox-Davis II	.602	.354	.044
Cox-Davis III	.700	.299	.001

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Cox-Davis VI	.70	.28	.02
Cox-Hodson II	.00	.98	.02
Cox-Hodson III	.10	.88	.02
Cox-Hodson·IV	.20	.78	.02
Cox-Hodson V	.30	.68	.02
Cox-Hodson VI	.40	.58	.02
Cox-Hodson VII	.50	.48	.02
Cox-Hodson VIII	.90	.08	.02
Cox-Hodson IX	.98	.00	.02
Deupree III	.65	.34	.01
Deupree IV	.70	.29	.01
Deupree V	.75	.24	.01
Cogan II	.800	.195	.005
Cogan VI	.700	.295	.005
HE9C1	0	.900	.100 (C)
HE5C5	0	.500	.500 (C)
C505	0	0	.500 (C) . 500 (0)
C109	0	0	.100 (C) . 900 (0)

3. Intermediate Mass Population I Composition Tracks

For masses between one and ten solar masses there are several tabulations. This is the region where there is no radiation pressure induced mass loss. Also,there are no problems of semiconvection in the core.

Near the main sequence, composition (or opacity) effects have been discussed by Flannery and Ayres (1978, Astrophys. J. 221, p.175) for the α Cen binary system which consists of two equal age equal composition but non interacting systems. At 0.92 and 1.11 $M_\odot$ tracks were computed. For Y = 0.26 it appears that Z = 0.004 for these two stars if Z = 0.02 is used for the sun which serves as a calibration star. This work does not consider opacity variations separately preferring to put all the relative errors from the sun to the α Cen binary into a Z value.The evolution tracks over the first 0.8 magnitude of brightening seem satisfactory since both stars are predicted to be at their observed H-R diagram position.

Another study at constant X = 0.7 which discusses the effects of various Z values on evolution tracks is by Alcock and Paczyński (1978, Astrophys. J. 223, p.244). In addition to getting the main sequence effect of lower Z hotter T_e, these authors look at the red giant regions and the Cepheid blue loops. Lower Z gives hotter red giants, hotter blue loop tips, and higher luminosity in most cases. At 7 and 10 $M_\odot$ at Z = 0.001 and at 5, 7 and 10 $M_\odot$ at Z = 0.0004 the loops start blueward even before the evolution reaches the red giant region. Fortunately, the morphology change in the tracks needs large changes in Z, and, therefore, the opacity errors that might be present and equivalent to a Z change are not highly important in establishing the overall H-R diagram evolution picture.

A similar study by Becker, Iben, and Tuggle (1977, Astrophys. J. 218, p.633) has found the same effects plus those which occur when Y is changed. Convenient mass-luminosity relations which depend on X, Y, and Z are given for the Cepheid loops.

Harris and Deupree (1976, Astrophys. J. 209, p.402) have given tracks for 3.5, 4.5, 6.0 and 9.0 $M_\odot$ with two compositions (Z = 0.01 and 0.04) for use in isochrone construction for cluster color magnitude comparison.

Unusual opacity effect has been discussed by Lauterborn and Siquig (1976, Astron. Astrophys. 49, p.285). Earlier studies were done by Lauterborn (1976, Astron. Astrophys. 53, p.419). Evolution tracks across the Hertzsprung gap for 4, 6 and 8 $M_\odot$ have real unstable secular eigenvalues. For these stars evolving with a slight thermal imbalance, it was found that the evolution proceeded at the rate given by the

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most unstable eigenvalue, and it has a radial variation very similar to the associated eigenfunction. The opacity connection is that the extent of the evolution time where there are these unstable eigenvalues depends on the opacity law. At high luminosity where the opacity throughout the star is not so temperature dependent, the instability occurs over as much as half the Herzsprung gap and even includes part of the evolution along the Hayashi line.

Further studies of these instabilities using strictly static models have been made by Lauterborn and Zeuge (1978, Astron. Astrophys. 66, p.367).

Additional tracks for both population I and II compositions have been computed by Saio, Shibata, and Simoda (1977, Astrophys. Space Sci. 47, p.151) in order to determine the ages of the oldest population I cluster (NGC 188) and the oldest population II cluster (M 92). The tracks are given for 3 different masses for each population and for Z = 0.02 and 0.0002. No opacity variations were made, but the authors note that their ages are slightly longer than those obtained before by others, even though Los Alamos opacities were used by all studies.

The causes of the blue loops and whether they really are suppressed by red giant stage mass loss have been studied by Schlesinger (1977, Astrophys. J. 212, p.507) and Siquig and Sonneborn (1976, Bull. Am. Astron. Soc. 8, p.230). In the former case at 5 $M_\odot$ no tracks were calculated but only static models with various structures in an intermediate zone between the hydrogen burning shell and the homogeneous envelope made so by the outer convection. The intermediate zone structures and helium context give either red or blue giants. In the second work, which has appeared so far only in abstract form, the loss of mass for a 7 $M_\odot$ star is calculated in detail. The result is that about 20% mass loss is enough to penetrate into the evolved structure and prevent blue loops. Thus Cepheids have masses which are only slightly less than no-mass-loss evolution tracks indicate.

Carson and Stothers (1976, Astrophys. J. 204, p.461) have done the evolution tracks both with the Los Alamos and the Carson opacities. This is the only case where the opacity effects are clearly separated from abundance (such as Z) changes. The main difference between the Los Alamos and Carson opacities is that there is an opacity increase and then a decrease at temperatures above about 3×10^5 K. This bump is clearly associated with the CNO abundance because it is larger with larger Z. Thomas-Fermi potential calculations at Los Alamos which have attempted to exactly reproduce the Carson results do not find this bump even for pure carbon. The cause of the CNO bump is unknown and no details of the calculations are yet published or even available.

It should be noted that there is one other region in the ρ, T-plane where the Carson opacities differ from those computed at Los Alamos. The Carson opacity has a bump at about 40,000 K and $\rho = 10^{-6}$ to 10^{-8} g/cm^3. This small feature is not relevant for stellar evolution tracks, but it does make the pulsation instability more strong for Cepheids and puts them at a pulsation amplitude somewhat larger than observed (Vemury and Stothers, 1978, Astrophys. J. 225, p.939). Also, in the blue edge of the region for fundamental mode pulsation is bluer than for Los Alamos opacities. Both the CNO and the He bumps are surprising because they occur where the ionization of these elements is almost complete. The one remaining, bound electron is surely a hydrogen-like system which the Los Alamos program is well suited to compute.

Evolution tracks given by Carson and Stothers are for 5 and 7 $M_\odot$ with X = 0.73 and Z = 0.02 using both sets of opacities. They cover the evolution from the main sequence to the end of core helium burning. The Carson opacity models are fainter and bluer in the main sequence region, but they are only fainter along the common Hayashi line. Robertson in 1972 using even larger earlier Carson opacities got even lower luminosities. The Cepheid mass-luminosity relation is $L \sim M^{3.3}$ instead of the $L \sim M^{3.8}$ of Becker, Iben and Tuggle for Y = 0.25 and Z = 0.02 in their fit formula.The

Carson and Stothers blue loops occur at an earlier age because the opacities at the bottom of the red giant stage convection zone near 10^6 are larger making a deeper convection zone which promotes blue loops. This difference in evolution rate has been used with counts of blue and red giants in clusters to see if the relative lifetime for these two evolution stages can indicate the proper opacities. The theoretical evolution data is not accurate enough for the test, however.

4. High Mass Population I Composition Tracks

The tracks by various authors for models with mass above 10 $M_\odot$ are even more varied than for those of the lower masses. The problems in addition to composition and opacity differences are semiconvection and mass loss. Stothers and Chin (1976, Astrophys. J. 204, p.472) discuss the evolution tracks for these higher mass stars using the Schwarzschild rather than the Ledoux criterion for semiconvection in deep inhomogeneous composition layers. This work is based on previous studies by the two authors where no mixing and the Ledoux criterion was used. The Z values are 0.021 and 0.044 and the X values are 0.739 and 0.602. As usual, the lower Z and lower X gives higher luminosity when crossing the Hertzsprung gap. No opacity variations are included in this series of papers.

Opacity effects using Carson opacities have been studied by Stothers (1977, Astrophys. J. 210, p.434) for masses 10.9 and 15 $M_\odot$ and by Stothers and Chin (1977, Astrophys. J. 211, p.189) for 7 - 60 $M_\odot$. In the first paper, tracks just through the core hydrogen burning to helium ignition were calculated to try to match the β Cepheid variables. The larger Carson opacities give redder tracks (as does the track at a higher Z of 0.044) than those with Los Alamos opacities. Thus the β Cep variables may be in the core hydrogen burning stage instead of at the later stages (where the evolution is briefly blueward at core hydrogen exhaustion, or even after helium ignition) as deduced from using the Los Alamos opacities.

More complete evolution tracks at higher masses for the Carson opacities show that these larger opacities in the envelope make the models much larger and redder than those using Los Alamos opacities. The criterion for semiconvection does not matter in these models. Core helium burning does not start until the models enter the red super-giant region. While the existence of supergiants all across the Hertzsprung gap is explained with these new opacities, there does seem to be disagreement between observation and theory on the hottest T_e values. These evolution tracks give a maximum T_e of 39,000 K whereas the Los Alamos opacities give T_e up to 50,000 K.

Stothers and Chin (1977, Astrophys. J. 216, p.61) have considered the parallel problems of the evolution using Carson opacities of pure helium stars with masses between 4 and 15 $M_\odot$. Again the main sequence band is much wider and cooler above log $L/L_\odot$ = 4 than with the smaller Los Alamos opacities. The evolution for Z = 0.02 and 0.04 has been followed to the end of core carbon burning. In these models, the highest T_e at lowest mass approaches 10^5K, but it has a slope of lower T_e at higher L, different from the 1971 Paczyński slope of higher L higher T_e using Los Alamos opacities.

Further studies by Stothers and Chin (1978, Astrophys. J. 226, p.231) using the Carson opacities have been made with extensive mass loss. The recent studies of others (Sreenivasan and Wilson, 1978, Astrophys. Space Sci. 53, p.193; and Chiosi, Nasi, and Sreenivasan, 1978, Astron. Astrophys. 63, p.103) have been able to explain the appearance of many supergiants all across the Hertzsprung gap with mass loss, but the width of the main sequence still seems to require higher envelope opacities such as those of Carson. Also, at 30 and 60 $M_\odot$ both with and without mass loss, the models are red supergiants even before the core hydrogen is exhausted. Since the mass loss rates are very uncertain; and in any event the tracks do not seem very dependent on the opacity, we will not discuss these results.

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The population I tracks of Lamb, Iben, and Howard (1976, Astrophys. J. 207, p.209) for 15 and 25 $M_\odot$ have been discussed in the light of semiconvection theory by Chiosi and Nasi (1978, Astrophys. Space Sci. 56, p.431). They find for 20 $M_\odot$ that the neglect of semiconvection makes the track everywhere bluer during the core helium burning stages because the different H profile outside of the H burning shell.

5. Population II Tracks

There is a very large number of papers on low mass population II composition evolution. In these cases the opacity and even the Z value are of importance. Demarque and McClure (1977, Astrophys. J. 213, p.716) show that color magnitude diagrams for 47 Tuc and NGC 2420 imply either helium or Z difference. Post horizontal branch evolution and the appearance of BL Her and W Vir variables with Z = 0.001 is presented by Gingold (1976, Astrophys. J. 204, p.116).

Taam, Kraft, and Suntzeff (1976, Astrophys. J. 201, p.204) have also evolved models from the zero age horizontal branch to see what happens for metal rich models (Z = 0.02). These are the metal rich RR Lyrae variables which comprise about 25% of the field stars but are rarely seen in even the metal rich globular clusters. Evolution times for these metal rich models are longer than for the Z = 0.001 models corresponding to the observed slow period changes for them. These metal rich models must have a mass within a few percent of 0.55 $M_\odot$ to enter the RR Lyrae variable instability strip at all, however. Changes of Z as well as X and Y (which were 0.7 and 0.28) to population II compositions would give evolution more like the normal horizontal branch evolution where a large range (like 0.2 $M_\odot$) can populate this H-R diagram region.

Higher Z (= 0.01)models have been studied by Gingold (1977, Monthly Notices Roy. Astron. Soc. 178, p.533) and there is a mass range of ±10% around 0.55 $M_\odot$ where RR Lyrae stars can form. The discussion centers around how much mass loss must occur if the 0.8 - 0.9 $M_\odot$ red giants which evolve to red giants in globular cluster lifetimes are the progenitors of the horizontal branch stars and RR Lyrae variables. At Z = 0.01 or 0.02 errors due to the opacities have not been considered yet.

A series of evolution tracks has been calculated for six values of Z (10^{-5}, 10^{-4}, 4×10^{-4}, 10^{-3}, 4×10^{-3}, and 10^{-2}) and four values of Y (0.1, 0.2, 0.3, 0.4) by Caloi, Castellani, and Tornambe (1978, Astron. Astrophys. Suppl. 33, p.169). Larger Y gives a larger luminosity in the horizontal branch region with masses like 0.6 $M_\odot$, and lower Z, as usual, gives bluer colors. To whatever extent one can change Z and the opacity, any errors in the opacity may be interpreted using these extensive results including core He burning semiconvection.

An even more comprehensive set of evolution tracks has been given by Sweigart and Gross (1976, Astrophys. J. Suppl. 32, p.367; 1978, Astrophys. J. Suppl. 36, p.405) for late evolution, and Mengel, Sweigart, Demarque, and Gross (1978, Astrophys. J. Suppl., in press) for early evolution.

Castellani and Tornambe (1977, Astron. Astrophys. 61, p.427) have discussed two horizontal branch problems, the relative CNO abundances and the variations in the branch location caused by opacities. They show that at Z = $10^{-4}$to 10^{-3} the opacities are affected at temperature between 10^5 and 10^7 by the CNO elements. Below 8000 K the other elements in Z give electrons to affect the H^- abundance and its absorption. Increasing the Z from 10^{-4} to 10^{-3} moves a model of 0.625 $M_\odot$with 0.5 $M_\odot$in the helium burning core along the zero age horizontal branch, the move consists of a luminosity increase and a T_e decrease due to the nuclear burning and an almost purely T_e decrease of $\Delta \log T_e$ of 0.15 due to the opacity increase. At these low Z values, the distribution of masses along the zero age horizontal branch is critically dependent on the Z and the Z_{CNO}. Errors in the hydrogen shell burning which depend on the

Z_{CNO}, and the opacity can greatly influence the interpretation of globular cluster color magnitude diagrams.

Wagner (1978, Astron. Astrophys. 62, p.9) has discussed the evolution of very metal poor stars with $Z = 10^{-4}$ for masses 0.55, 3.25, and 4.0 $M_\odot$. Among the several conclusions is the fact that these stars evolve very rapidly and might be able to increase abruptly the Z value in our galaxy in its early life.

Two recent studies have been made to investigate the helium content of RR Lyrae variables. Caputo, Castellani, and Tornambe (1978, Astron. Astrophys. 67, p.107) have used tracks from previous publications and have considered how horizontal branch evolution proceeds to either the red or blue. The Oosterhoff types of RR Lyrae period distributions have been interpretated by van Albada and Baker as: I. initial zero horizontal branch blueward evolution starting red enough to have pulsation in the fundamental mode up to almost the fundamental blue edge; and II. blueward evolution starting even bluer so that the overtone occurs until the ultimate redward evolution moves the variable to a transition line beyond which only the fundamental can occur. The immediate pre-horizontal branch evolution is redward as O^{16} burning reaches equilibrium. Depending on the pre-horizontal branch evolution either Oosterhoff group can occur. Using the post horizontal branch, tracks, and pulsation period data the authors derive a Y of 0.22 - 0.25 and a mean mass of 0.72 $M_\odot$.

Caputo, Castellani, and Wood (1978, Monthly Notices Roy. Astron. Soc. 184,p.377) have continued the horizontal branch calculations with $Z = 10^{-3}$. Using the ratio of observed horizontal branch stars to those on the first giant stage branch and the ratio of the later asymptotic giant branch stars to the number on the first giant branch, they derive Y values of 0.18 to 0.26 for 5 globular clusters. They show that indeed semiconvection on the horizontal branch is required. In both these studies no variation of Z or opacity is discussed even though there could be a dependence of the derived Y on the Z value.

5. EFFECTS OF MASS LOSS ON STELLAR EVOLUTION (D. S. P. Dearborn and D. N. Schramm)

1. Introduction

Mass loss has been observed to occur in stars of both early and late type. Ultraviolet observations beginning with Morton (1967a) and leading to such surveys as that of Snow and Morton (1976) indicate that mass loss is a general property of early type stars. Analysis of both Visible and UV data (Hutchings 1976 and references therein) show mass loss rates ranging from 10^{-7} to 10^{-5} $M_\odot$/yr. More recently, infrared observations by Barlow and Cohen (1977) of free emission coupled with an assumed velocity law have confirmed such rates for O-B stars.

Red giants and supergiants have also been observed to be losing mass. Observations of infrared excess and resonance line profiles indicate mass loss rates ranging from 10^{-7} to 10^{-4} $M_\odot$/yr (Reimers 1975, Sanner 1976, Bernat 1977 and Hagen 1978). These observations have stimulated a resurgence of interest in studying the effects of mass loss on the evolution of stars. Recent calculations on massive stars (Chiosi and Nasi 1974; DeLoore, DeGreve, and Lamers 1977; Dearborn, Blake, Hainebach, and Schramm, 1978; Stothers and Chin 1978; Czerny 1978; Dearborn and Blake 1978; Chiosi, Nasi and Streenivasan 1978) though varying somewhat in approach have achieved similar results in mapping the effects of mass loss.

In early type stars, when the mass loss time scale ($\tau_{\dot{m}} = |M/\dot{M}|$ is much greater than the main sequence time scale, the effects on the star are relatively minor. Low rates of mass loss will cause a star to be less luminous than a mass conserving star, but overluminous for its actual mass. Higher rates of mass loss can affect the surface composition, nucleosynthetic yield, and post-main sequence evolution of a star.

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Mass loss from red giants seems necessary to understand the appearance of blue horizontal branches in globular clusters (Rood 1973) and is important in determining which stars evolve to white dwarf instead of ending in a supernova. Mass loss in evolved stars may also be necessary to understand the composition anomalies sometimes observed, and the slow rotation (low angular momentum) seen in stellar remnants.

2. Mass loss mechanisms

A comprehensive theory of the mass loss mechanism in stars should predict the temperature and velocity distribution of the ejected material as well as the mass loss rate. It should also account for the observed spectral features in all wavelength regions, and explain the apparent variability observed in some stars. The mass loss mechanisms are probably different for early and late type stars, and so the theories must be discussed separately.

a) Mass loss in early type stars

No theory to date is sufficiently complete to predict all observed features in early type stars but certain points are generally agreed upon (Hearn 1978). The large terminal velocity observed in the ejected material ($V > 1000$ km s^{-1}) is probably due to radiation pressure. Also, the existence of OVI in the ejected material is not predicted by the simplest form of the radiation pressure theory and seems to require the existence of a corona. There is no consensus however on whether radiation pressure, a corona, or some unspecified mechanism initiates the mass loss.

The radiation pressure of Castor, Abbott, and Klein (1975) is the most successful theory in terms of being able to describe the expected mass loss for a star of specified mass luminosity temperature and composition. In this theory, mass loss is driven by radiation pressure on ultraviolet absorption lines of carbon, nitrogen, and oxygen. Not only is a mass loss rate predicted, but line profiles (Klein and Castor 1978) and terminal velocities (Abbott 1978).

Models using a corona, of "Warm Wind" to initiate mass loss (Thomas 1973, Cannon and Thomas 1975, Rogerson and Lamers 1975) require mechanical energy deposition in the atmosphere. Hearn (1972, 1975) proposed a mechanism in which density waves are produced by the strong radiation field in early type stars. The efficiency of this mechanism is, however, uncertain (Hearn 1975) and without constraints on the energy input, the magnitude of the resulting mass loss is unpredictable.

The existence of OVI in the outflowing material seems to indicate the existence of a corona (or at least a chromosphere, Lamers and Snow 1978). Castor, Abbot, and Klein (1976), however, point out that x-ray observations constrain this warm region to temperatures of less than 300,000K. This rules out a hot corona, but not the warm wind model of Rogerson and Lamers (1975).

The radiation pressure model of Castor et al does not exclude the existence of a corona, but their assumption of radiative energy balance does not produce one. By relaxing this assumption, a small corona may be produced and the OVI observations explained. According to Castor (1978) a small corona can exist without significantly disturbing the radiation pressure model.

Finally, all of these models are steady state theories, and so do not predict any fluctuation in the mass loss rate. Observations of Hα (Hammerschlag 1978) show variation on short time scales, possibly indicating fluctuations in the mass loss rate. Conti (1978) has pointed out that these line strength fluctuation may be caused by small variations in the mass outflow; however, Thomas (1978) argues that mass loss varies dramatically due to small scale structure under the photosphere.

b) Mass Loss in late type stars

The primary theories proposed for mass loss in red giants and supergiants are coronal models and radiation pressure on dust grains. A coronal model was developed by Fusi-Pecci and Renzini (1975) in which accoustic energy produced in the convection is deposited in circumstellar material producing a corona and mass loss. The mechanism was scaled to the solar mass loss rate, and was successful in explaining the mass loss needed to produce a blue horizontal branch. As the accoustic energy available is sensitive to the luminosity, mass loss rates increase rapidly with brightness. Coronal models may then drive sufficient mass loss to explain the observed rates.

A mass loss model should, however, be able to reproduce the observed spectral features in mass losing stars. As shown by Weymann (1963) the coronal model has difficulty. In order to avoid too much hydrogen emission, it is necessary to have a low density through the temperature transition region. It was then difficult to avoid velocities in excess of the observed terminal velocity ($v_T \sim 10$ km s^{-1}).

Radiation pressure models generally assume the radiation field acts on circumstellar dust (Kwok 1975, Goldreich and Scoville 1976). As discussed by Weymann (1978), the dust model also has difficulty in reproducing observed spectral features. The Ca, H and K emission is blue shifted suggesting that mass loss is already under way in the chromosphere. The temperature there should be too hot for grains to exist. The radiation pressure mechanism may however be rescued from this dilemma if the grain forming region is supported above the chromosphere by turbulent pressure. In this cooler circumstellar environment, grains may form and be accelerated outwards. Outflow of material to replace the accelerated gas may then cause the observed velocity at the chromosphere.

3. Evolution with mass loss

Mass loss has been parameterized in a number of ways, but most commonly:

$\dot{M}=\theta NL/C^2$ (DeLoore et al 1977)

or

$\dot{M}=\mu LR/M$ (McCray 1962).

The results obtained with these different formulations have, however, been quite similar, indicating the results are not sensitive to this choice.

As mentioned in the introduction, low rates of mass loss lead to relatively minor effects. In O or B type stars, low rates of mass loss will cause a star to be less luminous than it would have been without mass loss, but it will be overluminous for its lowered mass. The amount of mass contained within the convective core decreases at the same rate as the luminosity and so the main sequence lifetime is unaffected (i.e., low rates of mass loss will not extend the main sequence lifetime of a star). Since a slightly smaller core develops, the post main sequence evolution of a mass losing star is increased.

As the mass loss rate increases ($\tau_{\dot{m}}$ decreases), the general form of the mass loss becomes significant. Dearborn and Blake define a critical rate of mass loss at which the main sequence lifetime of a mass losing star begins to rapidly increase. Stars which begin losing mass at a rate higher than this, <u>must</u> reduce their mass loss rate, or become totally depleted.

When the time averaged mass loss rate nears the critical rate, the resulting evolution can depend on the parameterization of the mass loss rate. Different results will be obtained for an increasing mass loss rate when compared to a constant one. A star initially losing mass at a low rate will develop a large core in spite of a high mass loss rate during subsequent evolution. A constant or decreasing mass loss (as is predicted in stars losing mass at or above the critical rate) results in a smaller core on affecting the post main sequence phases of evolution, and the nucleosynthetic yield.

As shown by Dearborn and Eggleton (1977), losing 1/3 of the initial mass in stars of less than 30 $M_\odot$, or 8 to 10 $M_\odot$ in more massive stars results in ^{14}N enhancement of 3 to 5 times. Stars losing mass at a rate below the critical rate may show such ^{14}N enhancement at the end of the main sequence, or during post-main sequence evolution. Mass loss at the critical rate exposes the ^{14}N rich material early in the main sequence lifetime, and may expose deeper region in which ^{16}O has been converted to ^{14}N causing an enhancement of $\sim$10 times. Quantitative observations of single OBN stars can potentially give valuable information on how much mass has been removed. The existence of a single OBN star with ^{14}N enhancement of $\sim$10x would strongly indicate the occurence of mass loss at the critical rate.

Mass loss at the critical rate can remove the hydrogen rich envelope and expose the core. This would result in a hydrogen deficient (nitrogen enriched) star (DeLoore et al 1978), or helium star (Dearborn and Blake 1978). These models could be identified as WN stars.

Continued mass loss at rates $\dot{M}>10^{-5}$ $M_\odot$/yr (Barlow 1978) will affect the evolution of helium stars; in fact, low mass helium cores $M \lesssim 8M_\odot$ could not maintain such mass loss rates over their entire helium burning lifetime. They would necessarily evolve to lower luminosity objects with reduced mass outflows. This suggests the existence of a more quiescent low luminosity form of helium star.

Higher mass helium stars can survive mass loss rates of $\dot{M} >10^{-5}$ $M_\odot$/yr, but material once contained within the helium burning convective core will be exposed. This material will be rich in carbon and possibly oxygen. Also, as deeper regions are exposed, one sees material in which ^{14}N has been converted to ^{18}O and ^{22}Ne. Continued mass loss from helium cores then naturally results in a WN-WC sequence. Mass loss at rates below the critical rate will result in a star which attempts to become a red giant. Mass transfer in a binary system (Van beeveran and DeGreve 1978), or a very large mass loss rate ($\sim10^{-4}M_\odot$/yr) may still allow the star to become a stripped core (or Wolf Rayet star). As expected however, the cores produced in this manner are larger than those resulting from mass loss at the critical rate.

Due to reduced core size (as compared to mass conserving stars) and the elimination of semiconvection (Falk 1978) in mass-losing stars, the C/O yield of helium burning should be increased (Dearborn 1978). After helium is depleted the C-O core contracts until temperatures are suitable for carbon burning. The post carbon evolution is so quick that mass loss should not have any further effect. The constant mass models of Arnett (1972) should adequately represent the subsequent evolution. The ratio of core mass to zero age main sequence mass will, however, be affected.

Mass loss during later stages of evolution is important to determine which stars (in the 1.4 to 8 $M_\odot$ range) lose sufficient mass to become white dwarfs. An observational search for white dwarfs in clusters (Romanishen and Angel 1978) indicates that stars of 5 $M_\odot$ and possible 7 $M_\odot$ regularly lose sufficient mass to become white dwarfs. In more massive stars, mass loss in the red giant can solve the discrepancy between pulsational mass and evolutionary mass (Cox 1978), and as mentioned above, may aid in removing the remainder of the envelope to produce a Wolf Rayet Star. Unfortunately, our understanding of the mass loss mechanism in red giants is inadequate to accurately understand its effect. Still, studies (Scalo 1978) have been made indicating the observed mass loss rates are sufficient to cause the effects stated above.

4. Summary

Observed mass loss rates ($>10^{-6}$ $M_\odot$/yr) are sufficient to affect the evolution of stars, and if continued over the main sequence life-time of an O-B star may produce single Wolf Rayet Stars. While many of the effects of mass loss have now been

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explored, there are still many unsolved questions.

The basic mechanism by which mass is ejected in both early and late type stars is still subject to dispute. Further observations to accurately determine mass loss rates, as well as temperature and velocity profiles in the ejected material are needed to help resolve this. Quantitative observations of ^{12}C and ^{14}N abundances in early type single stars will also be useful in determining the total amount of mass which is lost. Determining CNO abundances and isotope ratios in evolved stars may also give information on the total mass lost (Dearborn, Schramm, and Eggleton 1976).

More calculations need to be made on the effects of mass loss in binary systems (particularly those systems which become x-ray binaries) and mass loss in red supergiants. Studying the effects of mass loss in red giants is, however, difficult due to a lack of understanding the mass loss mechanism involved.

The phenomenon of mass loss is important for understanding the appearance of some stars, and their evolution. Massive stars are responsible for most of the heavy element production, mass loss can have important effects on their yield, and so affect chemical evolution of the galaxy. The interaction of the ejected material with the interstellar medium may also have interesting effects. While much has been learned on the effects of mass loss on evolution, there are more questions to answer.

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