STARMAKER: Programs for calculating stellar evolution

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Summary

A description of a computer program for the calculation of stellar evolution is presented. The program employs a Henyey code based on the Kippenhahn et al. (1967) prescription. Details of the treatment of the equation of state, stellar opacity, nucleosynthesis and convection are summarised. Further development of the program is planned in conjunction with its recent implementation on CRAY-1 computers.

1 Introduction

Computer programs for the calculation of stellar evolution are now widely available. Since each code has its own advantages and drawbacks no defence of adding to this number is made. This article describes a versatile program written originally as part of a PhD Thesis between 1979 and 1982 at the University of St Andrews. The program has recently been implemented on the CRAY-1 computers at the University of London computer centre (ULCC) in conjunction with the Collaborative Computational Project No. 7 and at the Konrad-Zuse-Zentrum für Informationstechnik in Berlin (KZZ). Substantial improvements to the code are due to be made, so this article simply describes its present form. Fuller details are given by Jeffery (1982) in a study of the effect of Carson opacities on the structure and evolution of horizontal branch stars. The program has also been used in studies of the apsidal motion constant in main-sequence binaries (Jeffery 1984a) and of the evolution of the extreme-helium star BD+13^o3224 (Jeffery 1984b).

2 The stellar evolution code

The classical equations of stellar evolution are described in many texts (e.g. Schwarzschild 1958). The assumption of spherical symmetry (rotation and magnetic fields are neglected) reduces the spatial component of the stellar evolution equations to 1-dimension. This component is expressed as a system of partial differential equations in 4 stellar variables (r, l, P, T) with a Lagrangian independent variable (m). Boundary values at the stellar centre and surface enable a solution to be determined. A Henyey code based on the prescription Kippenhahn et al. (1967) is adopted for this purpose. In brief, this procedure translates the partial differential equations into a system of different equations. The non-linear system of simultaneous equations is linearised by assuming that an approximate starting solution exists, and then solved by means of a Newton-Raphson iteration.

The surface boundary conditions $P_g = 0, T = T(\tau, R_*, L_*)$ are translated to a set of linearized boundary relations between the dependent variables (r, l, P, T) beneath the H and He ionisation zones. This is achieved by a separate integration of the stellar envelope of a triangular grid in the $(L, T_{\rm eff})$ plane (see Kippenhahn et al 1967). The routine which carries out this integration (ENVELOPE) is separately available for investigations of the structure of static stellar envelopes. Here 'envelope' means the portion of the star between the photosphere and some ill-defined point above which no nuclear reactions occur. ENVELOPE is at present only valid in the approximation that there is no energy sources or sinks present in the domain of the integration. Starting values for the integration are provided by simple grey Eddington atmosphere which calculates P and T down to $\tau = 2/3$.

Temporal terms in the stellar evolution equations enter because of stellar energy production and absorption. Gravitational energy changes are dealt with by an additional term in the linearised equations solved by the Newton-Raphson iteration. Nucleosynthesis is calculated separately as a change in the chemical structure of the star after each timestep.

3 Physics

3.1 EQUATIONS OF STATE

The equations of state are solved in two T, ρ domains. At low temperatures Saha's ionisation equilibrium equation is solved to determine the electron density. The treatment closely follows that of Cox & Giuli (1968) and Mihalas (1978). Contributions from ions of H (including H^-), He, C,N,O, and a representational metal (Mg) are calculated. At high temperatures, the effect of non-relativistic electron degeneracy is included in the equations of state.

3.2 STELLAR OPACITY

STARMAKER was originally written to investigate the effect of the Carson opacities of models of horizontal branch stars (Jeffery 1982). These opacities are described by Carson et al. (1968) and Carson & Stothers (1976). Tables appear in Carson et al. (1981) and Jeffery (1982). A multi-dimensional interpolation procedure (T, ρ, Y, Z, or T, ρ, C, O) was used to derive the (harmonic) mean of the Rosseland mean radiative opacity and the Hubbard-Lampe (1968) conductive opacity. The 'bump' at low densities and $T \approx 10^6$ K in these opacities is apparently unreal (Carson et al. 1984).

Opacities currently available are the Christy (1966) and Stellingwerf (1975) analytic fits to the radiative opacity. The validity ranges for these fits are limited. Other opacities ar being implemented.

3.3 NUCLEAR ENERGY GENERATION AND NUCLEOSYNTHESIS

The nuclear energy production and nucleosynthesis rate are calculated using the formulae of Fowler et al. (1967,1975) and Harris et al (1983). Electron-Screening factors are calculated following Graboske et al. (1973). Hydrogen-burning calculations follow Fowler et al. (1975) for the relative contributions of the different pp chains and Demarque et al. (1971) for the temperature dependence of the N^{14} abundance in the CNO cycle. Helium-burning reactions follow the 3α process and α-capture reactions up to Ne^{20} (α, γ) Mg^{24}. Neutrino losses are calculated with the analytic interpolation formulae of Beaudet et al. (1967).

3.4 CONVECTION

Where the radiative gradient in the star becomes superadiabatic, convection is treated according to local mixing-length theory (Böhm-Vitense 1958). At high temperatures, the limiting case of adiabatic convection is adopted. The ratio of the mixing-length to the pressure scale height and the theory dependent constant a_0 (Cox & Giuli 1968) may be specified by the program user.

Deupree & Varner (1980) employed 2-dimensional hydrodynamical-calculations to obtain a better estimate for the local value of the 'mixing-length'. The analytic fit which they derived is optionally available. A further modification suggested by Deupree (1979) which allows for the difference of the horizontally-averaged opacity and the opacity of material with a horizontally-averaged temperature is also available, but is very costly.

Provision has been made for the treatment of semiconvection and convective overshooting following the prescriptions of Roberson & Faulkner (1972) and Castellani et al. (1985). This feature is not complete.

4 Use of the code

4.1 HISTORY

The stellar evolution code was originally developed on a Honeywell computer of the University of Aberdeen. It was moved in 1982 to a VAX 11/780 computer at the University of St Andrews (SAVA). Calculations are best suited to a BATCH environment but preparation of input and output data requires interaction with the programmer. Therefore an interactive management system was written (in DCL) and acquired the name STARMAKER (version 1). The CRAY implementation currently has no such supervisory system but consists of a suite of programs described below (see Table 1).

Table 1. Summary of main components of STARMAKER.

Name	Description	Implementation
STARMAKER	Batch job and data supervisory package	SAVA
ENVELOPE	Stellar envelope integration	SAVA,KZZ
NEWZAMS	Construct approximate model for ZAMS	SAVA,KZZ
NEWZAHB	Construct approximate model from ZAHB	SAVA,KZZ
RELAX	Relax approximate solution to obtain zero-age model	SAVA,KZZ,ULCC
EVOLVE	Construct an evolutionary sequence	SAVA,KZZ,ULCC

4.2 INITIAL MODELS: RELAX

The starting point of the evolutionary sequence is defined by an initial stellar model. In STARMAKER these models are required to be in equilibrium. Two cases which fulfil this condition have been considered so far, namely the zero-age main sequence (ZAMS) and the zero-age horizontal branch (ZAHB). In the case of ZAMS star a homegeneous composition is assumed, the star is specified by its mass, helium and metal abundances (M, Y, Z). The ZAHB star additionally requires the core mass M_c to be defined. Starting with an existing initial stellar model with parameters close to those desired, the required parameters are simply substituted for those in the existing model. Programs NEWZAMS and NEWZAHB should carry out this function. This model may then be used as the starting approximation for the Newton-Raphson relaxation iteration described in $\oint 2$, yielding a 'zero-age' model in thermal equilibrium. The current version of STARMAKER makes no provision for nuclear evolution during pre-ZAMS or pre-ZAHB evolution, or the failure of some reaction networks be become fully established at the 'zero-age' position.

4.3 EVOLUTIONARY SEQUENCES: EVOLVE

Once a starting model in equilibrium is available, the time-dependent equations may be introduced. A subroutine DTSTAR currently carries out several functions. The timestep is automatically adjusted to optimise the code in phases of slow and rapid evolution. The composition ia modified according to the current rates of nucleosynthesis and fixed in full convective zones. Provision for the treatment of mass-loss is incomplete.

Several properties of the evolving stellar model are evaluated at the completion of each timestep. These are under review, but currently include basic surface parameters $(L, T_{\rm eff}, \log g, R)$ luminosities for nuclear, neutrino and gravitational sources, positions of convective-radiative boundaries, etc. The apsidal motion constant k_2 (Schwarzschild 1958) is optionally computed. Two output files are generated. One contains detailed information about the progress of the calculations, the other contains a summary of the sequence of models.

Every ten timesteps, two models separated by a single timestep are stored externally. These may be used to restart an evolutionary sequence from an advanced position if required.

5 Future Developments

A number of modifications to be the stellar evolution code are being considered. The code for the Newton-Raphson iteration and for the time-step integration will be modified to achieve greater efficiency on a CRAY. At present the CRAY version is approximately 30 time faster than the VAX (double precision) version. Several changes to the physics are in progress, including extensions to the equation of state and the opacity routines. The treatment of semi-convection and mass-loss will be completed.

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