

THEORY OF STELLAR STRUCTURE AND EVOLUTION

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The theory of stellar structure and evolution is the oldest research field of the Padova group that goes back to the sixties of the past century. It has always been a very lively area in which the Padova group has reached important achievements world widely recognized. At the present studies in the following areas are carried on.

(1) Theory of thermally pulsing AGB stars

During the past years particular care has been devoted to study in detail the structure and evolution of thermally pulsing AGB stars up to the planetary nebula stage. They bear very much on a number of problems going from the correct luminosity function of Carbon stars in galaxies of the Local Group, to the interpretation of the Color-Magnitudes Diagrams of cool stars in external galaxies, to the chemical enrichment of the interstellar medium.

(2) The Planetary Nebulae Luminosity Function

The luminosity function of Planetary Nebulae which is observationally known not to change with the galaxy type is currently used as a distance indicator as far as the Virgo Cluster. The theoretical understanding of it is not yet firmly grounded. We have addressed the issue showing that it can be used as distance indicator only in galaxies with ongoing star formation (spirals, irregulars) whereas in galaxies like elliptical in which star formation is extinguished since long time, it can be used as age indicator of the last star forming episode. Studies are currently being aimed at understanding whether an important yet exotic type of stars existing in elliptical and missing in our theory could restore the nature of distance indicator of the luminosity function even in this type of galaxies.

(3) Theoretical isochrones in many photometric systems

The unprecedented flow of observational data from ground-based and space instrumentation requires that the theoretical counterpart for stellar properties (magnitudes and colors) keep the same pace providing those properties in the many photometric system currently in use. Continuing a long tradition of the Padova group is the aim of these studies.

(4) Stellar models with enhanced alpha-elements

The abundance ratios $[O/Fe]$...of the so-called alpha elements in low metallicity stars (and in oldest stellar populations of galaxies early-type in particular) differ from those in the Sun. Therefore it is important to investigate how stellar models with the same total metallicity but different abundance ratios (otherwise known as alpha-enhanced patterns) would evolve with respect to the standard ones. Models of this type are sparse and often limited to narrow ranges of initial masses. In this project we generated accurate grids of stellar models over wide ranges of initial masses and chemical parameters at given alpha-enhancement (as suggested by observational data).

(5) Observational tests of convective mixing

It has been long known that the classical Schwarzschild criterium to determine the extension of convective regions in stellar interiors is not physically correct as it neglects that convective elements accelerated by the buoyancy forces have to cross the Schwarzschild border penetrating into radiative region to dissipate their kinetic energy. How far they can go and how they modify the thermodynamical structure of a star in these regions is not clearly understood and the same has long been the subject of vivid debate to which the Padova group has much contributed. If the convective regions are indeed larger than predicted by a simple theory there should be a number of consequences (already known) that should affect the observational properties of the stars. The

project we have recently undertaken is along a line of thought developed over the years and it aims to address the question both from theoretical and observational points of view.

(6) Primordial Stars

The zero metallicity stars are the first objects ever formed in the Universe. Owing to the many implications, much interest toward these object has being boosted by novel data at high redshift in relation to the formation of the first baryonic structures. We have presented modern evolutionary models for primordial stars in presence of rotation and mass loss by stellar wind all over the entire mass range from low to high mass. With aid of these results we have predicted some possible effect on the very initial chemical enrichment and the possible existence of a novel type of low mass pulsators, the analogues of the δ Scuti stars at zero metallicity.

(7) Structure and evolution of White Dwarfs with under-barrier nuclear reactions

Thanks to recent advancements in the theory of under-barrier and piono-nuclear reaction we explore the possibility that WDs after cooling down to the stage at which they pass from liquid to solid regimes may actually undergo under-barrier reactions whose implications may go from simply slowing down the cooling rate, to restructuring the star into a non degenerate object to even full explosion. The project intends to explore these possibilities.

(8) The Padova databases of stellar tracks, isochrones and Single Stellar Populations

The Padova database of stellar tracks, isochrones and Single Stellar Populations has long been recognized as the largest set of this type of theoretical data whose best exploitation is the interpretation of spectrophotometric properties of stellar assemblies of different complexity from clusters to galaxies. The database is continuously updated by extending and improving the stored grids of models, isochrones and Single Stellar Populations.

For each project we report on recent achievements and when appropriate we shortly summarize the scientific rationale and outline the future plans.

Project 1: THEORY OF THERMALLY PULSING AGB STARS

(1) Marigo P. *Asymptotic Giant Branch evolution at varying surface C/O ratio: effects of changes in molecular opacities.* (2002). *Astronomy and Astrophysics*, vol.387, pp. 507-519

We investigate the effects of molecular opacities on the evolution of TP-AGB stars that experience the third dredge-up, i.e. with surface abundances of carbon and oxygen varying with time. To this aim, a routine is constructed to derive the molecular concentrations through dissociation equilibrium calculations, and estimate the opacities due to H_2 , H_2O , OH , C_2 , CN , and CO for any given density, temperature and chemical composition of the gas. Then, synthetic TP-AGB models with dredge-up are calculated by either adopting the newly developed routine, or interpolating between fixed opacity tables for solar chemical composition. The comparison between the two cases shows that the change in the dominant opacity sources, as the C/O ratio grows from below to above unity, crucially affects the evolution of the effective temperature, i.e. causing a notable cooling of the carbon-rich models (with $C/O > 1$). From the comparison with observational data, it turns out that TP-AGB models with variable molecular opacities are able to reproduce the observed range of effective temperatures, mass-loss rates, and wind expansion velocities of C-type giants in the solar neighbourhood, otherwise failed if assuming fixed molecular opacities for solar-scaled mixtures. Finally, we mention other possibly important evolutionary and observational effects that result from the adoption of the variable opacities, such as: i) significant shortening of the C-star phase due to the earlier onset of the super-wind; ii) consequent reduction of the carbon yields iii) reproduction of the observed range of near-infrared colours of C-stars.

(2) Marigo P. *A unified formalism for the core mass-luminosity relations of shell-burning stars.* (2000). *Astronomy and Astrophysics*, Vol. 360, pp. 617-626

The luminosity evolution of stars with highly condensed cores surrounded by nuclear-burning shell(s) is analytically investigated with the aid of homology relations. With respect to earlier works using a similar approach (e.g. Refsdal & Weigert 1970; Kippenhahn 1981), the major improvement is that we derive all the basic dependences (i.e. on core mass, core radius, and chemical composition) in a completely generalised fashion, then accounting for a large range of possible physical properties characterising the burning shell(s). Parameterised formulas for the luminosity are given as a function of the (i) relative contribution of the gas to the total pressure (gas plus radiation), (ii) opacity source, and (iii) dominant nuclear reaction rates. In this way, the same formalism can be applied to shell-burning stars of various metallicities and in different evolutionary phases. In particular, we present some applications concerning the luminosity evolution of RGB and AGB stars with different chemical compositions, including the case of initial zero metallicity. It turns out that homology predictions provide a good approximation to the results of stellar model calculations. Therefore, the proposed formalism is useful to understand the possible differences in the luminosity evolution of shell-burning stars within a unified interpretative framework, and can be as well adopted to improve the analytical description of stellar properties in synthetic models.

Future Plans

The calculation of the TP-AGB phase by means of complete evolutionary codes is very demanding in terms of computational time, and in most cases it fails to predict basic observational facts such as the conversion from M to C spectral types in low-mass AGB stars, and the chemical properties of planetary nebulae. Such difficulties derive from the complex structure of these stars, as well as the uncertainties in the modelling of convective dredge-up and mass-loss process. In order to provide extended grids of TP-AGB models, the only viable alternative is the use of the so-called synthetic codes, in which the stellar evolution is described by means of simplified relations derived from complete stellar models, while convective dredge-up and mass-loss are described by means of a few free parameters.

A very detailed code for the synthetic evolution of TP-AGB stars has been developed by Marigo et al. (1996, 1998), Marigo (2000 and references therein). It couples the use of updated analytical relations (e.g. the core mass-luminosity relation, the interpulse duration), with a parametric description of the third dredge-up episodes, and numerical integrations of a complete envelope model. Over the last years, several additional improvements have been obtained, namely: a consistent method for dealing with the over-luminosity effect caused by hydrogen burning at the bottom of the convective envelope (hot-bottom burning; see Marigo 1998); the adoption of more physically-sound dredge-up parameters, linked to the post-flash effective temperature at the bottom of the convective envelope. The two free parameters associated with the possible occurrence and the efficiency of the third dredge-up were calibrated by fitting the carbon stars luminosity functions in both Magellanic Clouds (Marigo et al. 1999).

Recently, Marigo (2002) called attention to the importance of considering molecular opacities consistently coupled to the current CNO abundances in the envelope, instead of the usually-assumed solar-scaled ones. The introduction of variable molecular opacities has produced a remarkable impact on carbon star models (with surface C/O ratio larger than unity), leading to cooler Teffs (hence redder NIR colours), shorter lifetimes, reduced mean C/O ratios. All these aspects that allow for a better agreement between models and observations. It is worth remarking that so far Marigo's AGB models are the only ones in the literature that include variable molecular opacities.

To cope with the effect of the new molecular opacities, it will be necessary to re-calibrate the dredge-up and mass-loss parameters, using the available data for the C-stars luminosity functions in the LMC, SMC and the Galaxy, (Costa & Frogel 1996; Kunkel et al. 2000; Bergeat et al 2002) and C-stars in LMC clusters (Frogel et al. 1990). This procedure will ensure that the model lifetimes and luminosities are reasonably well described, as well as their dependences on age and metallicity.

The revision and update of the synthetic TP-AGB code will involve the careful consideration of the following aspects: (1) The efficiency of the third dredge-up and its dependence on mass and metallicity, as recently derived by Karakas et al. (2002) on the base of full evolutionary calculations of the TP-AGB phase. (2) The pulsation properties of AGB models in terms of theoretical P-M-R relations and their dependence on the pulsation mode. In particular, with the aid of available pulsation models for long-period variables (e.g. Ostlie & Cox 1986), we will predict the switch from the second to the first overtone and then to fundamental mode during the AGB evolution. (3) The mass loss efficiency and its dependence on pulsation properties (periods) and chemical type. The transition between different pulsation modes, as mentioned in (2), will impact on the predicted mass-loss rates, given their observed positive correlation with the pulsation period (e.g. Vassiliadis & Wood 1993). Moreover, we will investigate the sensitiveness of mass loss on chemical properties of AGB stars, by adopting different descriptions of dust-driven superwinds in AGB models with oxygen-rich (e.g. Willson 2000) or carbon-rich surface composition (e.g. Wachter et al. 2002).

Project 2: THE PLANETARY NEBULAE LUMINOSITY FUNCTION

(1) Marigo P., Girardi L., Weiss A., Groenewegen M.A.T., Chiosi C. *Evolution of planetary nebulae. II. Population effects on the bright cut-off of the PNLF.* (2004). *Astronomy and Astrophysics*, vol. 423, pp. 995-1015

We investigate the bright cut-off of the [OIII 5007] planetary nebula luminosity function (PNLF), that has been suggested as a powerful extragalactic distance indicator in virtue of its observed invariance against populations effects. Theoretical PNLFs are constructed via Monte-Carlo simulations of populations of PNe, whose individual properties are described with the aid of recent PN synthetic models (Marigo et al. 2001, *A&A*, 378, 958), coupled to a detailed photoionisation code (CLOUDY). The basic dependences of the cut-off magnitude M^* are then discussed. We find that : (i) In galaxies with recent or ongoing star formation, the modelled PNLF present M^* values between -4 and -5, depending on model details. These are very close to the observationally-calibrated value for the LMC. (ii) In these galaxies, the PNLF cut-off is produced by PNe with progenitor masses of about $2.5 M_{\odot}$, while less massive stars give origin to fainter PNe. As a consequence M^* is expected to depend strongly on the age of the last burst of star formation, dimming by as much as 5 mag as we go from young to 10-Gyr old populations. (iii) Rather than on the initial metallicity of a stellar population, M^* depends on the actual [O/H] of the observed PNe, a quantity that may differ significantly from the initial value (due to dredge-up episodes), especially in young and intermediate-age PN populations. (iv) Also the transition time from the end of AGB to the PN phase, and the nuclear-burning properties (i.e. H- or He-burning) of the central stars introduce non-negligible effects on M^* . The strongest indication derived from the present calculations is a serious difficulty to explain the age-invariance of the cut-off brightness over an extended interval, say from 1 to 13 Gyr, that observations of PNLFs in galaxies of late-to-early type seem to suggest. We discuss the implications of our findings, also in relation to other interpretative pictures proposed in the past literature.

(2) Marigo P., Girardi L., Groenewegen M.A.T., Weiss A. *Evolution of planetary nebulae. I. An improved synthetic model.* (2001). *Astronomy and Astrophysics*, vol. 378, pp. 958-985

We present a new synthetic model to follow the evolution of a planetary nebula (PN) and its central star, starting from the onset of AGB phase up to the white dwarf cooling sequence. The model suitably combines various analytical prescriptions to account for different (but inter-related) aspects of planetary nebulae, such as: the dynamical evolution of the primary shell and surrounding ejecta, the photoionisation of H and He by the central star, the nebular emission of a few relevant optical lines (e.g. H α ; He II λ 4686; [O III, 5007]). Particular effort has been put into the analytical description of dynamical effects such as the three-winds interaction and the shell thickening due to ionisation (i.e. the thin-shell approximation is relaxed), that are nowadays considered important aspects of the PN evolution. Predictions of the synthetic model are tested by comparison with both findings of hydrodynamical calculations, and observations of Galactic PNe. The sensitiveness of the results to the model parameters (e.g. transition time, mass of the central star, H-/He-burning tracks, etc.) is also discussed. We briefly illustrate the systematic differences that are expected in the luminosities and lifetimes of PNe with either H- or He-burning central stars, which result in different "detection probabilities" across the H-R diagram, in both H α and [OIII, 5007] lines. Adopting reasonable values of the model parameters, we are able to reproduce, in a satisfactory way, many general properties of PNe, like the ionised mass-nebular radius relationship, the trends of a few main nebular line ratios, and the observed ranges of nebular shell thicknesses, electron densities, and expansion velocities. The models naturally predict also the possible transitions from optically-thick to optically-thin configurations (and vice versa). In this context, our analysis indicates that the condition of optical thinness to the H continuum plays an important role in producing the observed "Zanstra discrepancy" between the temperatures determined from H or He II lines, as well as it affects the mass-increasing part of the ionised mass-radius relation. These predictions are supported by observational indications by Méndez et al. (1992). Another interesting result is that the change of slope in the electron density-nebular radius relation at $R_{ion} \sim 0.1$ pc, pointed out by Phillips (1998), is also displayed by the models and may be interpreted as the result of the progressive convergence of the PNe to the condition of constant ionised mass. Finally we would like to remark that, thanks to its computational agility, our synthetic PN model is particularly suitable to population synthesis studies, and it represents the basic ground from which many future applications will be developed.

Future Plans

The PNLF in galaxies of different morphological type is commonly used as an extra-galactic distance indicator thanks to the constancy of the cut-off magnitude passing from spiral with ongoing star formation to elliptical galaxies with extinguished star formation (e.g. Méndez & Soffner (1997, A&A 321, 898 and references). Understanding this observational evidence has been the subject of the studies by Marigo et al (2004). The theoretical PNLF while reproducing the observed one in the case of spirals, it predicts a substantially fainter cut-off magnitude in the case of ellipticals. Actually in these latter it gets fainter at ageing the underlying populations. Therefore, either the PNLF changes from distance to age indicator passing from spirals to ellipticals, or in the theoretical PNLF some important ingredient is still missing, in particular some non standard AGB and PNe that may exist only in high metallicity environments. The theory of stellar structure predicts that high metallicity stars (2- 3 times solar) with mass from 0.8 to 2 M_{\odot} have a peculiar evolution that lead them to spent a large fraction of their He-burning in the same region occupied by the classical PNe (Bressan et al. (1994, ApJS 94, 63). High metallicity star may perhaps exist in ellipticals (Bressan et al 1994; Tantalo et al 1996, 1998). Even if this type of stars may constitute a minute fraction of the total, their high luminosity and long lifetime make them good candidates to

represent the missing population in the PNLF able to restore even in ellipticals the standard cut-off luminosity.

Project 3: THEORETICAL ISOCHRONES IN MANY PHOTOMETRIC SYSTEMS

Girardi L., Bertelli G., Bressan A., Chiosi C., Groenewegen M.A.T., Marigo P., Salasnich B., Weiss A. *Theoretical isochrones in several photometric systems. I. Johnson-Cousins-Glass, HST/WFPC2, HST/NICMOS, Washington, and ESO Imaging Survey filter sets. (2002). Astronomy and Astrophysics, v.391, p.195-212*

We provide tables of theoretical isochrones in several photometric systems. To this aim, the following steps are followed: (1) first, we re-write the formalism for converting synthetic stellar spectra into tables of bolometric corrections. The resulting formulas can be applied to any photometric system, provided that the zero-points are specified by means of either ABmag, STmag, VEGAmag, or a standard star system that includes well-known spectrophotometric standards. Interstellar absorption can be considered in a self-consistent way. (2) We assemble an extended and updated library of stellar intrinsic spectra. It is mostly based on "non-overshooting" ATLAS9 models, suitably extended to both low and high effective temperatures. This offers an excellent coverage of the parameter space of T_{eff} , $\log g$, and $[M/H]$. We briefly discuss the main uncertainties and points still deserving more improvement. (3) From the spectral library, we derive tables of bolometric corrections for Johnson-Cousins-Glass, HST/WFPC2, HST/NICMOS, Washington, and ESO Imaging Survey systems (this latter consisting on the WFI, EMMI, and SOFI filter sets). (4) These tables are used to convert several sets of Padova isochrones into the corresponding absolute magnitudes and colours, thus providing a useful database for several astrophysical applications. All data files are made available in electronic form.

Project 4: STELLAR MODELS WITH ENHANCED ALPHA-ELEMENTS

Salasnich B., Girardi L., Weiss A., Chiosi C. *Evolutionary tracks and isochrones for alpha-enhanced stars. (2000). Astronomy and Astrophysics, vol.361, pp.1023-1035*

We present four large sets of evolutionary tracks for stars with initial chemical compositions $[Y=0.250, Z=0.008]$, $[Y=0.273, Z=0.019]$, $[Y=0.320, Z=0.040]$ and $[Y=0.390, Z=0.070]$ and enhancement of alpha elements with respect to the solar pattern. The major improvement with respect to previous similar calculations is that we use consistent opacities - i.e. computed with the same chemical composition as adopted in the stellar models - over the whole relevant range of temperatures. For the same initial chemical compositions $[Y,Z]$ and otherwise identical input physics we present also new evolutionary sequences with solar-scaled mixtures of abundances. Based on these stellar models we calculate the corresponding sets of isochrones both in the Johnson-Cousins UBVRIJHK and HST/WFPC2 photometric systems. Furthermore, we derive integrated magnitudes, colours and mass-to-light ratios for ideal single stellar populations with total mass equal to $1 M_{\odot}$. Finally, the major changes in the tracks, isochrones, and integrated magnitudes and colours passing from solar-scaled to alpha-enhanced mixtures are briefly outlined. Retrieval of the complete data set is possible via the www page <http://pleiadi.pd.astro.it>.

Project 5: OBSERVATIONAL TESTS OF CONVECTIVE MIXING

(1) Bertelli G., Nasi E., Girardi L., Chiosi C., Zoccali M., Gallart C. *Testing Intermediate-Age Stellar Evolution Models with VLT Photometry of Large Magellanic Cloud Clusters. III. Padova Results. (2003). The Astronomical Journal, Volume 125, Issue 2, pp. 770-784*

The color-magnitude diagrams (CMDs) of three intermediate-age Large Magellanic Cloud clusters, NGC 2173, SL 556, and NGC 2155, are analyzed to determine their age and metallicity based on Padova stellar models. Synthetic CMDs are compared with cluster data. The best match is obtained using two fitting functions based on star counts in the different bins of the cluster CMD. Two different criteria are used. One of them takes into account the uncertainties in the color of the red clump stars. Given the uncertainties on the experimental values of the clusters metallicity, we provide a set of acceptable solutions. They define the corresponding values of metallicity, age, reddening and distance modulus (for the assumed initial mass function). The comparison with Padova models suggests for NGC 2173 a prolonged star formation (spanning a period of about 0.3 Gyr), beginning 1.7 Gyr and ending 1.4 Gyr ago. The metallicity Z is in the range 0.0016-0.003. For SL 556 an age of 2.0 Gyr is obtained. The metallicity value is in the range 0.002-0.004, depending on the adopted comparison criterion. The derived age for NGC 2155 is 2.8 Gyr, and its metallicity Z is in the range 0.002-0.003. The CMD features of this cluster suggest that a more efficient overshoot should be adopted in the evolutionary models. A period of extended star formation is not required to fit the SL 556 and NGC 2155 observations. Based on observations collected at the European Southern Observatory, Paranal, Chile.

(2) Barmina R., Girardi L., Chiosi C. *NGC 1866: A workbench for stellar evolution.* (2002). *Astronomy & Astrophysics* vol. 385, pp. 847-861

NGC 1866 is a young, rich star cluster in the Large Magellanic Cloud. Since the cluster is very well populated both in the main sequence and post main sequence stages, thus providing us with a statistically complete sample of objects throughout the various evolutionary phases of intermediate mass stars, it represents a good laboratory for testing stellar evolutionary models. More precisely, NGC 1866 can be used to discriminate among classical stellar models, in which the extension of the convective regions is fixed by the classical Schwarzschild criterion, from models with overshooting, in which an "extra-mixing" is considered to take place beyond the classical limit of the convective zone. Addressing this subject in a recent work, Testa et al. (1999) reached the conclusion that the classical scheme for the treatment of convection represents a good and sufficient approximation for convective interiors. Using their own data, we repeat here the analysis. First we revise the procedure followed by Testa et al. (1999) to correct the data for completeness, second we calculate new stellar models with updated physical input for both evolutionary schemes, finally we present many simulations of the colour-magnitude diagrams and luminosity functions of the cluster using the ratio of the integrated luminosity function of main sequence stars to the number of giants as the normalization factor of the simulations. We also take into account several possible physical agents that could alter the color-magnitude diagram and the luminosity function: they are unresolved binary stars, dispersion in the age, stochastic effects in the initial mass function. Their effect is analyzed separately, with the conclusion that binary stars have the largest impact. The main result of this study is that the convective overshoot hypothesis (together with a suitable percentage of unresolved binaries) is really needed to fully match the whole pattern of data. The main drawback of the classical models is that they cannot reproduce the correct ratio of main sequence to post-main sequence stars.

Project 6: PRIMORDIAL STARS

(1) Marigo P, Girardi L, Chiosi C., Wood P.R. (2001). *Zero-metallicity stars. I. Evolution at constant mass.* (2001). *ASTRONOMY & ASTROPHYSICS*. vol. 371, pp. 152-173

We present extensive evolutionary models of stars with initial zero-metallicity, covering a large range of initial masses (i.e. $0.7 M_{\odot} \leq M \leq 100 M_{\odot}$). Calculations are carried out at constant mass,

with updated input physics, and applying an overshooting scheme to convective boundaries. The nuclear network includes all the important reactions of the p-p chain, CNO-cycle and alpha - captures, and is solved by means of a suitable semi-implicit method. The evolution is followed up to the thermally pulsing AGB in the case of low- and intermediate-mass stars, or to the onset of carbon burning in massive stars. The main evolutionary features of these models are discussed, also in comparison with models of non-zero metallicity. Among several interesting aspects, particular attention has been paid to describe: i) the first synthesis of ^{12}C inside the stars, that may suddenly trigger the CNO-cycle causing particular evolutionary features; ii) the pollution of the stellar surface by the dredge-up events, that are effective only within particular mass ranges; iii) the mass limits which conventionally define the classes of low-, intermediate-, and high-mass stars on the basis of common evolutionary properties, including the upper mass limit for the achievement of super-Eddington luminosities before C-ignition in the high-mass regime; and iv) the expected pulsational properties of zero-metallicity stars. All relevant information referring to the evolutionary tracks and isochrones is made available in computer-readable format.

(2) Marigo P, Chiosi C., Kudritzki R.P. *Zero-metallicity stars.II. Evolution of very massive objects with mass loss.* (2003) ASTRONOMY & ASTROPHYSICS. vol. 399, pp. 617-630

We present evolutionary models of zero-metallicity very massive objects, with initial masses in the range $120 M_{\odot}$ - $1000 M_{\odot}$, covering their quiescent evolution up to central carbon ignition. In the attempt of exploring the possible occurrence of mass loss by stellar winds, calculations are carried out with recently-developed formalisms for the mass-loss rates driven by radiation pressure (Kudritzki 2002) and stellar rotation (Maeder & Meynet 2000). The study completes the previous analysis by Marigo et al. (2001) on the constant-mass evolution of primordial stars. Our results indicate that radiation pressure (assuming a minimum metallicity $Z = 10^{-4} \times Z_{\odot}$) is not an efficient driving force of mass loss, except for very massive stars with $M > \sim 750 M_{\odot}$. On the other hand, stellar rotation might play a crucial role in triggering powerful stellar winds, once the Omega Gamma -limit is approached. However, this critical condition of intense mass loss can be maintained just for short, as the loss of angular momentum due to mass ejection quickly leads to the spinning down of the star. As by-product to the present work, the wind chemical yields from massive zero-metallicity stars are presented. The helium and metal enrichments, and the resulting $\Delta Y/\Delta Z$ ratio are briefly discussed.

Future Plans

The properties of Primordial stars bear very much on a number of astrophysical issues among which we recall:

- a) The initial chemical evolution of galaxies, when the first metal and other light elements have been made available to the second generation of stars, and likely to the inter-galactic (Matteucci 1997) and intra-cluster medium (Chiosi 2000b, Moretti et al. 2002, Portinari et al 2004)).
- b) The initial spectro-photometric evolution of galaxies (Bressan et al. 1994; Chiosi et al. 1998), when the first ionizing photons of stellar origin contributed to re-ionize the Universe (Ciardi et al. 2001).
- c) The features that primordial stars of low mass (which if they ever formed could survive today) should exhibit at the present time, in order to guide observational studies aimed at the detection of these stars (Marigo et al. 2001, Beers 2000).
- d) The chemical evolution of the diffuse medium in galaxy clusters.

Project 7: STRUCTURE AND EVOLUTION OF WHITE DWARFS WITH UNDER-BARRIER NUCLEAR REACTIONS

(1) Chiosi C., Trevisan P., Piován L. *Under-barrier nuclear reactions in White Dwarfs: Can these stars explode on their own?* 2005. PHYSICS REVIEW, submitted

It is commonly assumed that Type Ia Supernovae originate from the Carbon detonation-deflagration in highly electron-degenerate C-O White Dwarfs (WD) with the Chandrasekhar mass, $M_{\text{ch}} = 1.4 M_{\odot}$, which is also the limit mass for hydrostatic equilibrium in a complete degenerate configuration. Since WD are born with masses lower than M_{ch} , typically 0.5 - 0.6 M_{\odot} , it is believed that they can get the ignition mass through mass accretion from a companion. Binary accretion models are classified in *double-degenerate*, which consists in the merger of two gravitationally bounded WDs, and *single-degenerate*, which predicts the evolution to the explosive phases due to the accreting material from a companion star in an early evolutionary stage. At the present time, the latter model is the favoured one. Notwithstanding this, it implies a high fine-tuning for the accretion rates, and even neglecting this problem and the fact that the time required to reach the ignition mass could be larger than the Hubble time, the binary systems which involve a C-O WD observed by now are very few, in despite of the large number of Supernovae Ia discovered over the years. In this paper we explore the possibility that even isolated WDs with mass smaller than the Chandrasekhar limit, may undergo nuclear burning-ignition, thanks to the energy produced by under-barrier nuclear reactions occurring when the stars pass from the liquid to the solid state.

Project 8: THE PADOVA DATABASES OF STELLAR TRACKS, ISOCHRONES AND SINGLE STELLAR POPULATIONS

(1) Girardi L., Bertelli G., Bressan A., Chiosi C., Groenewegen M.A.T., Marigo P., Salasnich B., Weiss A. *Theoretical isochrones in several photometric systems.* (2003) MEMORIE DELLA SOCIETA' ASTRONOMICA ITALIANA. vol. 74, pp. 474 ISSN: 0037-8720.

(2) Girardi L., Bertelli G., Bressan A., Chiosi C., Groenewegen M.A.T., Marigo P., Salasnich B., Weiss A. *Theoretical isochrones in several photometric systems.I. Johnson-Cousins-Glass, HST/WFPC2, HST/NICMOS, Washington, and ESO Imaging Survey filter sets.* (2002). ASTRONOMY & ASTROPHYSICS. vol. 391, pp. 195-212

(3) Bressan A., Fagotto F., Bertelli G., Chiosi C., Girardi L., Nasi E. *Evolutionary sequences (Fagotto 1993-96).* (2001) Vizie Online Data Catalog. vol. 342, pp. 6096

(4) Girardi L., Bressan A., Bertelli P., Chiosi C. *Evolutionary tracks, isochrones for low, intermediate mass stars: From 0.15 to 7 M_{\odot} , from $Z=0.0004$ to 0.03.* (2000). ASTRONOMY & ASTROPHYSICS SUPPLEMENT SERIES. vol. 141, pp. 371-383

(5) Salasnich B., Girardi L., Weiss A., Chiosi C. *Evolutionary tracks and isochrones for alpha-enhanced stars.* (2000). ASTRONOMY & ASTROPHYSICS. vol. 361, pp. 1023-1035

(6) Girardi L., Bressan A., Bertelli G., Chiosi C. *Low-mass stars and evolutionary tracks and isochrones (Girardi et al. 2000).* (2000). Vizie Online Data Catalog. vol. 414, pp. 10371

(7) Salasnich B., Girardi L., Weiss A., Chiosi C. (2000). *Evolutionary models for alpha-enhanced stars (Salasnich et al. 2000).* (2000). Vizie Online Data Catalog. vol. 336, pp. 11023

Over the years a very large database of stellar models, isochrones and companions Single Stellar Populations (magnitudes, colors in many photometric systems and synthetic spectra) has been developed (Bertelli et al 1994, Girardi et al 2000; Salasnich et al 2000). The Padova database is known as the largest data set of this type in the world. So far more than 1500 users have accessed the site. Initially, the stellar tracks, isochrones and SSPs were transformed just to the UBVRIJHK (cf. Bertelli et al. 1994) and HST (Chiosi et al 1997, Salasnich et al. 2000) photometric systems. Recently, we revised the database of stellar spectra in use, and adapted the formalism such as to compute the transformations for a large set of intermediate- and broad-band photometric systems (Girardi et al. 2002), including now both standard photometric systems (Johnson-Cousins-Glass, WFPC2, Washington, etc), and the photometric systems in which large databases of LMC and SMC photometry are available (e.g. 2MASS, OGLE, MACHO, DENIS, EIS pre-FLAMES). For the present project, we aim at extending the database of isochrones including the updated TP-AGB models we have already described, which will allow a consistent description of late M and C stars. The data is being continuously added to a database at the web site <http://pleiadi.pd.astro.it>.

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Research products:

From NASA-ADS, referred to all the 4 programmes presented:

117 refereed articles

151 proceedings (mainly refereed)

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