Stellar Evolution at low Metallicity: Mass Loss, Eplosions, Cosmology
ASP Conference Series, Vol. 353, 2006
Henny J.G.L.M. Lamers, Norbert Langer, Tiit Nugis, Kalju Annuk

The role of non-gray model atmospheres in the evolution of low mass metal poor stars.

G. J. Harris, A. E. Lynas-Gray, J. Tennyson, and S. Miller.

University College London, UK.

Abstract. Gray model atmospheres are generally considered a reasonable approximation to make upon stars of mass greater than about 0.6 $M_\odot$. Here we show that non-gray atmospheres can significantly affect evolutionary models, with masses up to 0.9 $M_\odot$. The effect of including a non-gray atmosphere is strongest in the pre-main and post-main Sequence. This may have implications for the ages of the oldest globular clusters.

1. Introduction.

Stars with masses below about 0.85 $M_\odot$ have Main Sequence lifetimes in excess of 10 GYr. Many stars which have metallicity, colors and kinematics that suggest an age greater than 10 GYr have been observed. Numbered among these stars are the stars in old globular clusters, such as M 68, as well as isolated stars such as HE0107-5240 (Christlieb et al. 2002). Not only do these stars provide us with a means to study stellar evolution at low and very low metallicity, but they also allow a stellar estimates for formation timescales of the Galaxy and a lower age limit of the Universe.

The most accurate age estimates for metal poor stars is achieved by means of the fitting of theoretical isochrones to observed color magnitude diagrams (CMD). The accuracy of these fits is dependent upon the accuracy of the physics of the stellar models used to compute the isochrones. One potential avenues for the improvement of the modeling of stellar evolution lies in the atmosphere, the model atmosphere provides boundary conditions for the equations of stellar structure. Current low to intermediate mass stellar evolution models (Cariulo et al. 2004; Kim et al. 2002) in general use gray model atmospheres. However, Saumon et al. (1994), and later Baraffe & Chabrier (1996) Baraffe et al. (1997) and Chabrier & Baraffe (1997), performed stellar evolution computations using non-gray atmospheres. These works clearly demonstrate that the gray approximation is invalid for T_{ef} <5000 K, which corresponds to 0.8 or 0.6 $M_\odot$ depending upon metallicity. In this work we show that using non-gray models has a significant effect upon the effective temperature and luminosity of low metallicity model stars of 0.9 $M_\odot$ both undergoing pre-Main Sequence collapse and on the red giant branch.

2. Stellar evolution.

We have recently developed a stellar evolution code which makes use of a non-gray model atmosphere to provide the boundary conditions for the equations of stellar structure. This code is based upon the stellar evolution code CESAM

(Morel 1997), for which new opacity and equation of state subroutines have been written and a non-gray model atmosphere added. CESAM is a 1D low and intermediate mass stellar evolution code, which is capable of computing evolution for pre-Main Sequence to the Helium flash. The non-gray model atmosphere code which is used is based upon MARCS (Gustafsson et al. 1975), for which, again, new equation of state and opacity subroutines have been written. The resulting code we refer to as NG-ELMS.

2.1. Atmospheric equation of state and opacity.

The computation of a non-gray model atmosphere requires a monochromatic opacity. In turn to compute opacity it is essential to know the chemical and ionic composition of the gas. We have developed a new equation of state which we refer to as LoMES to model low metallicity gases, currently the equation of state accounts for 15 elements H, He, Li, C, N, O, Ne, Na, Mg, Al, Si, S, Ca, Ti, Fe and electrons. The first 2 ionization states and cations are considered for each metal. In total LoMES computes the number densities of 136 ions, atoms and molecules, which are all listed in table 1. Due to the temperature limitation of the molecular partition functions used by LoMES, LoMES is able to solve chemical equilibrium between 1000 and 10 000 K. LoMES has been successfully used to compute opacities for zero metallicity stars (Harris et al. 2004a) and helium rich white dwarfs (Harris et al. 2004b).

Table 1. The molecular, atomic, and ionic species accounted for in LoMES.

e^-	H_2	H	H^+	H^-	H_2^+	H_2^-	H_3^+	He
He^+	HeH^+	Li	Li+	Li^-	Li^{++}	C	C^+	C^-
C^{++}	N	N^+	N^-	N^{++}	O	O^+	O^-	O^{++}
Ne	Ne^+	Ne^-	Ne^{++}	Na	Na^+	Na^-	Na^{++}	Mg
Mg^+	Mg^-	Mg^{++}	Al	Al^+	Al^-	Al^{++}	Si	Si^+
Si^-	Si^{++}	S	S^+	S^-	S^{++}	Ca	Ca^+	Ca^-
Ca^{++}	Ti	Ti^+	Ti^-	Ti^{++}	Fe	Fe^+	Fe^-	Fe^{++}
CO	CO^+	CN	CN^+	C_2	C_2^+	CH	CH^+	OH
OH^+	NH	NH^+	NO	NO^+	O_2	O_2^+	N_2	N_2^+
CS	TiO	MgH	MgH^+	SiH	SiH^+	FeH	MgO	AlO
SiO	SiO^+	SO	SO^+	CaO	CaO^+	FeO	NaH	AlH
AlH^+	HS	HS^+	CaH	SiS	S_2	S_2^+	NS	NS^+
TiS	MgS	Al_2	Si_2	TiN	Na_2	LiH	HCN	H_20
CO_2	CH_4	C_2H_2	C_3	NH_3	$Fe(OH)_2$	SiH_4	SiC_2	Si_2C
MgOH	$Mg(OH)_2$	H_2S	Al_2O	AlOH	$Ca(OH)_2$	CaOH	NaCN	NaOH
TiO_2								

Many of the species in table 1 are directly and indirectly important in the computation of opacity. For example H^- is often the dominant source of continuous opacity, whilst molecules such as H_2O, TiO and HCN make extremely important contributions to opacity via their line absorption. Other species such as H_3^+ and HeH^+ are important electron donors at low metallicity, thereby indirectly affect opacity. We refer to our low metallicity opacity subroutine as LoMO. LoMO accounts for H, H^-, He, He^+ and H_2^+ bound-free continuous absorption, H, H^-, He, He^-, He^+, H_2^- and H_2^+ free-free absorption and H_2-He, H_2-H_2 and H-He collision induced absorption. LoMO also accounts for H_2, H and He Rayleigh scattering and Thomson scattering by electrons. Further details of the data used to account for these scattering and absorption processes can be found in Harris et al. (2004a). To account for molecular bands for each molecule a mean opacity is computed over a small frequency range and tabulated as a function of temperature and frequency, this allows the rapid computation of opacity at runtime. The approximation of using mean opacities is valid as molecular bands consist of many week lines which result in a near continuous opacity over the band. The molecular species for which we compute opacity tables are H_2O (Barber et al. in preparation), HCN (Harris, Polyansky, & Tennyson 2002), CO (Goorvitch 1994), CN (Jørgensen & Larsson 1990), CH (Jørgensen et al. 1996), TiO (Plez 1998), OH, NH (Kurucz et al. 1995) and FeH (Dulick et al. 2003).

2.2. Input physics.

The results of stellar evolution computations are dependent upon the input data. Our high temperature opacities are computed by interpolation upon the OPAL Rosseland mean opacity tables of Iglesias & Rogers (1996), the OPAL equation of state (Rogers & Nayfonov 2002) is used for high temperatures. For low temperatures ($>$ 9000 K) we use the data computed by LoMES and LoMO, at intermediate temperatures (9000–11 000 K) we interpolate between the OPAL data and the data from LoMES and LoMO. We use the NACRE (Angulo et al. 1999) compilation of nuclear reaction rates for temperatures below 50×10^6 K, and the Caughlan & Fowler (1988) rates for higher temperatures. Conductive opacity is computed by interpolating on the tables of Hubbard & Lampe (1969). Mixing length theory is used for convection.

3. Preliminary models.

Our preliminary models are non-rotating, with no element diffusion and are calculated in the mass range 0.7 to 0.9 $M_\odot$. In order to compare with the Y^2 models of Kim et al. (2002) we adopt a hydrogen mass fraction of X=0.76997 and a metal mass fraction of Z= 10^{-5}. Figure 1 shows a plot of our gray and the Y^2 0.8 $M_\odot$ models, we have used different values of the mixing length parameter in our calculations. The importance of the adopted value of the mixing length parameter is clear. Possible reasons for the other differences between our calculations and those of Y^2, are likely to be due in part to the lack of diffusion within our models and the differences in input physics. For the purposes of this work we adopt a value of α =2.0 for the mixing length parameter.

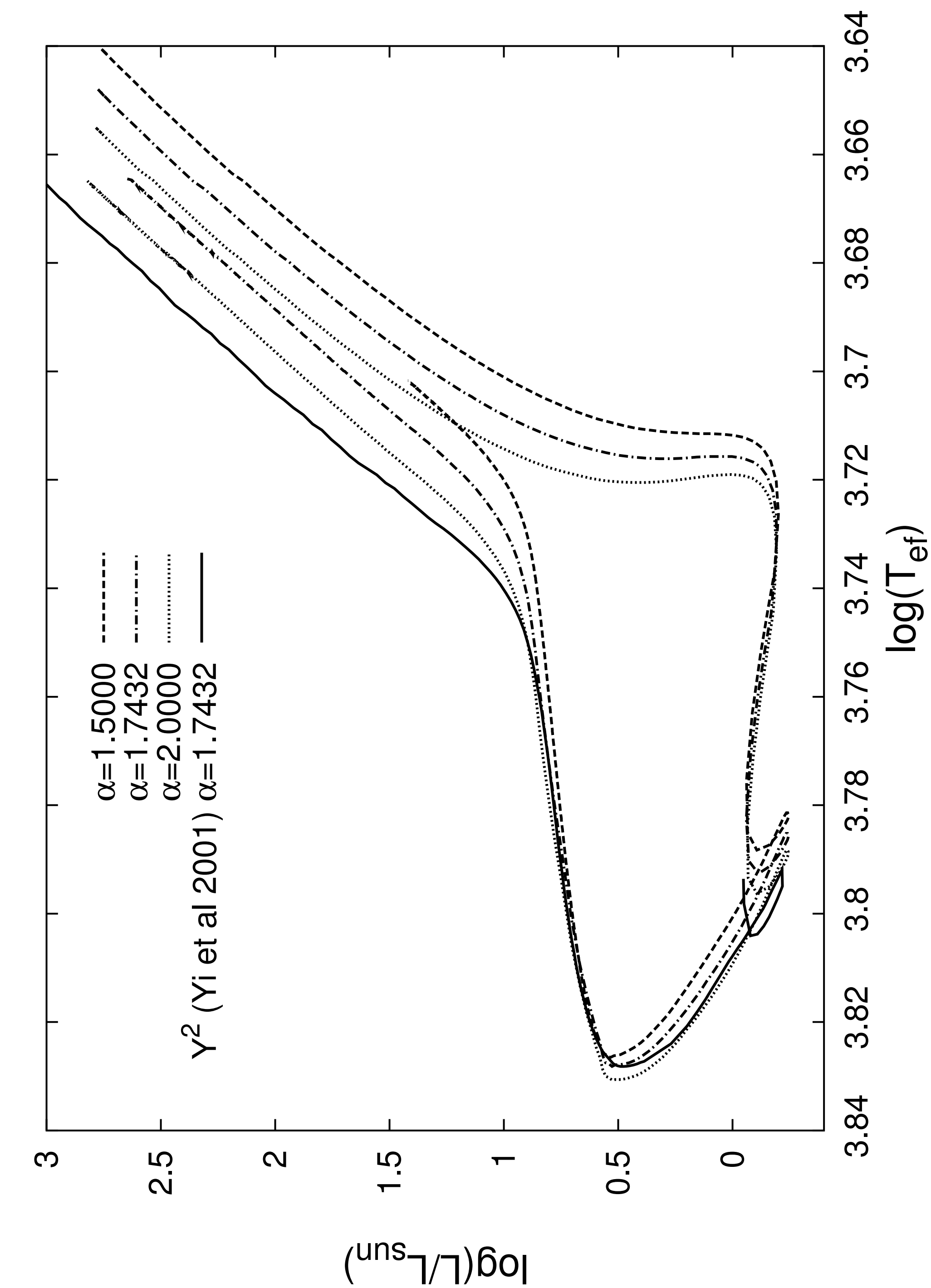

Figure 1. Stellar evolution tracks on the HR diagram, for the 0.8 $M_\odot$ model of Y^2 (Kim et al. 2002) and our gray models computed with values of the mixing length parameter of 1.5, 1.7432 and 2.0.

Figure 2 shows the evolutionary tracks on the HR diagram of stars of 0.7, 0.8 and 0.9 $M_\odot$, computed with gray and non-gray model atmospheres. The non-gray models show a significant difference in the gradient of the Hayashi track and the red giant branch. In general on the red giant branch non-gray models are cooler than gray models for a given luminosity. It is envisaged that this difference in effective temperature will result in different color magnitudes, and thus may have an effect upon the fitting of globular cluster CMDs.

The core hydrogen burning lifetimes of these models are given in table 2, we define the end of core hydrogen burning as the point at which the hydrogen mass fraction at the core falls below 10^{-5}. Overall the differences between the hydrogen burning lifetimes of the gray and non-gray models are small, but increase with decreasing mass, this indicates that the gray approximation has little effect upon main sequence evolution. The small effect of the non-gray atmosphere on the conditions in the core is supported by figure 3, which shows the evolution of the Central temperature and pressure. Along the main sequence there is no significant difference in central temperature and pressure between gray and non-gray models, however on the pre and post Main Sequence there are small differences in temperature between gray and non-gray models.

Table 2. Core hydrogen burning lifetimes for gray and non-gray models [Gyr].

M [$M_\odot$]	Gray	non-gray
0.7	21.305	21.393
0.8	13.260	13.257
0.9	8.738	8.739

4. Conclusion.

We present new low and high temperature equation of state and opacity subroutines. These subroutines have been incorporated with the non-gray stellar atmosphere code MARCS into the stellar evolution code CESAM to create a new stellar evolution code NG-ELMS. The non-gray atmosphere is used to provide the outer boundary conditions for the equations of stellar structure. NG-ELMS has been used to compute both gray and non-gray preliminary stellar evolution models with $Z = 10^{-5}$ and with masses between 0.7 and 0.9 $M_\odot$.

Acknowledgments. We thank Bob Barber for providing us with his water linelist prior to publication, and Prof. B. Gustafsson and Dr. P. Morel for making available versions of MARCS and CESAM. The UK Particle Physics and Astronomy Research Council (PPARC) is thanked for financial support.

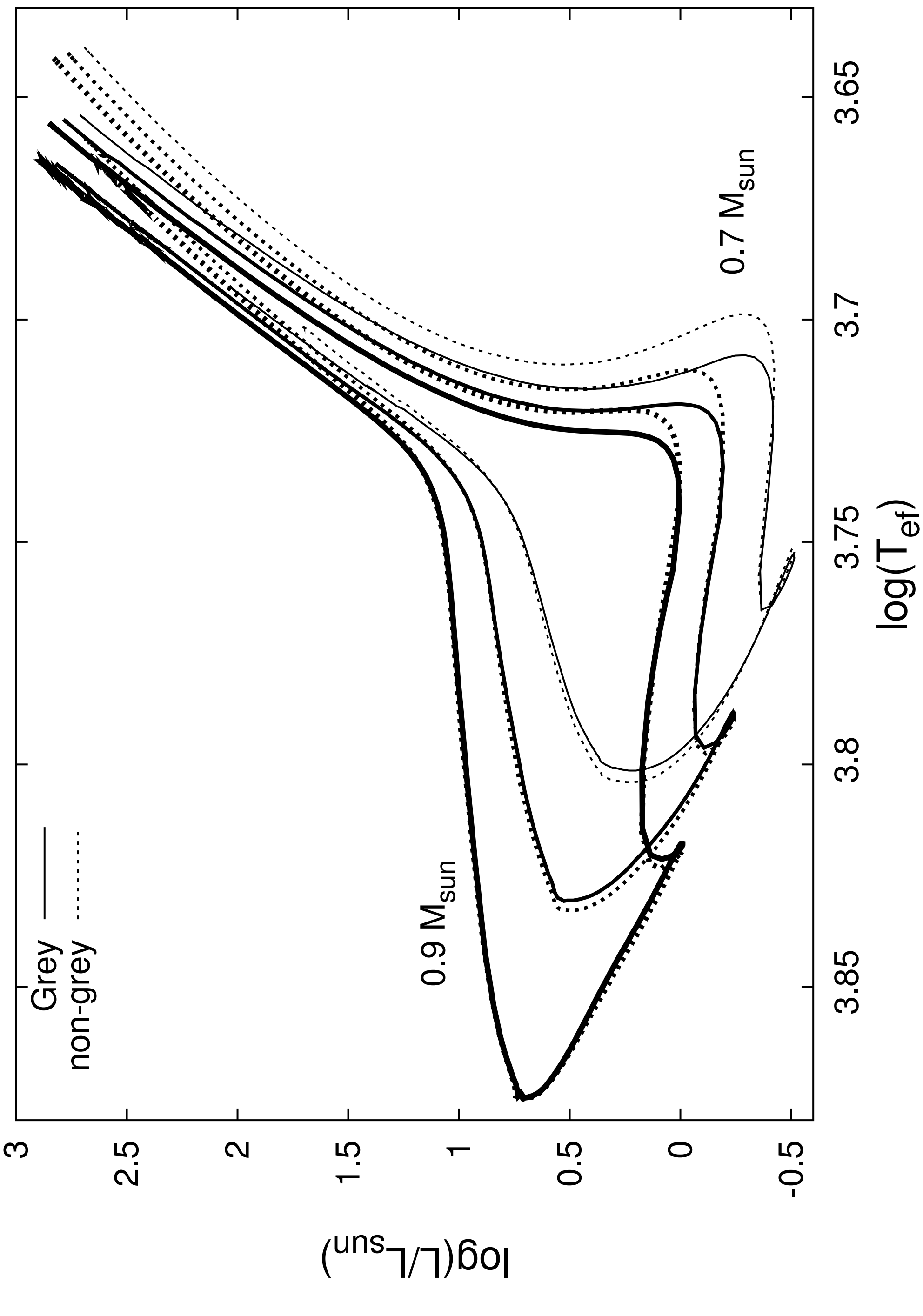

Figure 2. Stellar evolution tracks on the HR diagram, for both gray and non-gray models of 0.7, 0.8 and 0.9 $M_{\odot}$.

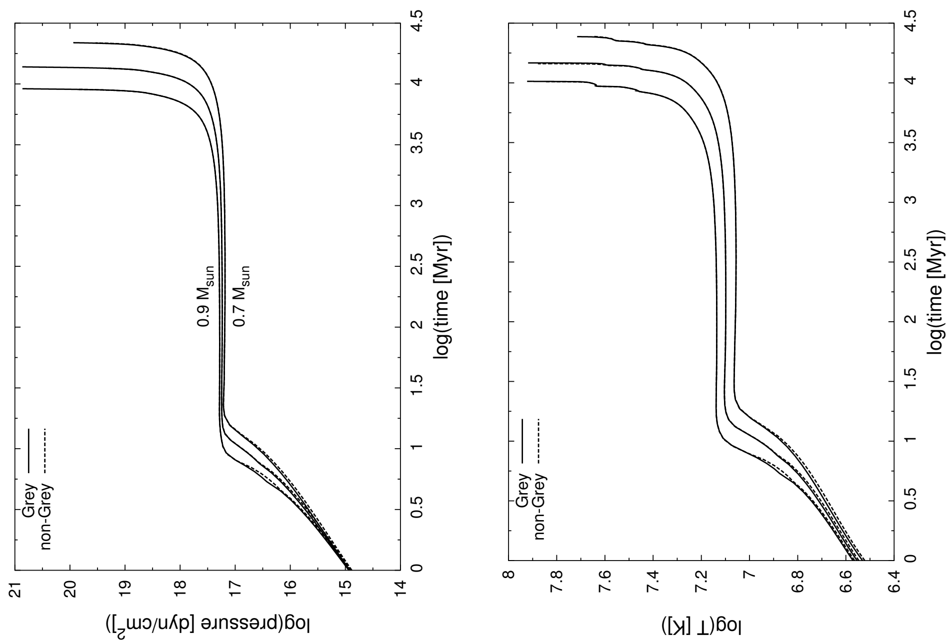

Figure 3. Evolution of the central temperature and pressure, for both gray and non-gray models of 0.7, 0.8 and 0.9 $M_{\odot}$.

References

Angulo, C., Arnould, M., Rayet, M., et al., 1999, Nuclear Physics A, 656, 3.

Baraffe, I., & Chabrier, G., 1996, in from stars to galaxies, eds. C. Leitherer, U. Fritze-von-Alversleben, & J. Huchra (ASP conference series) vol. 98, P. 209

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P., 1997, A&A, 327,1054.

Cariulo, P., Degl'Innocenti, S., & Castellani, V., 2004, A&A, 421, 1121.

Caughlan, G. R., & Fowler, W. A., 1988, Atomic Data and Nuclear Data Tables, 40, 283.

Chabrier, G., Baraffem I., 1997, A&A 327, 1039.

Christlieb, N., Bessell, M. S., & Beers, T. C., *et al.*, 2002, Nature, 419, 904.

Dulick, M., Bauschlicher, C. W., Jr., Burrows, A., Sharp, C. M., Ram, R. S., & Bernath, P., 2003, ApJ, 594, 651.

Goorvitch D., 1994, ApJS, 95, 535.

Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, Å., 1975, A&A, 42, 407

Harris, G. J., Polyansky O. L., & Tennyson J., 2002, ApJ, 578, 657

Harris, G. J., Lynas-Gray, A. E., Miller, S., & Tennyson, J., 2004a, ApJ, 600, 1025

Harris, G. J., Lynas-Gray, A. E., Miller, S., & Tennyson, J., 2004b, ApJ, 617, L143.

Hubbard, W. B., & Lampe, M., 1969, ApJS, 18, 297.

Iglesias, C. A. and Rogers, F. R., 1996, ApJ, 464, 943.

Jørgensen, U. G., & Larsson, M., A& A, 238, 424.

Jørgensen, U. G., Larsson, M., Iwamae, A., & Yu, B., 1996, A& A, 315, 204.

Kim, YC., Demarque, P., Yi, S. K., & Alexander D.R., 2002, ApJS, 143, 499.

Kurucz, R. L., 1995, in Laboratory & astronomical high resolution spectra, eds. A. J. Sauval, R. Blomme, & Grevesse (ASP Conference series) vol. 81, p. 583.

Morel, P., 1997, A& ASS, 124, 597.

Plez, B, 1998, A& A, 337, 495.

Rogers, F. J., & Nayfonov, A., 2002, ApJ, 576, 1064.
Saumon, D., Bergeron, B., Lunine, J. I, Hubbard, W. B., & Burrows, A., 1994, ApJ, 424, 333

Discussion

Maeder: Could you use the electron densities you are obtaining to also improve the calculation of the screening factors for nuclear reactions in low mass stars?

Harris: Our new equation of state is computed only for low temperatures ($T < 11\,000$ K). It therefore has no effect upon the interior high temperature regions, for which we use the OPAL equation of state.

Gustafsson: You demonstrate clearly that the effects of a non-grey treatment are important for the real giant stage. But, are not the uncertainties in convection even more significant there? Also, one may speculate that a proper treatment of convection, with 3D HD and radiative transfer would further increase the effects of non-greyness.

Harris: Yes, the uncertainties in mixing length theory are large. As we show by changing the mixing length parameter. However, accounting for non-grey effects changes the gradient of the red giant branch on the HR diagram, using different values of the mixing length parameter changes the position but not the gradient. A proper treatment of convection is still highly desirable.

Gregory Harris