Student reports, Advanced Stellar Evolution (10)

The course will be evaluated on the basis of reports on subjects related to material covered in the course, providing an overview of the chosen area. The present note concerns the evaluation of the 10-ECTS course given in Q1 and Q2, 2016. The projects to a large extent overlap with the list provided for the evaluation of the 5 ECTS course in Q1, but the requirements will of course be higher for this 10-ECTS course.

Suggestions for subjects are given below, with a few relevant references. Each subject can be used only once, in this quarter; they will be distributed on a first-come first-served basis. You are welcome to discuss the topics with Günter or me before starting the project, but it is clear that we can give only very limited help with the project, given that it serves as an evaluation of the course. The reports will be evaluated, based on how well they cover the subjects, possibly including material additional to the references provided here, and graded on the 12 scale. The reports should have a length of 10 – 15 pages and may be in either Danish or English. I expect the reports at the latest 23 January 2017, e-mailed to me (jcd@phys.au.dk) as a PDF file.

You may use the subjects discussed in the publications as a starting point for modelling using MESA; in that case I do not expect a very detailed review of the publications, although a comparison with the published results would be interesting. I have also included a specific MESA-based project (No 19).

As a final suggestion, I include at the end a project to investigate the properties of a set of computed models, for which detailed information has been made available.

Of course, you are also very welcome to propose a subject for the report, by e-mail and including a few lines on what you have in mind.

Please send me an e-mail as soon as possible with the number of the project you have selected.

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1. The age of stars and the Universe

Krauss, L. M. & Chaboyer, B., 2003. [Age estimates of globular clusters in the Milky Way: constraints on cosmology]. *Science*, **299**, 65 – 69.

Chaboyer, B., Demarque, P., Kernan, P. J. & Krauss, L. M., 1996. [A lower limit on the age of the Universe]. *Science*, **271**, 957 – 961.

D'Antona, F., Caloi, V. & Mazzitelli, I., 1997. [The Universe and globular clusters: an age conflict?]. *Astrophys. J.*, **477**, 519 – 534.

Salaris, M., Degl'Innocenti, S. & Weiss, A., 1997. [The age of the oldest globular clusters]. *Astrophys. J.*, **479**, 665 – 672 (Erratum: *Astrophys. J.*, **484**, 986).

2. Formation of stars

Several review papers in *Science*, **295**, pp. 64 – 90.

Padoan, P. & Nordlund, Å, 2002. [The stellar initial mass function from turbulent fragmentation]. *Astrophys. J.*, **576**, 870 – 879.

Palla, F. & Stahler, S. W., 1999. [Star formation in the Orion Nebula cluster]. *Astrophys. J.*, **525**, 772 – 783.

Lada, C. J. & Shu, F. H., 1990. [The formation of sunlike stars]. *Science*, **248**, 564 – 572.

3. Detailed tests of stellar evolution

Lebreton, Y., 2000. [Stellar structure and evolution: deductions from Hipparcos]. *Annu. Rev. Astron. Astrophys.*, **38**, 35 – 77.

Young, P. A., Mamajek, E. E., Arnett, D. & Liebert, J., 2001. [Observational tests and predictive stellar evolution]. *Astrophys. J.*, **556**, 230 – 244.

Young, P. A. & Arnett, D., 2005. [Observational tests and predictive stellar evolution. II. Non-standard models]. *Astrophys. J.*, **618**, 908 – 918.

4. Later evolution of the Sun

Jørgensen, U. G., 1991. [Advanced stages in the evolution of the Sun]. *Astron. Astrophys.*, **246**, 118 – 136.

Sackmann, I.-Juliana, Boothroyd, A. I. & Kraemer, K. E., 1993. [Our Sun. III. Present and future]. *Astrophys. J.*, **418**, 457 – 468.

Schröder, K.-P. & Smith, R. C., 2008. [Distant future of the Sun and Earth revisited]. *Mon. Not. R. astr. Soc.*, **386**, 155 – 163.

5. The first generation of stars

Siess, L., Livio, M. & Lattanzio, J., 2002. [Structure, evolution and nucleosynthesis of primordial stars]. *Astrophys. J.*, **570**, 329 – 343.

Picardi, I., Chieffi, A., Limongi, M., Pisanti, O., Miele, G., Mangano, G. & Imbriani, G., 2004. [Evolution and nucleosynthesis of primordial low-mass stars], *Astrophys. J.*, **609**, 1035 – 1044.

Meynet, G., Ekström, S. & Maeder, A., 2006. [The early star generations: the dominant effect of rotation on the CNO yields]. *Astron. Astrophys.*, **447**, 623 – 639.

Baraffe, I., Heger, A. & Woosley, S. E., 2001. [On the stability of very massive primordial stars]. *Astrophys. J.*, **550**, 890 – 896.

6. Lithium depletion in stars

Boesgaard, A. M. & Tripico, M. J., 1986. [Lithium in the hyades cluster]. *Astrophys. J.*, **302**, L49 – L53.

Michaud, G., 1986. [The lithium abundance gap in the Hyades F stars: the signature of diffusion]. *Astrophys. J.*, **302**, 650 – 655.

Schramm, D. N., Steigman, G. & Dearborn, D. S. P., 1990. [Main-sequence mass loss and the lithium dip]. *Astrophys. J.*, **359**, L55 - L58.

Richard, O., Michaud, G. & Richer, J., 2005. [Implications of *WMAP* observations on Li abundance and stellar evolution models]. *Astrophys. J.*, **619**, 538 – 548.

Korn, A. J., Grundahl, F., Richard, O., Barklem, P. S., Mashonkina, L., Collet, R., Piskunov, N. & Gustafsson, B., 2006. [A probable stellar solution to the cosmological lithium discrepancy]. *Nature*, **442**, 657 – 659.

7. Effects of mass loss on stellar evolution

Chiosi, C. & Maeder, A., 1986. [The evolution of massive stars with mass loss]. *Annu. Rev. Astron. Astrophys.*, **24**, 329 – 375.

Langer, N., 1989. [Mass-dependent mass loss rates of Wolf-Rayet stars]. *Astron. Astrophys.*, **220**, 135 – 143.

Willson, L. A., 2000. [Mass loss from cool stars: impact on the evolution of stars and stellar populations]. *Annu. Rev. Astron. Astrophys.*, **38**, 573 – 611.

8. The red-giant bump

Christensen-Dalsgaard, J., 2015. [On the red-giant luminosity bump]. *Mon. Not. R. astr. Soc.*, **453**, 666 – 670.

Salaris, M., Cassisi, S. & Weiss, A., 2002. [Red giant branch stars: the theoretical framework]. *Publ. Astron. Soc. Pacific*, **114**, 375 – 402.

Cassisi, S. & Salaris, M., 1997. [A critical investigation on the discrepancy between the observational and the theoretical red giant luminosity 'bump']. *Mon. Not. R. astr. Soc.*, **285**, 593 – 603.

Bono, G., Cassisi, S., Zoccali, M. & Piotto, G., 2001. [Star counts across the red giant branch bump and below]. *Astrophys. J.*, **546**, L109 – L113.

Nataf, D. M., 2014. [Red giant branch bump star counts and stellar models]. *Mon. Not. R. astr. Soc.*, **445**, 3839 – 3847.

9. Evolution through and after the helium flash

Serenelli, A. & Weiss, A., 2005. [On constructing horizontal branch models]. *Astron. Astrophys.*, **442**, 1041 – 1048.

Asplund, M., Gustafsson, B., Lambert, D. L. & Rao, N. K., 1997. [A stellar endgame – the born-again Sakurai's object]. *Astron. Astrophys.*, **321**, L17 – L20.

Schlattl, H., Cassisi, S., Salaris, M. & Weiss, A., 2001. [On the helium flash in low-mass population III red giant stars]. *Astrophys. J.*, **559**, 1082 – 1093.

Cassisi, S., Schlattl, H., Salaris, M. & Weiss, A., 2003. [First full evolutionary computation of the helium flash-induced mixing in Population II stars]. *Astrophys. J.*, **582**, L43 – L46.

10. Effects of convective overshoot on stellar evolution

Maeder, A., 1975. [Stellar evolution III: the overshooting from convective cores]. *Astron. Astrophys.*, **40**, 303 – 310.

Zahn, J.-P., 1991. [Convective penetration in stellar interiors]. *Astron. Astrophys.*, **252**, 179 – 188.

Schröder, K.-P., Pols, O. R. & Eggleton, P. P., 1997. [A critical test of stellar evolution and convective core 'overshooting' by means of ζ Aurigae systems]. *Mon. Not. R. astr. Soc.*, **285**, 696 – 710.

VandenBerg, D. A. & Stetson, P. B., 2004. [On the old open clusters M67 and NGC 188: convective core overshooting, color-temperature relations, distances and ages]. *Publ. Astron. Soc. Pacific*, **116**, 997 – 1011.

Herwig, F., 2000. [The evolution of AGB stars with convective overshoot]. *Astron. Astrophys.*, **360**, 952 – 968.

Cordier, D., Lebreton, Y., Goupil, M.-J., Lejeune, T., Beaulieu, J.-P. & Arenou, F., 2002. [Convective core mixing: A metallicity dependence?]. *Astron. Astrophys.*, **392**, 169 – 180.

11. Evolution of thermally pulsing AGB stars and neutron-capture nucleosynthesis

Iben, I. & Renzini, A., 1983. [Asymptotic giant branch evolution and beyond]. *Annu. Rev. Astron. Astrophys.*, **21**, 271 – 342.

Herwig, F., 2005. [Evolution of asymptotic giant branch stars]. *Annu. Rev. Astron. Astrophys.*, **43**, 435 – 479.

Yoon, S.-C., Langer, N. & van der Sluys, M., 2004. [On the stability of thermonuclear shell sources in stars]. *Astron. Astrophys.*, **425**, 207 – 216.

Straniero, O., Chieffi, A., Limongi, M., Busso, M., Gallino, R. & Arlandi, C., 1997. [Evolution and nucleosynthesis in low-mass asymptotic giant branch stars. I. Formation of Population I carbon stars]. *Astrophys. J.*, **478**, 332 – 339.

Stancliffe, R. J., Tout, C. A. & Pols, O. R., 2004. [Deep dredge-up in intermediate-mass thermally pulsing asymptotic giant branch stars]. *Mon. Not. R. astr. Soc.*, **352**, 984 – 992.

12. Evolution of close multiple stars

Iben, I., 1985. [The life and times of an intermediate mass star - in isolation/in a close binary]. *Q. Jl. Roy. astr. Soc.*, **26**, 1 – 39.

Iben, I. & Tutukov, A. V., 1984. [Supernovae of Type I as end products of the evolution of binaries with components of moderate initial mass ($M \lesssim 9\ M_\odot$)]. *Astrophys. J. Suppl.*, **54**, 335 – 372.

Iben, I. & Tutukov, A. V., 1985. [On the evolution of close binaries with components of initial mass between 3 $M_\odot$ and 12 $M_\odot$]. *Astrophys. J. Suppl.*, **58**, 661 – 710.

Iben, I. & Tutukov, A. V., 1999. [On the evolution of close triple stars that produce Type Ia supernovae]. *Astrophys. J.*, **511**, 324 – 334.

Perets, H. B. & Fabrycky, D. C., 2009. [On the triple origin of blue stragglers]. *Astrophys. J.*, **697**, 1048 – 1056.

13. Evolution of rotating stars

Maeder, A. & Meynet, G., 2000. [The evolution of rotating stars]. *Annu. Rev. Astron. Astrophys.*, **38**, 143 – 190.

Meynet, G. & Maeder, A., 2000. [Stellar evolution with rotation. V. Changes in all the outputs of massive star models]. *Astron. Astrophys.*, **361**, 101 – 120.

Maeder, A., 2002. [Stellar evolution with rotation IX: The effects of the production of asymmetric nebulae on the internal evolution]. *Astron. Astrophys.*, **392**, 575 – 584.

Palacios, A., Talon, S., Charbonnel, C. & Forestini, M., 2003. [Rotational mixing in low-mass stars. I. Effect of the μ-gradients in main sequence and subgiant Pop I stars]. *Astron. Astrophys.*, **399**, 603 – 616.

Palacios, A., Charbonnel, C., Talon, S. & Siess, L., 2006. [Rotational mixing in low-mass stars. II. Self-consistent models of Pop II RGB stars]. *Astron. Astrophys.*, **453**, 261 – 278.

14. Blue loops and helium burning

Xu, H. Y. & Li, Y., 2004. [Blue loops of intermediate mass stars. I. CNO cycles and blue loops]. *Astron. Astrophys.*, **418**, 213 – 224.

Xu, H. Y. & Li, Y., 2004. [Blue loops of intermediate mass stars. II. Metallicity and blue loops]. *Astron. Astrophys.*, **418**, 225 – 233.

Ventura, P. & Castellani, M., 2005. [Time dependent mixing in He-burning cores: The case of NGC 1866]. *Astron. Astrophys.*, **430**, 1035 – 1047.

This is a topic where experiments with MESA could be particularly interesting.

15. ONe white dwarfs

García-Berro, E., Ritossa, C. & Iben, I., 1997. [On the evolution of stars that form electron-degenerate cores processed by carbon burning. III. The inward propagation of a carbon-burning flame and other properties of a $9M_{\odot}$ model star]. *Astrophys. J.*, **485**, 765 – 784.

Gil-Pons, P., Garcia-Berro, E., José, J., Hernanz, M. & Truran, J. W., 2003. [The frequency of occurrence of novae hosting an ONe white dwarf]. *Astron. Astrophys.*, **407**, 1021 – 1028.

Gutiérrez, J., Canal, R. & García-Berro, E., 2005. [The gravitational collapse of ONe electron-degenerate cores and white dwarfs: The role of ^{24}Mg and ^{12}C revisited]. *Astron. Astrophys.*, **435**, 231 – 237.

16. Thermohaline mixing and the abundance of ^{3}He in the Universe

Eggleton, P. P., Dearborn, D. S. P. & Lattanzio, J. C., 2006. [Deep mixing of ^{3}He: reconciling Big Bang and stellar nucleosynthesis]. *Science*, **314**, 1580 – 1583.

Charbonnel, C. & Zahn, J.-P., 2007. [Thermohaline mixing: a physical mechanism governing the photospheric composition of low-mass stars]. *Astron. Astrophys.*, **467**, L15 – L18.

Charbonnel, C. & Zahn, J.-P., 2007. [Inhibition of thermohaline mixing by a magnetic field in Ap star descendants: implication for the Galactic evolution of ^{3}He]. *Astron. Astrophys.*, **476**, L29 – L32.

Cantiello, M. & Langer, N., 2009. [Thermohaline mixing in evolved low-mass stars]. *Astron. Astrophys.*, **521**, A9-(1 – 10).

17. Three-dimensional simulations of core helium flash

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Dearborn, D. S. P., Lattanzio, J. C. & Eggleton, P. P., 2006. [Three-dimensional numerical experimentation on the core helium flash of low-mass red giants]. *Astrophys. J.*, **639**, 405 – 415.

Mocák, M., Müller, E., Weiss, A. & Kifonidis, K., 2008. [The core helium flash revisited. I. One and two-dimensional hydrodynamical simulations]. *Astron. Astrophys.*, **490**, 265 – 277.

Mocák, M., Müller, E., Weiss, A. & Kifonidis, K., 2009. [The core helium flash revisited. II. Two and three-dimensional hydrodynamical simulations]. *Astron. Astrophys.*, **501**, 659 – 677.

Mocák, M., Campbell, S. W., Müller, E. & Kifonidis, K., 2010. [The core helium flash revisited. III. From Population I to Population III stars]. *Astron. Astrophys.*, **520**, A114-(1 – 15).

18. Problems with the solar composition and solar modelling

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Bahcall, J. N., Basu, S., Pinsonneault, M. & Serenelli, A. M., 2005. [Helioseismological implications of recent solar abundance determinations]. *Astrophys. J.*, **618**, 1049 – 1056.

Bahcall, J. N., Serenelli, A. M. & Basu, S., 2005. [New solar opacities, abundances, helioseismology, and neutrino fluxes]. *Astrophys. J.*, **621**, L85 – L88.

Bahcall, J. N., Basu, S. & Serenelli, A. M., 2005. [What is the neon abundance of the Sun?]. *Astrophys. J.*, **631**, 1281 – 1285.

Guzik, J. A. & Mussack, K., 2010. [Exploring mass loss, low-Z accretion, and convective overshoot models to mitigate the solar abundance problem]. *Astrophys. J.*, **713**, 1108 – 1119.

Christensen-Dalsgaard, J., Di Mauro, M. P., Houdek, G. & Pijpers, F., 2009. [On the opacity change required to compensate for the revised solar composition]. *Astron. Astrophys.*, **494**, 205 – 208.

19. MESA modelling of red-giant and helium-burning stars

Use the MESA code to investigate the evolution of stars up the red-giant branch, through helium ignition and to the end of central helium burning. Stars over a range of masses, e.g., between 1 and $3\,M_\odot$, should be considered, including possibly both normal ($X = 0.7, Z = 0.02$) and metal-poor ($X = 0.74, Z = 0.001$) compositions. Possible topics (I do not expect you to cover all of these!) are the validity of the shell-burning homology scaling laws, the properties of the red-giant bump, the mass of the helium core at helium ignition, and the evolution of the convective core during helium burning. You can perhaps get some inspiration from this review:

Salaris, M., Cassisi, S. & Weiss, A., 2002. [Red giant branch stars: the theoretical framework]. *Publ. Astron. Soc. Pacific*, **114**, 375 – 402.

20. Properties of evolving stars, from numerical models

At `http://owww.phys.au.dk/~jcd/emdl94/eff_v6` extensive tables of stellar-model properties are provided. The proposed project is to analyse some of these results, comparing them with what we have discussed about stellar evolution, making suitable plots, etc. The quantities provided are 'global' quantities, as opposed to the detailed variations of relevant quantities as functions of position in the star. Some further data on selected models can be made available, on (well-reasoned) request.