

Two computer programs for studying stellar evolution

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(Research report. Accepted on 15.01.2009)

Abstract. Two FORTRAN programs are presented which plot the Hertzsprung-Russell diagram and the temporal evolution of such stellar quantities as: central and photospheric isotopic abundances, central densities and temperatures, luminosities, effective temperatures and photospheric radii for a wide range of stellar masses. The programs, which are modifications and extensions of some modules of the *TYCHO 6.0* stellar evolution package, are accompanied by control input files as well as by a library of data. The data library is actually one of the output files generated by *TYCHO-GR* (a modified version of *TYCHO 6.0*), while the plots themselves are generated by the PGPLOT Graphics Subroutine Library which is also publicly available and well cited.

Key words: nuclear astrophysics, thermonuclear reactions, solar neutrinos, stellar oscillations

Две компютърни програми за изучаване на звездната еволюция

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Представени са две фортрановски програми, които представят графично върху диаграмата на Херцшпрунг-Ръсел еволюцията на звездните параметри централно и атмосферно обилия, централни плътност и температура, светимости, ефективни температури и фотосферни радиуси за широк интервал звездни маси. Програмите, които са модификации и разширения на някои модули от пакета за звездна еволюция *TYCHO 6.0*, са съпроводени с контролни входни файлове и библиотека от данни. Библиотеката данни е всъщност един от изходните файлове, генерирани от *TYCHO-GR* (модифицирана версия на *TYCHO 6.0*) докато графиките са генерирани от пакета PGPLOT Graphics Subroutine Library, който е публично достъпен и често цитиран.

1 Introduction

TYCHO 6.0 is a general, one dimensional (spherically symmetric) stellar evolution code, designed for hydrostatic and hydrodynamic stages, using state of the art procedures and microphysics (see *TYCHO 6.0* website). It is written in structured FORTRAN (f77) and has extensive on-line graphics using the PGPLOT graphics package (see PGPLOT website) in X-windows environments. It has being developed as an open-source, community code and can run very effectively on Linux laptop and desktop computers. *TYCHO 6.0* is

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being used by the University of Arizona astrophysics group (as well as by the first author) for ongoing research in stellar evolution (for relevant papers see (*TYCHO 6.0* website)) while it has also been used to generate low-noise initial models for multi-dimensional numerical hydrodynamic simulations. The *TYCHO 6.0* package includes various auxiliary files and subprograms which can monitor both the evolution of a star and nuclear reaction networks under various conditions.

Although *TYCHO 6.0*'s auxiliary programs focus on various aspects of stellar evolution, such as the Hertzsprung-Russell (HR) diagram or the composition and thermodynamics of each evolutionary sequence, there is no auxiliary program which can investigate the temporal evolution of the star (neither during nor after the actual simulation process). Since typical HR diagrams and static composition profiles are actually bereft of any temporal information reliable programs are needed to satisfy this obvious need for all *TYCHO 6.0* users. Moreover, such programs should not just be able to be used by *TYCHO* users. Anyone wishing to study the evolution of a star could benefit from an independent program which could be applied to a large library of data generated by *TYCHO*. This is the purpose of the programs presented here.

In the sections that follow we first describe the programs and then its input and output files. Then we implement the programs by performing a test-run for a 3M star and a particular initial composition. The present paper initiates an effort to improve the *TYCHO 6.0* package and extend its capabilities in order to investigate various nuclear astrophysics topics. A similar effort is going on by the university of Arizona astrophysics group which has already derived a new version, called *TYCHO 6.11*, which is also publicly available. *TYCHO 6.0* has now been equipped with screening effects in the derivation of thermonuclear reaction rates as well as with various new auxiliary programs such as those presented in this paper. Screening corrections in the equation of state for completely degenerate environments (e.g. White-Dwarf progenitors) will soon be available. These aspects are not included in the *TYCHO 6.11* version which, however, has very interesting improvements over *TYCHO 6.0*. To facilitate versioning and differentiation from the *TYCHO 6.11* sequence (and all relevant work from the Univ.of Arizona group), the version independently evolved and implemented in Greece by the author and his collaborators will be referred to as *TYCHO-GR*, while all relevant improvements and modifications over the *TYCHO 6.0* version will be consistently recorded and published, starting with the present paper. Note when the stellar evolution code is referred to as *TYCHO* then the relevant comment is applicable to all versions of the code.

2 HRTEMP

2.1 Brief description

Hrtemp is an *F77* program which reads a library of data (*hr.prefix*, generated by *TYCHO-GR*) as well as some control input files in order to plot the temporal evolution of such stellar quantities as: central and photospheric isotopic abundances, central densities and temperatures, luminosities, effective

temperatures and photospheric radii for a wide range of stellar masses. The program makes use of the PGPLOT Graphics Subroutine Library which is also publicly available and well documented. The source file *hrtemp.f* is located in */hr/src* along with its *Makefile.Linux* and *Makefile* files, which are actually those distributed with the *TYCHO 6.0* package with minor modifications. Note that the *Makefile.Linux* file should be informed about the location of the files *libpgplot.a*, *libX11.a* on the user's machine, while the PGPLOT package should have been already installed.

2.2 Input files

hr.prefix While simulating the evolution of a star, TYCHO generates at each time step a grid of data which include such quantities as : time, central and photospheric isotopic abundances, central densities and temperatures, luminosities, effective temperatures, mass loss/gain, angular rotational velocity and photospheric radii. All these data are stored in a file which is used by the program *hrtemp* presented here. This file is denoted by *hr.prefix*, where *prefix* is a two-character identification of the stellar evolution event. For example *hr.n1* indicates the evolutionary sequence of a 1M star, *hr.n2* that of a 2M star and so on. We have derived five such files. All evolutionary points in *hr.prefix* are numbered thus one can easily observe the density of the mesh. The size of such files is roughly 5MB to 10MB.

The *hrtemp* program can be integrated into the *TYCHO-GR* package by all its users in order to extend its capabilities. Of course it can always be used independently by simply using a library of pregenerated *hr.prefix* files. A typical form of an *hr.prefix* file is an array of the following blocks, each of which corresponding to a particular time-step:

model serial number, iterations, time, timestep, photospheric radius, photospheric density, photospheric velocity, log(L/Lo), log(Teff), mass interior, mass loss per year, solar masses ejected, angular rotational velocity, central temperature, central density, photospheric abundances (array), central abundances(array).

The control file hrtemp.in A control input file *hrtemp.in* is essential to the implementation of the program. Its form is as follows:

```
'.....'
' HRTEMP: for TYCHO-GR '
'.....'
' Display device: /ps, /xwin ..... ' 'device' '/xwin'
' Number of sequences to plot..... ' 'nfiles' 3
' Filename of sequence..... ' 'hrfile' 'hr.n1'
' Filename of sequence..... ' 'hrfile' 'hr.n3'
' Filename of sequence..... ' 'hrfile' 'hr.n5'
' log(L/L⊙)=0, log Te=1, log(R/R⊙)=2, Xej=3, Xc=4, log Tc=5, log ρc=6: ifunct'
' lg(L/Lo), lg Te, lg(R/Ro), Xej, Xc, lg Tc, lg Dc= ' 'ifunct' 4
' The serial number of the isotope (net.rc).. ' 'isotop' 79
' minimum log(t) for x axis..... ' 'xmin' 10.9
```

```
' maximum log(t) for x axis.....' 'xmax' 18.79
' minimum Yi for y axis.....' 'ymin' 0.0d0
' maximum Yi for y axis.....' 'ymax' 1.0d0
' Line style.1=solid line, else dots.....' 'linesty' 1
',.....'
```

The display device is defined in the fourth line. There are three options:/ps, /cps, and /xwin. The first two generate a figure in the form of a postscript file (named pgplot.ps) either black and white (/ps) or color(/cps), while the /xwin option generates an on-screen figure.

The fifth line indicates the number of sequences to be plotted in the same figure. Different plots are drawn using different line styles (not available in *TYCHO 6.0*) and colors. Thus, for example, one can use the input files *hr.n1,hr.n3* to follow the simultaneous temporal evolution of two stars (1M and 3M).

The sixth line (and all the similar ones that have to follow if the number of sequences specified in the fifth line is larger than unity) indicate the data files to be used. If only one sequence is to be followed then only one such line is necessary.

The seventh line is a dummy text line which serves as a reminder of the meaning of the switch to be used in the eighth line.

The eighth line stands for the switch *ifunct*, which defines the quantity to be plotted versus time. Namely:

$$\log(L/L_{\odot}) = 0, \log T_e = 1, \log(R/R_{\odot}) = 2, X_{ej} = 3,$$

$$X_c = 4, \log(T_c) = 5, \log(\rho_c) = 6$$

where $X_{ej}(X_c)$ is the isotopic abundances of the ejecta (in the center), T_c, ρ_c are the central temperatures and densities respectively, T_e is the effective temperature, L is the total luminosity, and R is the photospheric radii. The serial number of the isotope to be plotted (if the *ifunct* option is 4 or 3) is defined in the ninth line. That number can be found in the file *net.rc* which is included in this work (and is identical to the one found in *TYCHO 6.0*. For example 80 stands for ${}^4\text{He}$, 79 for H , and so on. That line is ignored unless the *ifunct* quantity is 4 or 3. Note that *TYCHO 6.0* uses a small reaction network for small temperatures ($T < 10^7 K$), which consists of only 29 isotopes (i.e. the first 26 of *net.rc* plus ${}^4\text{He}$, H and electrons), which should be taken into account when plotting the temporal evolution of an isotope.

The temporal limits for the plot are defined in the tenth and eleventh lines. Actually those limits stand for the logarithm of time $\log(t)$ when time is measured in seconds.

The limits for the vertical axes are defined in the twelfth and thirteenth lines. Note that except for the isotopic abundances all other limits are measured on a logarithmic scale.

Other auxiliary files The source code makes use of three files to be included upon compilation of the program namely: *dimenfile, cconst, caeps*. *Dimenfile* defines very fundamental quantities such as the dimension of the abundance

arrays; *ccosnt* defines some of the constants to be used; and finally *aeps* defines some of the arrays used in the simulation. Note that these three files are identical to the files distributed with the TYCHO package and in order to avoid any confusion we have retained the definition of various other quantities which are necessary to all TYCHO packages but are not needed in the present *hrtemp* program.

Another auxiliary file which has already been mentioned is *net.rc* which contains information about the isotopic network which has been used in the simulation. The data stored in that file are easy to follow and are of the form:

serial number, protons, neutrons, mass, abundance

2.3 Output files

The main function of the *hrtemp* program is plotting the temporal evolution of various stellar quantities for one or more simulations. *hrtemp* can generate an on-screen output (which is a family of plots against a black background) or a postscript file, which is a family of plots against a white background. The postscript file is named *pgplot.ps*. The quality of the output file, depends of course on the quality of the simulation itself. Therefore, one should have detailed information about the assumptions and the approximations entailed during the simulations. The assumptions made for the derivation of all the *hr.prefix* files are the same as the ones made in (Young et al., 2001), except for the mixing length which in our case is set equal to 1.8. Although we have equipped TYCHO-GR with Mitler's (Mitler, 1977) screening effects in the derivation of thermonuclear reaction rates, for simplicity we have chosen to turn screening off. A major parameter in the quality of our *hr.prefix* data files is the range of validity of the equation of state. We have run TYCHO-GR for various initial stellar masses until it cannot converge any more. However, since TYCHO's EOS needs adjustment for strong screening effects the quality of the plots in strongly screened domains (e.g. white-dwarf progenitor phases) may not be very satisfactory. Of course, all weakly screened stellar interiors are very reliably simulated and the corresponding plots can be safely used.

Another aspect of this program is that each *hr.prefix* file is generated not only for a specific stellar mass but also for a specific stellar composition: X, Y, Z . In fact all *hr.prefix* files which accompany the present program have been generated for a $X = 0.7, Y = 0.28, Z = 0.02$ composition. The users of the *hrtemp* program (or the *hrplot* one whose description follows) can always request new *hr.prefix* files from the first author, specifying each time the initial composition and stellar mass as well as all the other details of the requested simulations.

Regarding the quality of the plots, it should be emphasized that there is a wide range of options such as line width, colors, magnification etc. All these options can be modified in the source code if the user has some experience in using PGPLOT. Since the manual of PGPLOT is publicly available along with the source code itself no further analysis is deemed necessary here. All the advantages and disadvantages of using PGPLOT are built into the *hrtemp* plots. A thorough discussion of those can be found in the PGPLOT manual and in all relevant internet sites.

3 HRPLOT

3.1 Description

While *hrtemp* uses the file *hr.prefix* to plot the temporal evolution of the star, there is another auxiliary file distributed freely with TYCHO 6.0, namely *hrplot.f*, which uses the same input file to plot the HR diagram of the evolution. The *TYCHO-GR* version stores more data in the *hr.prefix* file than *TYCHO 6.0* does, such as central isotopic abundances, central temperatures and densities etc. Therefore, the original program *hrplot.f* has been modified accordingly to be able to read the *hr.prefix* file generated by *TYCHO-GR*. Moreover, the new version of *hrplot* included in the *TYCHO-GR* package has been further improved so that evolutionary lifetimes can now be depicted on the HR diagram. Except for those two improvements, all other aspects of the *hrplot* are similar to those of the *TYCHO 6.0* package.

3.2 Input files

hr.prefix The major input files used by *hrplot* are of course the *hr.prefix* files which have already been adequately analyzed in the description of *hrtemp*.

The control file hrplot.in A control input file *hrplot.in* is essential to the implementation of the *hrplot* program. Its form is as follows:

```
'
.....'
' HRPLOT: for TYCHO-GR'
'
' .....'
' Display device: /ps, /xwin ..... 'device' /xwin'
' Number of sequences to plot..... 'nfiles' 3
' Filename of sequence..... 'hrfile' 'hr.m1'
' Filename of sequence..... 'hrfile' 'hr.m3'
' Filename of sequence..... 'hrfile' 'hr.m5'
' 0 gives -logTe,logL,else logR,logL..... 'iradii' 0
' minimum log Xi for x axis..... 'xmin' 4.2
' maximum log Xi for x axis..... 'xmax' 3.3
' minimum log Yi for y axis..... 'ymin' -1.0
' maximum log Yi for y axis..... 'ymax' 3.5
' Line style.1=solid line, else dots..... 'linesty' 1
' Some observational points? (0=no)..... 'iobs' 0
' Evolutionary lifetimes?(0=no else number= 'nums' 0
' Evolutionary lifetime (nums<>0)..... 'logL' 2.028d0
' Evolutionary lifetime (nums<>0)..... 'logT' 4.06d0
' Evolutionary lifetime (nums<>0)..... 'logL' 2.153d0
' Evolutionary lifetime (nums<>0)..... 'logT' 4.029d0
' Evolutionary lifetime (nums<>0)..... 'logL' 1.918d0
' Evolutionary lifetime (nums<>0)..... 'logT' 3.688d0
'
.....'
```

The first eight lines bear the same meaning as those of *hrtemp.in*.

The fifth line carries a switch (*iradii*), which defines the type of plot to be generated by *hrplot* and is self-explanatory.

The next four lines are the logarithms of the luminosity and the effective temperature which will be the limits of the HR diagram.

The line style is defined by the switch *linesty* in the next line, just as it is the case with *hrtemp.in*.

The program *hrplot* included in the *TYCHO 6.0* package has the capability of depicting observational points on the HR diagram and that is controlled by the switch *iobs*. The observational points are defined in the source code *hrplot.f*.

The novel aspect in the *hrplot* presented here is the inclusion of evolutionary lifetimes, which is controlled by the switch *nums*. The user can enable that option defining simultaneously the number of evolutionary points to be included. The evolutionary points will be shown on the HR diagram as integers, each of which corresponding to a particular point ($\log(T_{eff}), \log(L/L_{\odot})$) according to the data in *hrplot.in*.

3.3 Output files

The output file is of course an HR diagram whose accuracy is a function of the accuracy of the simulation itself. It should be emphasized that all *TYCHO* codes can start the evolution from a homogeneous gas sphere and follow the evolution down the Hayashi track. In some cases (low-mass stars) the first few steps of the simulation may fail to converge but *TYCHO* soon overcomes the problem and converges rapidly along the Hayashi track. This effect is obvious at the HR plot of a 1M star where there is a small irregularity very high up the Hayashi track. The user can either discard the first non convergent steps of the *hr.prefix* file or can always choose to truncate a larger portion of the simulation and start the HR plot from the Zero-Age Main Sequence (ZAMS). Regarding the quality of the plots once again we should underline that it depends on the actual performance of the PGPLOT package.

Note that if the user switches *nums* on then the present sun is always indicated by a star on the HR diagram.

4 Test run

We follow the evolution of 1M_⊙, 3M_⊙ and 5M_⊙ stars ($X = 0.7, Y = 0.28, Z = 0.02$) by running *TYCHO-GR* until it fails to converge. The *hr.prefix* files that we have generated are respectively *hr.n1, hr.n3, hr.n5*. Then we implement our programs by plotting the temporal evolution of: a) the helium, hydrogen, and carbon-12 central abundances, b) the luminosity, c) the effective temperatures, d) the central temperature, e) the central density, and f) the radius, for a 3M star. We also plot the HR diagram for the same star including some enumerated life-times.

After $\log(t) = 16$ the star begins its ascend up the Asymptotic Giant Branch undergoing various breathing pulses. Those pulses are indicated by the irregularities which the plots depict in the relevant temporal regime. The physics of the AGB is being further elaborated in version *TYCHO-GR*

by including strong screening corrections to the EOS (to be published). Of course, the programs *hrtemp* and *hrplot* presented here can be safely used to study stellar evolution before the AGB regime.

ACKNOWLEDGMENTS

The first author (T.L) is grateful to Prof. D.Arnett for making TYCHO available to all of us as an open source stellar evolution code.

References

- TYCHO 6.0* website, University of Arizona: <http://chandra.as.arizona.edu/~dave/tycho-manual.html>
For instructions of obtaining PGPLOT and for details of supported operating systems:
<http://www.astro.caltech.edu/~tjp/pgplot/>
Mitler H. E., 1977, ApJ. **212**, 513
Young P.A., Mamajek E.E., Arnett D., Liebert J., 2001, ApJ **566** 230

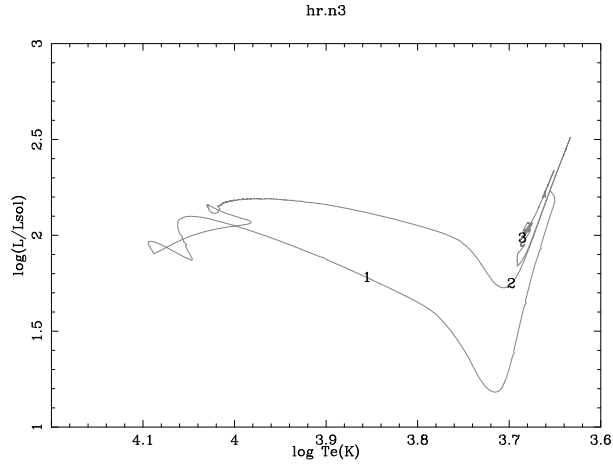


Fig. 1. The evolutionary track of a three-solar-mass star in the H-R diagram. The time required to reach the enumerated points is given in *hrplot.in*

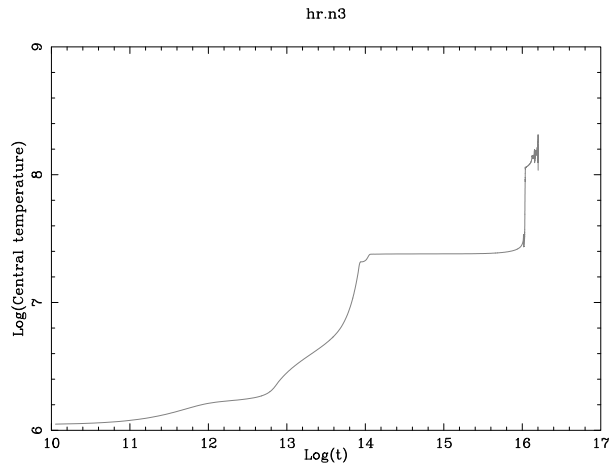


Fig. 2. The temporal evolution of the central temperature during the evolution of a three-solar mass star. After $\log(t) = 16$ the star begins its ascend up the Asymptotic Giant Branch undergoing various breathing pulses

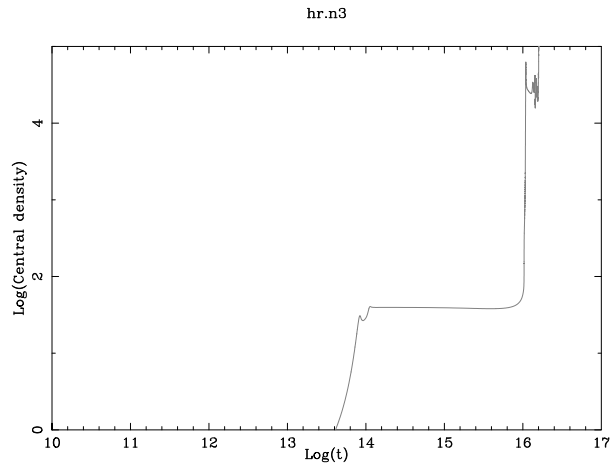


Fig. 3. The temporal evolution of the central density during the evolution of a three-solar mass star

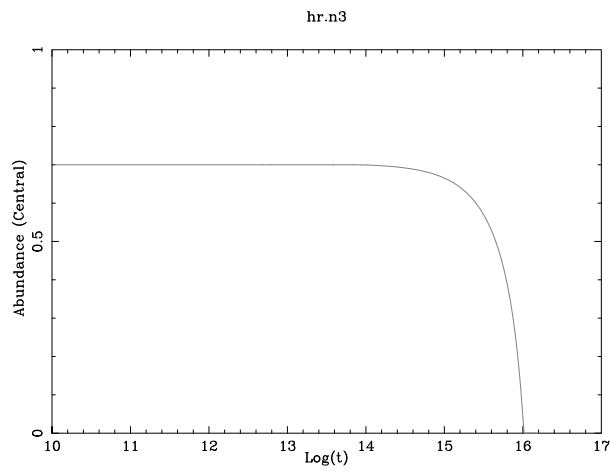


Fig. 4. The temporal evolution of the central hydrogen abundance (mass fraction) during the evolution of a three-solar mass star

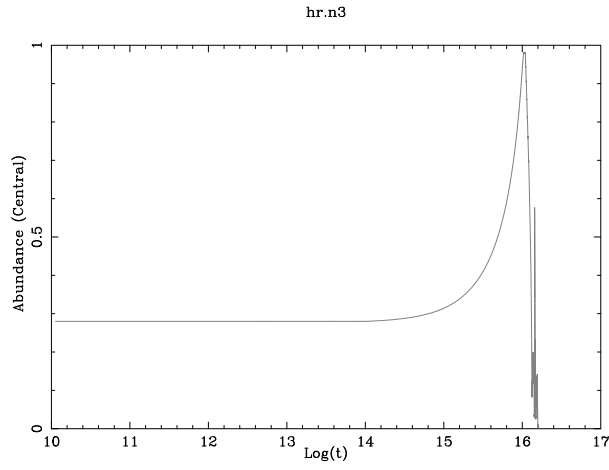


Fig. 5. The temporal evolution of the central helium abundance (mass fraction) during the evolution of a three-solar mass star

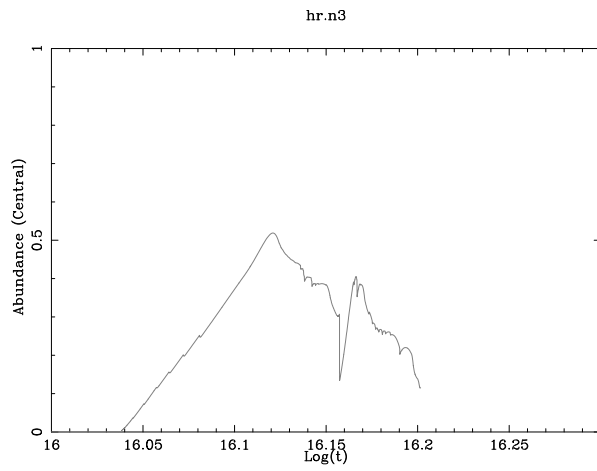


Fig. 6. The temporal evolution of the central carbon-12 abundance (mass fraction) during the evolution of a three-solar mass star. The comment in Figure 5 about AGB pulses applies here as well

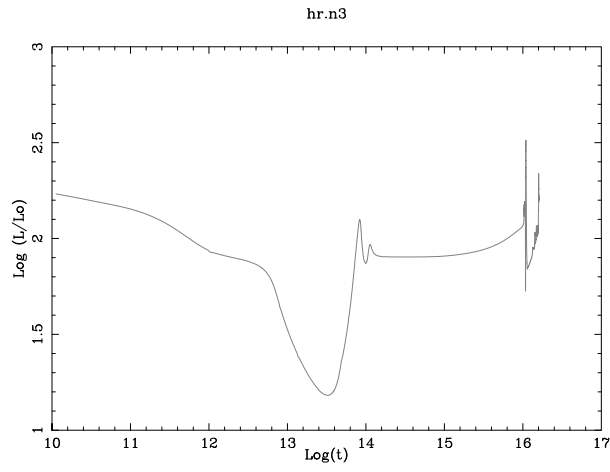


Fig. 7. The temporal evolution of the total luminosity during the evolution of a three-solar mass star

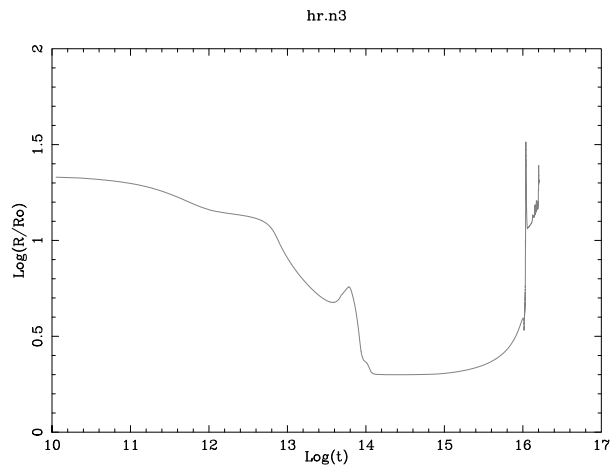


Fig. 8. The temporal evolution of the stellar radius during the evolution of a three-solar mass star