EVOLUTION OF LOW MASS STARS

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ABSTRACT. We describe the evolution of low mass ($1.5 \lesssim M/M_\odot \lesssim 0.02$) stars and brown dwarfs starting from the hydrostatic phases of pre–main sequence contraction and evolving along the deuterium and lithium burning to reach the hydrogen burning main sequence or the brown dwarf degenerate cooling. With the help of new models computed by us, which we describe to the community taking advantage of this occasion, we focus our attention on some open problems of the models, which are relevant in the subsequent interpretation of observational data, namely:

1. The role of the convection treatment and opacities in determining the age, age distribution and mass function of young stellar populations;
2. The role of deuterium burning and of the protostellar phases of evolution in determining the "young" isochrones ($t \lesssim 10^6$yr) location;
3. the great uncertainty in lithium depletion, and the inadequacy of our most recent models to describe the open cluster $\log N[Li]$– $T_{\rm eff}$ relations; the interesting fact that the boundary for lithium survival in brown dwarfs *does not* depend on detailed modeling;
4. the role of color – $T_{\rm eff}$ relation in determining the location of the main sequence and the distance of open clusters

1. Introduction

The first phases of stellar evolution of low mass stars, described by hydrostatic non rotating unidimensional stellar models (pre–main sequence, hereinafter pre–MS) have known a renewed interest in the latest years, motivated by the great amount of recent data for the stars in the young star forming regions. Placing the observational data in the HR diagram is a straightforward way of dating the systems and understand their mass function and star forming history. In the very first phases of evolution however, dating depends on the protostellar evolution (which is not considered) and on the detailed role of Deuterium burning.

Later on (at ages close to 10^7yr), hydrostatic models describe the important phase of pre–MS lithium burning, which is the first phase of lithium depletion encountered by stars of about the solar mass and below: a correct description of pre–MS lithium depletion is a prerequisite to understand the additional mechanisms for lithium depletion encountered during the stellar life. Only at the end of these phases, the stars arrive at the main sequence (MS) where hydrogen burning takes place. The MS location is the fundamental ingredient for a correct determination of distances and ages of stellar clusters. We will show an example of how much the correlations $T_{\rm eff}$– colors affect this determination.

The outline of this presentation is made through new pre–MS models updating the D'Antona and Mazzitelli (1994) release. We describe the improvements in the input physics made in these models and give warnings about their correct use.

2. The 1997 release of pre–MS evolution

After the DM94 tracks have been released, several improvements have been made possible in the input micro and macro–physics, so that it is presently time to provide an updated release. The new tracks have been computed by making use of the recently updated ATON 2.0 code; a complete description of it and of the input physics may be found in Mazzitelli et al. (1995) and in Ventura et al. (1997).

2.1. Metallicity and initial D–abundance

Although we are focused here mainly on the low mass tracks, the main set of tracks contains masses in the range $0.02 \leq M/M_{\odot} \leq 3.0$. Ages are in the range $t \lesssim 5 \times 10^8$yr and $\log L/L_{\odot} \gtrsim -3.5$. The helium mass fraction is Y=0.28 and the metal one Z=0.02 (at the upper end of the possible solar metal abundance). For this set we provide results for three different D–abundances, in mass fraction: $X_D = 1$, 2 and 4 $\times 10^{-5}$. We also provide two grids of results, for Z=0.01 and Z=0.03. The metallicity does not play a clearly interesting role in the pre–MS evolution, although it obviously shifts the three main sequence locations.

2.2. Updates in the microphysics

The main changes in the microphysics are the following:

1. for the equation of state (EOS) we adopt Mihalas et al. (1988, MHD) in the range $\log T < 3.7$; $\log \rho < -2$; in the range $3.7 \leq \log T \leq 8.7$ the OPAL thermodynamics tables (Rogers et al. 1996) are instead used. In DM94 models only of the Mihalas *et al.* EOS was used;
2. we use Alexander and Ferguson (1994) opacities for $T \leq 6000$K, and OPAL updated opacities (Rogers & Iglesias 1992a,b, Iglesias et al. 1992, Rogers & Iglesias 1993) at larger T: DM94 models were computed either with a preliminary release of Alexander opacities (1993, private communication), or with Kurucz (1993) opacities at low–T, and with the 1992 OPAL tables in the interior.

2.3. The convection model

For the macrophysics, we must discuss the updates in the description of turbulence. The convection models adopted in DM94 were either the Mixing Length Theory (MLT) model calibrated on the Sun, or the Full Spectrum of Turbulence (FST) model by Canuto and Mazzitelli (1991), with the details given in the paper. The difference between the two convection models have been often summarized in the literature, but they are particularly significant for giant stars evolution (and so also for the extended envelopes of pre–MS stars) which have important superadiabatic regions. The 1997 release of tracks employs again an FST model, so that we describe here both the differences between

MLT and FST models and the differences between the 1994 and 1997 release of the FST theory adopted.

First of all, the MLT is a "one – eddy" description of turbulence, while the FST takes into account the whole eddy distribution. This was done in 1994 adopting the Canuto and Mazzitelli (1991) fluxes, while in the present models we use updated turbulent fluxes by Canuto, Goldman and Mazzitelli (CGM 1996).

The scale length in the MLT is assumed to be proportional to the pressure scale heigth H_p: $\ell = \alpha H_p$. In the FST models it is assumed to be the armonic mean between the distance of the layer from the top and the distance from the bottom of the convective region. With this choice the Solar $T_{\rm eff}$ fits within 1.5%. A *fine tuning* of the solar radius is achieved by introducing a small amount of *overshooting* from the surface convective layer: we take in fact:

$$\ell = z + \beta H_p^{top} \tag{1}$$

and β is ~ 0.2 for the CM fluxes, while it is now ~ 0.1 for the CGM fluxes.

Both the new fluxes and the new definition of scale length do not have a dramatic effect on the HR diagram location of the tracks, although they affect the lithium pre–MS depletion; some problems are present in the models for which convection starts in the optical atmosphere, since z is computed starting from the bottom of the photosphere (see a more detailed discussion in D'Antona and Mazzitelli 1997). Comparison with the old tracks shows that this latter choice lowers the $T_{\rm eff}$ of tracks of mass below $\sim 0.4 M_\odot$, by a maximum amount of $\sim$ 150K, which is important both for the pre–MS and for the MS (see the right side of figure 3). The resulting MS is close to the most recent MS models by Chabrier and Baraffe (1997), although we must warn that this coincidence is purely accidental.

3. Impact of the description of convection on pre–MS models

3.1. The reasons to adopt an FST treatment of convection

We take this opportunity to remark that, even if both MLT and FST have free parameters, it is not "optional" to adopt the former or the latter. The FST fluxes are based on modern and sound treatments of turbulence for low–viscosity fluids, as found in the very inviscid stellar interiors, and allow for the billions of scales of eddies present in these conditions, with both forward and back–scatter of energy among eddies. This has to be compared (and opposed) to the one–eddy MLT treatment of extremely viscous fluids, suitable for oil or glycerine. Very large Reynold's number laboratory experiments show close agreement with the predictions of FST models, while the heat fluxes predicted via the MLT are too low by one order of magnitude or more (Canuto 1996). This reason alone compels researchers who look for really "new" results to at least try the FST treatment, *even if in this way they will not be able any longer to perfectly fit any kind of observation* by resetting a *completely free* parameter, like it is possible with the α parameter in the MLT.

To assume as convective scale length the distance from the nearest convective boundary is consistent with experiments and Von Karman law. This is particularly important close to the convective boundaries, and it is at variance with the *local* pressure scale height chosen in the MLT. The small overshooting introduced in our treatment, on the one side acts as a *fine tuning* parameter, necessary mainly to get the precise fit of the solar radius for helioseismological purposes, on the other side it is the first step towards a truly non–local scale length. Use of $\ell = z$ was obviously tried also with MLT at its beginning, but it badly failed (and still badly fails, see CGM) to fit the sun, and was abandoned in favor of the *strictly local and non–turbulent* pressure scale height (H_p).

In 1993, when we released the DM94 models, very few data were available for low mass star pre–MS evolution. We *asked* then researchers to use mainly the "Alexander CM" set. The choice of opacities was motivated by the fact that Kurucz's opacities were inadequate for $T_{\rm eff} \lesssim 4000$K, where molecules would play a fundamental role. The CM set was selected because we wished the researchers to use these tracks as a "test" for the convection model. Now, after some years, this set of tracks has been shown to provide at least "reasonable" results for the location in the HR diagram of young star, and for the mass we attribute to them. While this is by no means a proof of "truth" of the results, at least it has shown that the FST treatment of convection is NOT worse than the MLT. We will show in the next section that also on observational grounds, for the pre–MS, it is probably more reliable than MLT based results. Consequently, we have to thank the researchers who actually used the Alexander CM set and helped us to make this further test of FST models. We do not make here a list of the good performance of the FST models for other stellar structures, from main sequence to red giants, to asymptotic giant branch stars, to white dwarfs. References to various tests performed by various authors in a variety of evolutionary phases can be found in D'Antona et al. 1997 and references therein.

3.2. Impact on the age determination from the HR diagram

We remember a simple but important point of the pre–MS evolution and of the determination of isochrones. The low mass pre–MS stars are fully convective during their first phases of evolution. Further, the external layers, due to the low densities, are largely superadiabatic. Therefore, the $T_{\rm eff}$ location of tracks depends considerably from the convection model. This is easily seen when using the MLT models: comparing tracks of different l/H_p, the MS location is affected by less than 100K, the pre–MS location can vary by several hundreds of degrees! In addition, the FST models have two interesting peculiarities: 1) the pre–MS location of the solar track does not correspond to the location of the MLT track which fits the present solar model with the same input microphysics (this has been shown, e.g., in DM94); this fact alone may cast doubt on the capillary procedure of fitting the MLT l/H_p on the solar model, as this does not guarantee that other phases are correctly described); 2) FST and MLT models show to differ in the dependence of the $T_{\rm eff}$ location of the Hayashi tracks on the stellar mass: namely, while at masses $\sim 0.8M_\odot$ the tracks occupy similar locations, the FST tracks of low mass ($M \lesssim 0.4M_\odot$) are generally hotter than the corresponding MLT tracks.

This second characteristic has an interesting impact on the isochrones. In fact – disregarding D–burning– the evolution of these stars is simple contraction over the Kelvin – Helmoltz timescale $t_{KH} \propto GM^2/(RL)$, and it is then proportional to the

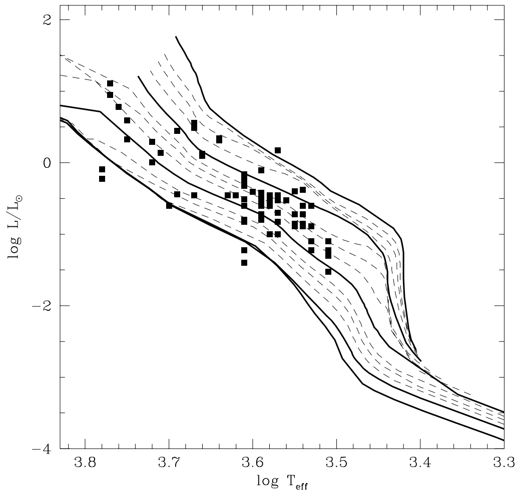

Fig. 1. Isochrones by D'Antona and Mazzitelli 1997. The thick lines from top to bottom represent the isochrones of 10^5, 10^6, 10^7, 10^8 and 5×10^8 yr. The intermediate dashed lines represent the ages 2, 3, and 5 times the age of the thick isochrone above. The data for the star forming region in Chamaleon (Lawson et al. 1996) are shown as full squares. Notice that for the bulk of the points there is a relatively small dispersion of ages.

square of the total mass. If we have two sets of tracks, and the low masses of the first (e.g. the set distributed by F.J. Swenson, hereinafter FJS) are cooler than the low masses of the second one (e.g. the Alexander CM set of DM94), what happens when we use the tracks to attribute a mass and an age to an object located at a given $\log L/L_\odot - T_{\rm eff}$? It is clear that the first set will attribute to the star a *larger* mass than the second one, and therefore a *larger* age! (In other words, in the HR diagram the FJS isochrones have a smaller slope than the DM94 isochrones). Let us make an example of the consequences by looking at the analysis by Lawson et al. (1996) of a sample of stars in Chamaleon. For both FJS and DM94 sets, the stars show a spread of ages, but the star formation rate using DM94 is very much peaked around 2–3 million years, while FJS models produce a much more constant star formation rate, over a wider range of ages.

From Lawson et al. data it is easy to see –and a careful analysis would confirm it– that the smaller the $T_{\rm eff}$ (mass), the larger is the average age of the sample when using the FJS models. Thus, the results from DM94 isochrones seem more consistent, unless we have a good reason to think that cooler stars have been formed earlier (!). This result is not altered by DM 1997 tracks (figure 1).

We warn again that this analysis does not guarantee that the FST tracks are perfectly reliable: the point here is that *users of tracks should not infer very strong conclusions on the star forming history of a region (e.g. peaked versus almost constant star formation rate) without being aware of these uncertainties in the models.*

3.3. Impact on the mass determination

A very similar case to that described above is the analysis made very recently by Luhman and Rieke (1998), who focus their attention on the derivation of the initial mass function (IMF) for the stars in the region L1495E of Taurus (see the left side of figure 3). They adopt the DM94 tracks, the FJS tracks and the recent set computed by Baraffe et al. (1997, hereinafter BCAH97). They find that the IMF derived by the BCAH97 models is very peculiar, although these are the models which best reproduce the *main sequence* location of very low mass stars. DM94 models provide a very reasonable IMF, slowly increasing towards low masses. The problem here is again tied to convection. The atmospheric integration used by BCAH97 is certainly more physically sound than the plain grey atmosphere integration employed by us and by FJS. But this provides results which in principle are better for the MS, not for the pre–MS: in fact, at the MS the convection model is of scarce importance, as convection in low mass stars is almost purely adiabatic. On the contrary, in pre–MS we have seen –as it has been known for about 30yr– that superadiabaticity determines the $T_{\rm eff}$ location. A smaller l/H_p, e.g., leads to a cooler track. The BCAH97 tracks have been computed with $l/H_p = 1$, so they are cooler than the FJS (who adopts an l/H_p which fits the solar model) and much cooler than the DM94 FST tracks. Thus an object which in DM94 is $0.25M_\odot$, is a $0.5M_\odot$ in BCAH97 tracks, just due to their assumption for convection: the differences between BCAH97 and previous models in pre–MS *are not* due to their different –and more reliable– atmospheric integration, but to their choice in the modeling of convection. No doubt that Luhman and Rieke (1998) find very different IMFs! The DM 1997 models produce a better agreement with the MS binaries location, nevertherless they still are much hotter, in pre–MS, than the BCAH97 tracks, so that Luhman and Rieke conclusion should be scarcely altered by use of our new models. A detailed comparison should however be made.

4. What is the "age" in the first phases of evolution?

4.1. Can we re–normalize the times of hydrostatic evolution?

What is the "age" of a star? We should in principle define it as the time elapsed from when the protostellar cloud began its dynamical evolution, forming a central hydrostatic core accreting the remaining diffuse matter of the outer regions (Larson 1969). Only when the main accretion phase –proceding at rates of $\sim 10^{-5} - 10^{-6} M_\odot$/yr in the case of low or intermediate mass stars– ends, dust is dispersed and the core emerges at visible wavelengths. Only then we can talk about pre–MS. If we follow consistently the protostellar evolution, we will have the "age". On the contrary, in the hydrostatic model evolution, $t_{ev} = 0$ is chosen at an arbitrarily extended fully convective configuration, which the real star probably never attains, and the zero of the ages of the stellar model is thus arbitrary. In our models, we generally begin the evolution starting from a central temperature value of $\log T_c = 5.7$, thus at a point preceding the onset of deuterium (D) burning. How can we correlate the real "age" t_{true} with t_{ev}? For masses $M \gtrsim 0.5M_\odot$ we can chose this line of reasoning: let us assume that the protostellar evolution follows the Palla and Stahler (1993) description for low mass stars, namely that the onset of

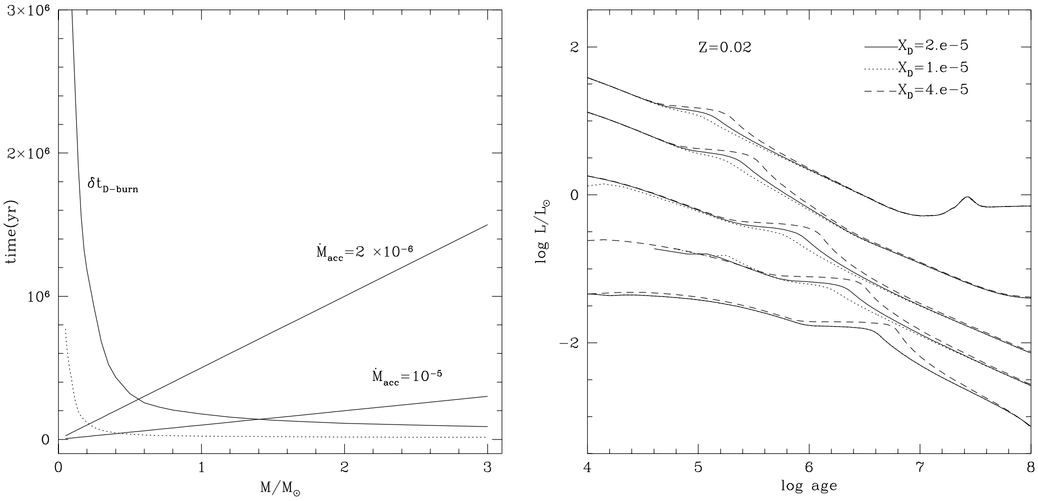

Fig. 2. The left side shows the time spent by hydrostatic models in the phase of D–burning ($\delta t_{\mathrm{D-burn}}$) and compares it to the accretion time, defined simply as $M/\dot{M}$ for two values of accretion rate $\dot{M}_{acc}$. The dotted line represents the initial time at which D begins burning in the hydrostatic models.
The right figure shows the luminosity versus time evolution for stars of different D initial abundance. From bottom to top the masses are 0.05, 0.1, 0.2, 0.5 and $1.0 M_\odot$.

Deuterium burning in the accreting protostar acts as a thermostat, as the stars remains frozen in this phase till accretion stops. In the hydrostatic evolution, we can re–normalize the time zero to the onset of D–burning $(t_{in}(Db))$, and add the protostellar accretion time $M/\dot{M}$. We finally have:

$$t_{true} = t_{ev} - t_{in}(Db) + M/\dot{M} \tag{2}$$

This is a simplification, as actually the mass is increasing during the accretion phase, while we choose to adopt the evolutionary times (renormalized) of the final mass, but we can use it, with a choice of accretion rates, to explore how much the isochrones will be modified. Even so, this approximation is NOT correct for the lower mass stars: in fact, it takes a finite amount of time to increase the central temperature of the accreting core in order to ignite deuterium: depending on the accretion rate, a mass of $\gtrsim 0.2 M_\odot$ ($\dot{M} = 2 \times 10^{-6} M_\odot$/yr) or of $\gtrsim 0.4 M_\odot$ ($\dot{M} = 10^{-5} M_\odot$/yr) must be accumulated *before* D–burning begins (Palla, private communication). Also the hydrostatic models provide timescales for D–ignition comparable to those quoted for accreting protostars: this can be seen in figure 2, where we show the $t_{in}(Db)$ from our models as a function of the mass (dotted line), and compare it to the time $M/\dot{M}$ for accretion rates of $\dot{M} = 2 \times 10^{-6}$ and $10^{-5} M_\odot$/yr).

If accretion stops before D is ignited, first of all the initial structure is not yet fully convective, second, we can not assume equation 2 as valid. In this case, a simple

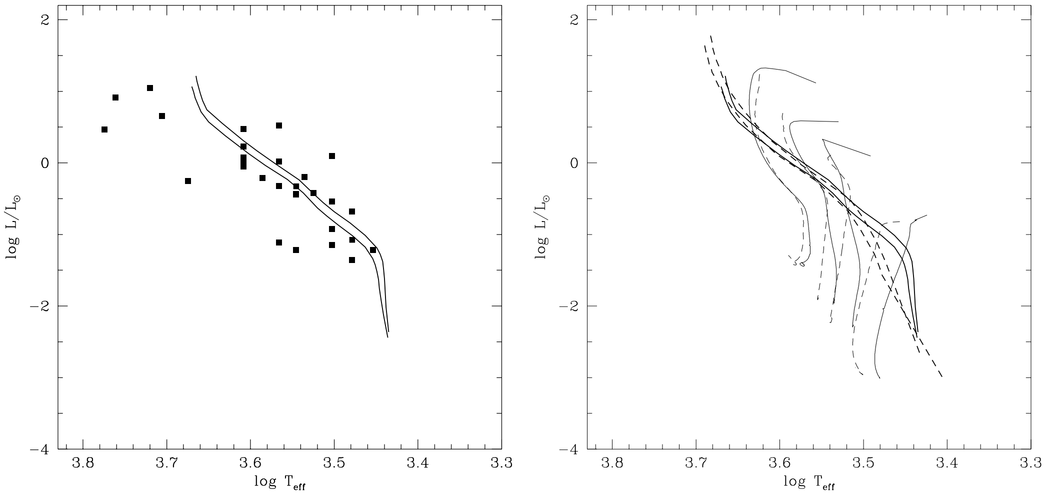

Fig. 3. The left side shows the data of L1495E by Luhman and Rieke (1998) and the D–burning band for DM 1997 models. The right side shows the same band, compared to the D–burning band from DM94 (Alexander CM set) models. The displacement to lower $T_{\rm eff}$ of the low mass end is determined by the low mass model tracks being cooler (as explained in the text). Tracks of 0.5, 0.3, 0.2 and $0.1 M_\odot$ from DM94 (dashed) and DM 1997 (full line) are shown to remark the differences.

reasoning may show that actually the choice of adopting the unaltered t_{ev} makes sense. In fact, whatever is the status of the hydrostatic core of mass $< 0.4 M_\odot$ when the main phase of accretion stops, the reaching of a fully hydrostatic and convective configuration along the Hayashi track will necessarily go through transformation of gravitational into thermal energy and viceversa. Since the star is also approaching conditions in which the virial theorem begins to hold, this phase will last for a time not far different from a Kelvin Helmoltz timescale. But also the evolution described by the hydrostatic models (apart from the temporary stop due to the nuclear burning of Deuterium) in this case simply describes the gravitational contraction of the object on thermal timescales. So, rough as it has been defined, the time t_{ev} whose zero point is chosen arbitrarily, may result a reasonable approximation to reality for stars of low mass.

We see in figure 2 that the mass accretion time is shorter than the D–burning time for $M \lesssim .5 M_\odot (\dot{M} = 2 \times 10^{-6})$ or for $M \lesssim 1.2 M_\odot (\dot{M} = 10^{-5})$, therefore low mass stars live a part or most of their D–burning as TTauri.

Also the initial D–abundance is important to determine the location of the young isochrones in the HR diagram. This can be seen in the right part of figure 2, where the time, for three different D initial abundances.

Infrared observations allow to explore the evolutionary status of younger and younger stellar objects. These stars are just emerging from the protostellar clouds, so that, in principle, their "dating" can not be done through hydrostatic models. Often we have

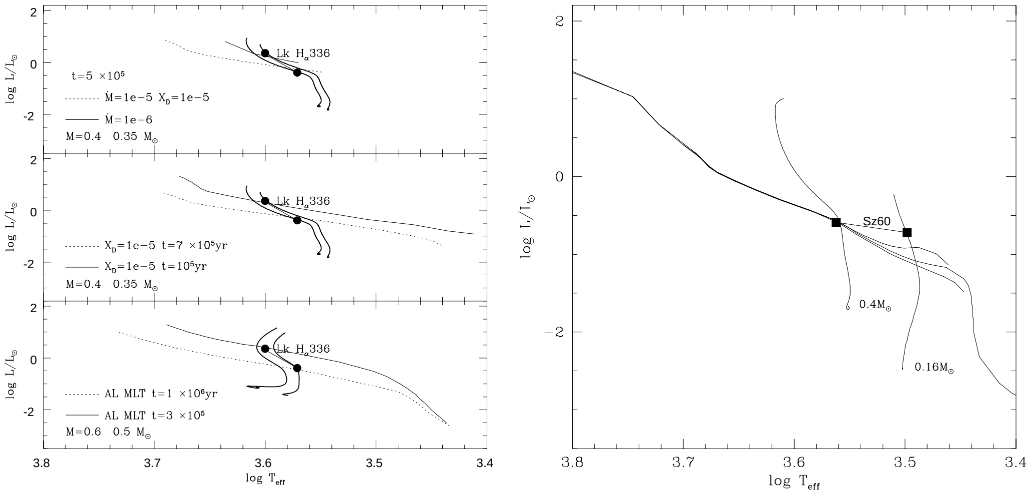

Fig. 4. The left side shows possible attempts to fit the data of the binary Lk Hα336 in a coeval system. The right side shows the isochrones of age 2×10^6yr with D–abundance 1, 2 and 4 $\times 10^{-5}$, compared to the system SZ60. Binary data are from Hartigan et al. 1994.

referred to the D–burning locus as to the "birthline" of stars (Stahler 1988, Palla and Stahler 1993), but this can not hold for the very low mass stars either, as we have just discussed. In effect, there are low mass stars which, in very young star forming regions, are found *above* the D–burning band, as it can be seen in the data for L1495E by Luhman and Rieke (1988) shown in figure 3 together with the D–burning band from our new models: many of the stars appear well above the band. This confirms that we still need to understand how a very low mass star forms and what causes the end of the accretion phase.

4.2. Example of the use of the tracks: comparison with pre–MS binaries

Based on the preceding discussion we see that, for the relatively young isochrones, we have two different parameters which may alter their HR diagram location: the protostellar rate of mass accretion (for masses larger than $\sim 0.3 M_\odot$) according to the definition of equation 2, and the initial X_D. In a first approximation the time spent in the D–burning phases is in fact:

$$\tau_{Db} = \frac{E_{p+D} N_A M_* X_D}{L_{Db}} \tag{3}$$

where E_{p+D} is the energy released in one reaction of p+D, N_A is Avogadro's number, M_* is the stellar mass and L_{Db} the luminosity at which D–burning occurs for the mass M_*.

Different assumptions may help in allowing some binaries to lie on isochrones. For example let us discuss with the help of the left part of figure 4 the system LkH$_\alpha$336. The hotter component clearly lies on a younger isochrone, if we take the isochrones from the same set. If we use MLT models, the hotter component is also the more massive ($0.6M_\odot$), and it lies on the 10^6yr isochrone, while the cooler ($0.5M_\odot$) lies on the 3×10^6yr isochrone. If we take the FST isochrones, the hotter component is less massive ($0.35M_\odot$) than the cooler one ($0.4M_\odot$), they result younger, but still do not lie on an isochrone (respectively the $0.4M_\odot$ has almost 10^6yr, and the $0.35M_\odot$only 10^5yr!) The discrepancy becomes smaller if we adopt the ages which take into account the protostellar accretion time according to equation 2, as the ages become 10^5 and 5×10^5yr. But the best situation is obtained by assuming that the $0.4M_\odot$formed at a much smaller accretion rate ($10^{-6}M_\odot$/yr). As shown in the top plot of the figure, in this case an age of 5×10^5yr can be reasonable for both stars.

Obviously a much more careful analysis of the observational data and of the isochrone fit should be done before we even try to understand whether this is a "real" possibility: we show it to make a simple example of how to use again these tracks as a tool for understanding the star formation problems.

The right side of figure 4 shows the system Sz60 in the HR diagram and three isochrones, all of them passing through the location of the primary component, which results to be a $0.4M_\odot$. The three isochrones have age of 2×10^6yr, and the three different D–abundances adopted in the present computations. The secondary (having a mass of $0.16M_\odot$) is closer to the isochrone of abundance $X_D = 4 \times 10^{-5}$. In other words, this system can be coeval if in the $0.16M_\odot$ component the phase of D–burning is very very prolonged. This also is a simple example of use of the isochrones. We have to learn much by exploring these results, keeping always in mind that "standard sets" of tracks and isochrones are first–order approximation only to reality!

5. Lithium depletion

5.1. Lithium burning in solar type stars

Once we have described the success of the "standard" models in the description of the HR diagram, it is now time to describe the main problem they bring into evidence. Already in DM 94 we had noticed a large dependence of Lithium depletion in pre–MS on the opacities and convection model adopted, and had found an easy escamotage for that: as Lithium depletion is somewhat model dependent, it is not clear at all what set of opacities is more appropriate to describe it. So, the comparison with the data of the cluster αPer were more easily interpreted through the "Kurucz CM" set (see figure 19 in DM94) than with our preferred standard "Alexander CM" set. In so doing, we remarked that the tracks for the masses which define the Li–$T_{\rm eff}$ relation of open clusters were such that the Kurucz opacities also described them correctly. Martin (1998, in this volume) shows in fact that the DM94 Alexander CM set is really in contrast with the data on lithium depletion in clusters, as it has a much too large solar pre–MS depletion (a factor 10). *Here we show that the DM97 models are even more incompatible with the cluster data!*

Figure 5 shows modeling of lithium burning of a $1M_\odot$ star. We will adopt as *standard*

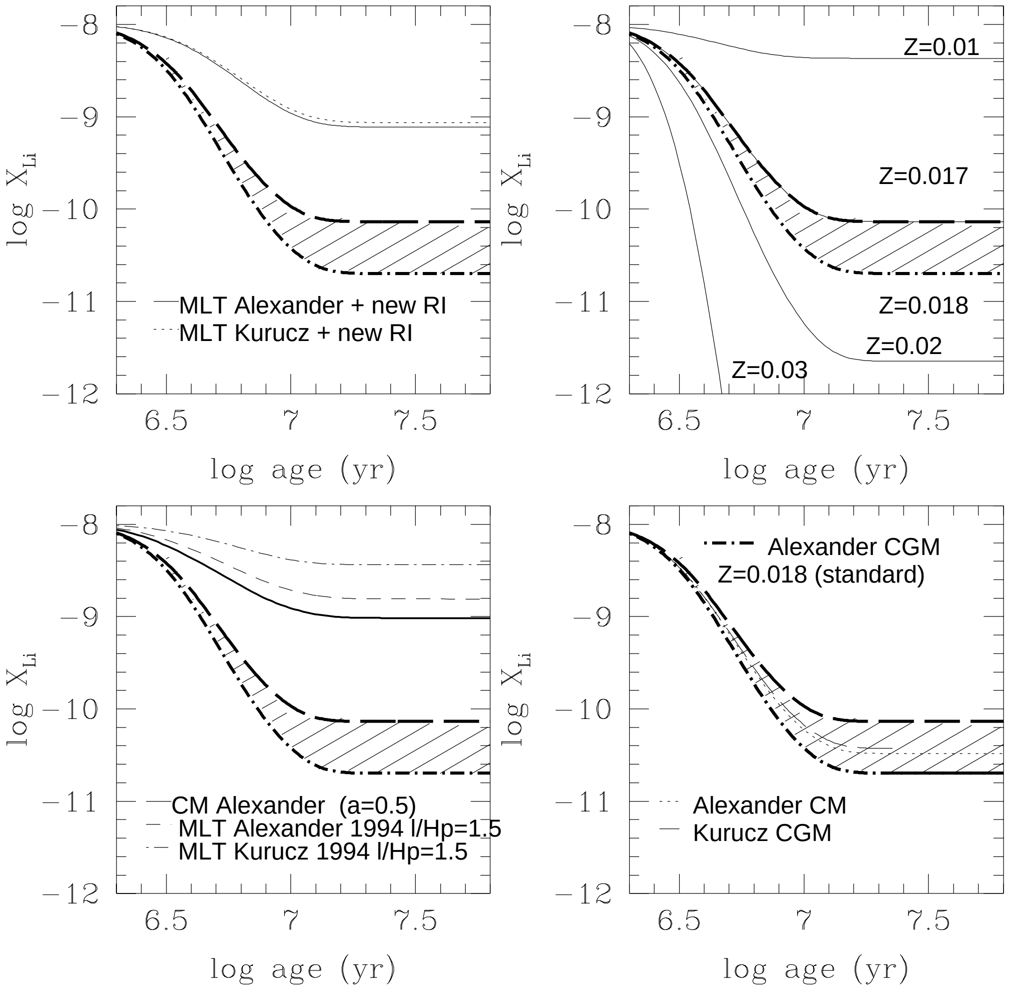

Fig. 5. Dependence of Lithium pre–MS burning on several input parameters. The band in all figures shows the most probable depletion in a "standard" solar model, Y=0.28, FST convection with CGM fluxes, and Z 0.017 and 0.018. The bottom left shows the comparison between the new models and the 1994 CM and MLT models: the new models deplete at least 10 times more lithium. As the 1994 models assumed Z=0.019, the depletion difference is close a factor 100, as it can be desumed from the right top figure showing the dramatic dependence on the metallicity, varying from Z=0.01 to 0.03; the top left figure shows the comparison with new MLT models assuming Z=0.018 the recent interior opacities by Rogers and Iglesias, and the low temperature opacities either by Kurucz 1993 or by Alexander and Ferguson 1994; the bottom right figure shows the differences by varying the fluxes (CM versus CGM) and the external opacities (Kurucz versus Alexander and Ferguson, for Z=0.018).

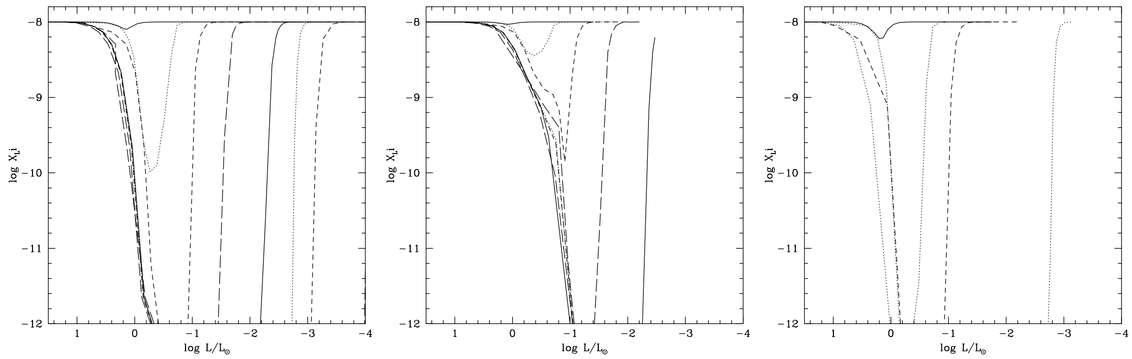

Fig. 6. The isochrones of lithium burning. The "lithium chasm" is shown for several ages for Z=0.02 (left), Z=0.01 (center) and Z=0.03 (right). The ages are 2×10^6yr(full line), 5×10^6yr (dotted), 10^7yr (dashed), 2×10^7yr (long dashed), 5×10^7yr (full), 10^8yr (dotted) and 2×10^8yr (dashed) for the Z=0.02 part; the same symbols are used for the Z=0.01 and 0.03 part, but less isochrones are given. Notice that the left boundary of the chasm (lithium depletion in partially convective stars) is very much dependent on the metallicity (and on the other input parameters), while the right side does not depend on the metallicity. This renders the boundary of lithium depletion a powerful tool for age determination.

tracks here not the track with Z=0.02, but two especially computed having Z=0.017 and Z=0.018 (Anders and Grevesse 1989). We see that depletion is a factor 100 – 400, so that these models provide all the burning needed to explain the present solar lithium abundance *by pre–MS depletion only.* There is no way to reduce this value as much as we should to make it consistent with the open clusters data, at variance with the DM94 result: we see in the figure that it depends dramatically on the metallicity, and less dramatically on the FST fluxes adopted (CM versus CGM). Furthermore, even the MLT models, which still show a less dramatic depletion (a factor ~ 10) are incompatible with the clusters data.

A part of the difference between DM94 and present models must rely in the opacities and equation of state (eos) adopted in the present code. The updated opacities by Alexander and Ferguson 1994 play the most important role, but it will be shown elsewhere (Ventura et al. 1998) that also the eos has a relevant effect: adoption of the Rogers Swenson and Iglesias (1996, RSI) eos makes a difference by a factor > 4 in depletion. The rest of the difference must be attributed to the new way of modeling the convective scale length (equation 1).

While some features were, qualitatively, already known, we notice with some surprise the great effect of metallicity: even small variations in the abundance from star to star, within the errors in the analysis of atmospheric abundances, leads to huge differences. This is due to the fact that the solar model is at the boundary between burning and non–burning, so any effect is amplified here.

Should we trust these results? Our opinion is that we must take them into serious consideration and avoid adopting models which, with a worse input physics, provide more palatable results (e.g. a factor $\sim$ 2 or 3 of pre–MS solar burning which leaves space for the long term MS depletion mechanisms, and provides a reasonable fit with the clusters data).

We begin to be convinced that the problem is reduced to inhibit Lithium burning in pre–MS. Rotation has been invoked as a possible mechanism to structurally reduce burning (Martin and Claret 1996), and it would be consistent with the observations of generally larger Lithium abundances in fast rotating stars (e.g. the Hyades binaries, Barrado y Navascues and Stauffer 1996). Martin and Claret result was at variance with the findings by Pinsonneault et al. (1990), but now it is at variance also with our own preliminary results for rotating stellar models (Sanctos Mendes et al. 1997). Both our group and Pinsonneault et al. find that rotating models *structurally* (that is: without including the transport of angular momentum and associated chemical mixing) deplete more lithium than non–rotating models. So we do not think that the "structural" effect of rotation can solve the problem.

Inhibition of Lithium burning is possibily linked with the stabilizing influence of the dynamo induced magnetic field at the base of the convective envelope induced by rotation (Spruit 1987) and we plan to work in this direction (Ventura et al. 1997).

5.2. Lithium burning at the low mass end

Because of the Virial theorem, smaller masses take a longer time to reach the temperature of lithium burning, so that the depletion phase occurs later for smaller mass. For a stellar system of a given age, the more massive stars will show the effect of lithium burning; at lower L lithium will totally disappear, but it will reappear again in the spectra of stars of still lower L. In DM94 we proposed that this reappearence of lithium could in principle be used to date the system. When we produced the relevant figures and made the statement, we had no idea that really Basri et al. (1996) and Rebolo et al. (1996) would be able to use this feature to date the Pleiades. In figure 6 we show the "lithium chasm" for several ages and the three metallicities employed in the new models. It is self evident that the left boundary of the chasm is dramatically dependent on metallicity (and, we have seen, on a lot of other parameters) while the right boundary *is practically independent on the details of the models* including the opacity. This renders the Lithium test a powerful way of dating a cluster!

6. The main sequence

Once we have the theoretical models, the most natural project to do is to convert luminosity and $T_{\rm eff}$ into colors and magnitudes and use the sequences to compare with open clusters data. Dating of open clusters rely heavily on these procedures, although the recent results from Hipparcos may give a new flavour to this field.

It is well known that the conversions below $T_{\rm eff}\sim$ 4000K are very difficult, and large errors still weight on the transformations. For $V-I>2$, the color may differ by several tenths of magnitude according to the chosen transformation. To this, we have to add that the $T_{\rm eff}$ of stars becomes more model dependent, as the grey atmosphere approximation is no longer valid when convection penetrates in the atmosphere (Baraffe et al.

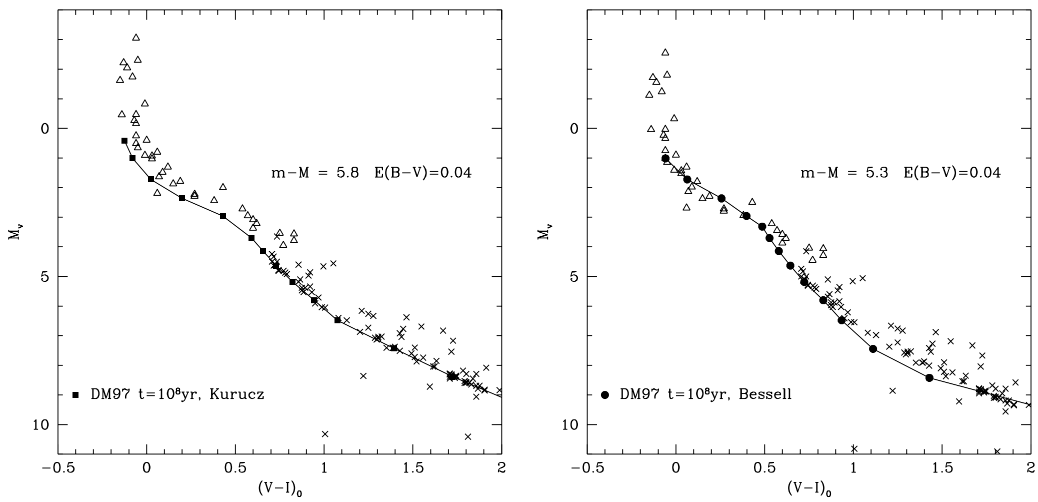

Fig. 7. Two possible fits of the Pleiades data by Iriarte (1969) – open triangles– and Stauffer (crosses). These latter data, being in the Kron system, have been transformed into Cousins system through Leggett (1992). The left figure shows the isochrone of 10^8yr transformed into M_v and $V-I$ via the Kurucz (1993) relations; the right figure shows the same isochrone transformed via the Bessell (1991) relation. The two relations differ by less than 0.1mag in the $V-I$ to be attributed to the same $T_{\rm eff}$: nevertheless, the high slope of the MS requires a difference by 0.4mag in distance modulus to fit the Pleiades MS.

1995). Further, as remarked above, the models of mass $M \lesssim 0.5M_\odot$would require also a consistent convection model to provide reliable $T_{\rm eff}$ values (contrary to well established previous results based on the MLT –D'Antona and Mazzitelli 1997). Thus the situation at $T_{\rm eff} \lesssim 4000$K is still very fluid, and one should not disregard parametric approaches such as that by Stauffer et al. 1995, which at least is reasonable for *differential* dating, once the MS of the Pleiades is pinned down by assuming a given set of models and a given set of transformations color – $T_{\rm eff}$.

What might have been less appreciated in the recent literature is that *even at larger* $T_{\rm eff}$ the conversions are still uncertain enough to render the comparison with observations difficult. We make here the comparison between Bessell (1991) and Kurucz (1993) $V-I$ vs. $T_{\rm eff}$ conversions. They differ by almost 0.1mag at $T_{\rm eff}\sim$ 5500K. By adopting our new isochrone at 10^8yr, and Kurucz conversions, the Pleiades result to have a distance modulus of $(m-M)_0 \sim 5.8$, while by Bessell's conversions the distance modulus is eeasily reduced to $(m-M)_0 = 5.3$, consistent with Hipparcos data. This is shown in figure 7 as a further warning about the difficulties in this analysis.

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