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Uncertainties associated with mass and age determination of pre-main sequence stars

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Abstract. We present an overview of the problems and uncertainties associated with the modeling of pre-main sequence (PMS) stars. As an illustration, we analyze how a change in the constitutive physics a stellar evolution code (convection treatment, equation of state, chemical composition, boundary conditions) modifies the path followed by a PMS star in the HR diagram. We also discuss the effects of rotation and mass accretion during this evolutionary stage. Finally, we compare the different PMS evolutionary tracks available in the literature and estimate the uncertainties associated with mass and age determination of young stars.

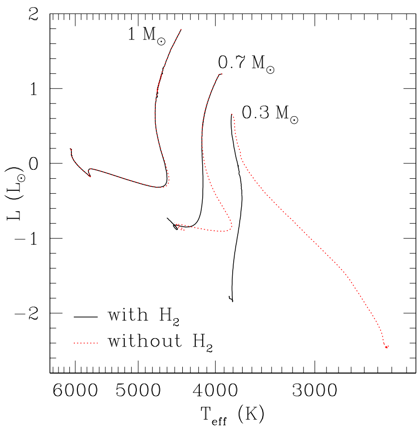
1. Introduction

Stellar mass and age are usually inferred from a comparison of the star's position in the HR diagram (HRD) with evolutionary tracks. But the derived values for the parameters depend on the protostellar evolution (which is generally not considered), on the input physics of the stellar evolution code and also on the treatment of non-standard processes such as accretion or rotation. All these factors modify the evolutionary path of the star in the HRD and thus affect the scientific results. In particular, understanding the initial mass function or the star forming history strongly depends on these estimated values.

In this presentation, we will briefly review the main physical ingredients that most affect the PMS tracks and then try to estimate the expected error bars on the mass and age estimates.

2. Uncertainties in PMS stars modeling

The computation of the stellar structure is challenging because it connects different fields of physics, from the radiative transfer at the surface to the microphysics of dense and degenerate plasmas in the interior and through a correct description of the different modes of energy transport. This is a complex task and some approximations have been made that deteriorate the accuracy of stellar models. We briefly review here the salient points that most influence the evolutionary path of a star in the HRD.



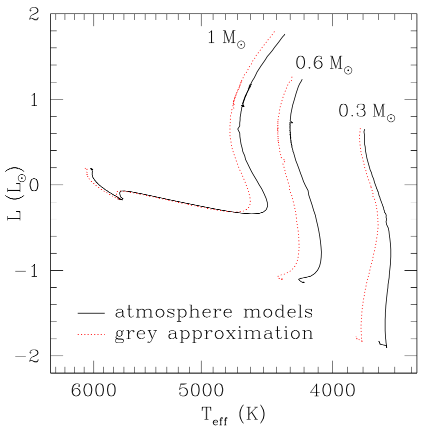


Figure 1. Effects on pre-main sequence tracks of the treatment of molecular hydrogen in the Saha equation (left panel) and of the use of grey/realistic atmosphere models (right panel).

2.1. The Equation of state

In dense, cold and partially degenerate plasma characteristic of very low-mass stars (VLMS, $M \lesssim 0.4\,\mathrm{M}_\odot$), non-ideal effects associated with pressure ionization and Coulomb shielding become very important and must be accounted for. In the recent years, a tremendous amount of work has been done and several equations of state (EOS) have emerged. They show good agreement within their domain of validity which tends to indicate that we are now correctly computing the thermodynamical quantities inside VLMS (see e.g. Saumon et al. 1995). To illustrate the relevance of an accurate treatment of the EOS, we show in Fig. 1 the effects of including H_2 in the Saha equations. The formation of molecular hydrogen in cool stars ($T_{\rm eff} \lesssim 4500\,$K) provokes an increase in the mean molecular weight in the surface layers. In this region, the adiabatic gradient decreases and convection develops, pushing the photosphere to larger radii. The morphology of the tracks is strongly affected below 4500 K and temperature shifts as large as 100 - 1300K are reported.

2.2. Boundary conditions

In VLMS, the emergent spectrum differs significantly from a pure black body due to molecular absorption bands (H_2O, TiO ...) and because convection penetrates farer into the optically thin layers. In a stellar evolution code, the diffusion approximation used in the interior structure do not hold at low optical depth and boundary conditions are then applied. Different codes propose different treatments, using either realistic models which compute correctly the radiative transfer in the atmosphere and which account for convection and molecules formation or on the other hand grey models based on the Eddington approximation. The later models yield temperature and density profiles in the atmosphere substantially cooler and denser than the non-grey ones so that a higher effective temperature is required to match the internal structure (i.e. Chabrier, Baraffe, & Plez 1996). From Fig. 1 we see that grey models are hotter by $\sim 100-200\,$K,

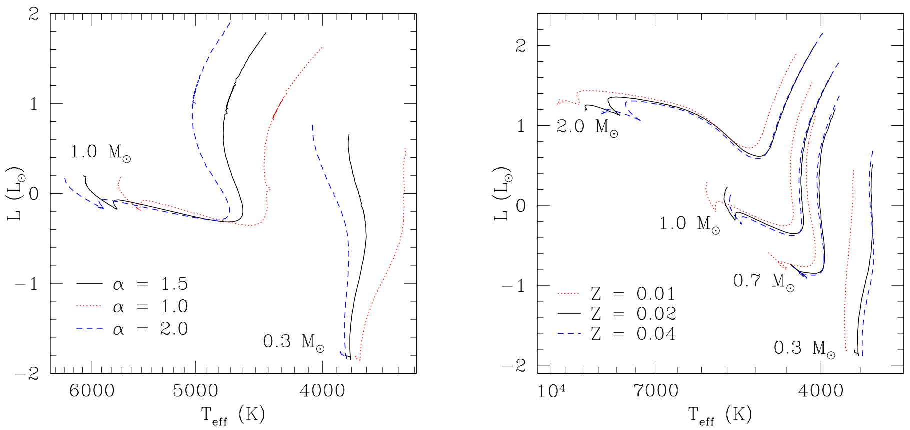


Figure 2. Modification to the PMS tracks due to different values of the parameter α in the MLT (left panel) and of different chemical composition (right panel).

depending on the evolutionary status, metallicity and mass of the star. However, it must be mentioned that grey models remain a good approximation for $T_{\rm eff} \gtrsim 4800$ K, where convection and molecular absorption disappear from the surface.

2.3. Treatment of convection

The computation of the convective transport of energy in a stellar evolution code is still based on simplistic theories that are one dimensional, do not account for the time dependence and non-locality of the convective flows and that present at least one free parameter that allows us to fit the sun.

For example, in the standard mixing length theory (MLT), it is commonly assumed that the parameter α (which represents the ratio of the distance over which the convective cell dissolves and releases its energy to the pressure scale height) keeps a constant value during all the evolution of the star and is assumed to be identical for stars of different masses, different chemical composition and different rotation rates! Recent studies (Ludwig, Freytag, & Steffen 1999) clearly show that this is certainly not the case. Thus, assuming a fixed value of α is wrong and one has to keep in mind the evolutionary effects of a modification to this parameter. A larger value of α allows the energy to be carried out more efficiently towards the surface and decreases the distance required to release the heat excess. Consequently, the radius is smaller and for a given luminosity, the effective temperature is higher as shown in Fig. 2. Quantitatively, a change in α of ± 0.5 about the solar value ($\alpha_\odot \simeq 1.5$) leads to differences in $T_{\rm eff}$ of $\sim \pm 300$ K. As expected, the effects are more pronounced early in the evolution when the star is fully convective and the superadiabatic region is more extended. It should also be pointed out that an increase in the MLT parameter will dramatically increase the surface lithium depletion. Finally, let us mention that in its formulation, the MLT arbitrarily assumes values for certain constants whose effects on evolutionary tracks can be significant (see Henyey, Vardya, & Bodenheimer 1965).

2.4. Effects of the chemical composition

When observing young star forming regions, it is generally assumed that the chemical composition of the cloud is solar (Z=0.02). However this might not be the case (see e.g. Rubin et al. (1997) who found that Z=0.001 may be more appropriate for the metallicity of the Orion's clusters) and large uncertainty in the mass and age determination can ensue. Stars with higher metallicity (Z), i.e. with more metal atoms and thus absorption lines, have a larger opacity. They are more opaque to radiation and are consequently less luminous and cooler. From our computations (Fig. 2), we estimate that a shift of $\Delta Z \approx \pm\, 0.1$ produces a shift in $T_{\rm eff}$ of the order of 300K and of $\Delta \log L \sim \pm 0.2 L_\odot$ in luminosity. We also see that decreasing Z produces a larger shift in the tracks. This demonstrates that a careful determination of the chemical composition of the observed stars is particularly needed for a good derivation of stellar parameters.

2.5. Effects of rotation

The effect of rotation is to shift the PMS tracks towards lower effective temperatures and luminosities as a consequence of structural readjustments. However, the shifts depend on the initial conditions (initial rotation rate) and on the adopted angular momentum loss rate. Including rotation in the stellar structure equations produces effective temperature differences of the order of $\Delta T_{\rm eff}/T_{\rm eff} \lesssim 5\%$, i.e. $\sim 100 - 300\,$K (Martin & Claret, 1996). Note also that rotation can significantly affect the lithium depletion (e.g. Pinsonneault, Kawaler, & Demarque 1990; Martin & Claret 1996).

In this section, we have seen that given a stellar evolution code, the existence of free parameters and approximations in some theories make the position of PMS tracks uncertain. We estimate that for reasonable values of the parameters, the uncertainties are typically of $\Delta T_{\rm eff} \sim 100 - 200\,$K and $\Delta \log(L) \simeq \pm 0.1\,L_\odot$.

3. How reliable are mass and ages estimates ?

Given the above mentioned uncertainties in the modeling of PMS stars, we now estimate how these theoretical error bars affect the mass and age determination. We opt for a statistical approach and consider a sample of ~ 600 points that we place randomly and uniformly in the HR diagram in order to cover a large range of effective temperature and luminosity. Then, for each point we determine the mass (M_0) and age (t_0) from its location in the HRD, using reference tracks coming from Siess, Dufour, & Forestini (2000, hereafter SDF00) and covering the mass range $0.1 - 7.0 M_\odot$. In a second step, we shift the grid either in effective temperature or in luminosity by $\Delta T_{\rm eff} = \pm 100\,$K or $\Delta \log(L) = \pm 0.1\,L_\odot$, and rederive the new mass (M) and new age (t) coming out from these shifted tracks. The different values are compared using the variables $\Delta t = t(\text{shifted track}) - t_0$ and $\Delta M = M(\text{shifted track}) - M_0$. In our study, we also consider separately convective and radiative stars for which the evolutionary paths and masses are different.

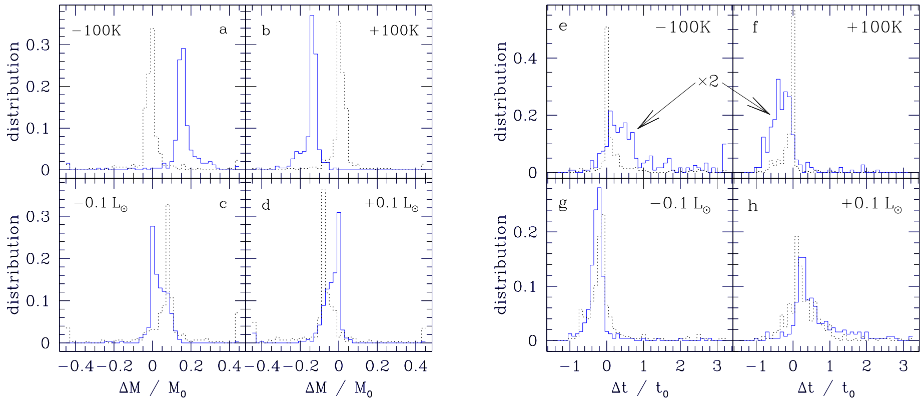


Figure 3. Distribution of mass (left) and age (right) uncertainties for pre-main sequence stars. The quantity ΔX represents the difference between the value of the variable X estimated from the shifted tracks and from the reference tracks. The shifts are equal to ± 100 K in effective temperature and to $\pm 0.1 L_\odot$ in $\Delta \log L$ and are labeled in each panel. The solid histograms refer to convective stars while dotted lines correspond to stars located on their radiative path. The sample encompasses $\sim$ 600 stars and the distributions are normalized.

3.1. Mass determination

For stars located on their radiative tracks, shifts in effective temperature of ± 100 K do not significantly alter the mass determination since radiative tracks are almost horizontal in the HRD. We observe (Fig. 3a-b, dotted lines) a typical spread about the standard value of $\Delta \mathrm{M}/\mathrm{M}_0 \sim 5\,\%$. Conversely, the mass determination of stars still located on their Hayashi path (solid lines) is substantially affected by these temperature shifts. *Hotter tracks systematically underestimate the stellar mass* by $\Delta \mathrm{M}/\mathrm{M}_0 \sim 15-20\,\%$, for the adopted $\Delta \mathrm{T}_{\mathrm{eff}}$. The simulations also indicate that the mass uncertainty is larger for the coolest stars, i.e. the less massive stars.

Shifting the tracks in luminosity does not greatly change the mass determination of convective stars since they evolve at almost constant effective temperature(Fig. 3c-d). We observe however a spread of the distribution with the more luminous tracks providing globally lower mass estimates ($\Delta \mathrm{M}/\mathrm{M}_0 < 0$). For stars located on their Henyey path, i.e. on their radiative track, the effects are more systematic : *stellar models more luminous underestimate the mass of the radiative stars.* The peak of the distribution is located at $\Delta \mathrm{M}/\mathrm{M}_0 = \pm 10\,\%$ from its standard position and the dispersion is small.

Finally, we also report that for certain stars that are developing a radiative core, large uncertainties of the order of $\Delta \mathrm{M}/\mathrm{M}_0 \sim 40\,\%$ have been detected.

3.2. Age determination

The determination of stellar ages is problematic because of the unclear definition of time zero (see e.g. D'antona & Mazzitelli 1997, hereafter DM97). We adopt here the same approach as D'antona and Mazzitelli (1994) which consists to

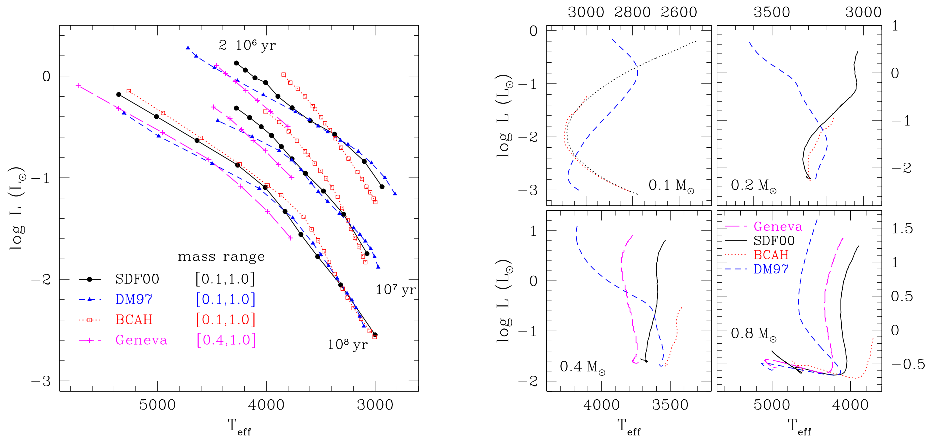


Figure 4. Comparative plots of the different isochrones (left panel) and evolutionary tracks (right panel) available in the literature. The models come from D'antona and Mazzitelli (1997, DM97, short-dashed line), Siess et al. (2000, SDF00, solid line), Charbonnel et al. (1999, Geneva, long-dashed line) and Baraffe et al. (1998, BCAH, dotted line)

begin the evolution at a point in the HR diagram of sufficiently high luminosity such that the Kelvin-Helmholtz timescale is relatively short, much less than some acceptable errors ($\tau_{KH} < 10^4$ yr). Then, we use the same method as before : we first determine the age of the stars from reference tracks and then from tracks that have been shifted either in effective temperature or luminosity by ± 100 K or $0.1\,L_\odot$, respectively. The general trend is that *stellar models cooler or more luminous overestimate the age.*

Figures 3e-f show that the age determination of radiative stars is slightly altered by shifts in effective temperature with a typical $\Delta t/t_0 \lesssim 10-20\,\%$. On the other hand, for stars located on their Hayashi track, the effects can be large since a shift in $T_{\rm eff}$ corresponds to a shift in the mass tracks. For convective stars, the distribution of age uncertainties is off-centered by $\Delta t/t_0 \sim \pm 40\,\%$ and presents a large dispersion of $\Delta t/t_0 \lesssim 80\,\%$, indicating that an accurate age determination is relatively illusive.

The effects of a luminosity shift are smaller ($\Delta t/t_0 \lesssim 10-20\,\%$) and evenly affect convective and radiative stars. Our study also indicates that in general, the largest age uncertainties are associated with the lowest mass stars ($M \lesssim 1\,M_\odot$). We also note that the age dispersion is quite large early in the evolution with $\Delta t/t_0$ as large as 4 for $t_0 \lesssim 1-2\times 10^6$ yr. Consequently, assigning an age for young stellar objects remains very hazardous.

4. Comparing different evolutionary tracks

4.1. Morphological differences

The differences between the pre-main sequence tracks available in the literature is a consequence of the problems associated with stellar modeling and exposed in §2. As shown in Fig 4, below $\sim 0.6\,M_\odot$, large discrepancies exist between the different sets of tracks. They result in part from different treatments of convection (the use of the convection models developed by Canuto and Mazzitelli (1991) by DM97 and use of the standard MLT prescription by the other groups), in part from the use of different boundary conditions (grey atmosphere models for DM97 and Charbonnel et al. (1999, hereafter geneva) and realistic atmosphere models for SDF00 and Baraffe et al. (1998, hereafter BCAH)) and also due to slightly different treatments of the thermodynamics. Above $\sim 0.6\mathrm{M}_\odot$, the tracks morphology is very similar and the disparities mainly result from different chemical compositions and/or values of α in the MLT since in this regime non-ideal effects are small and grey atmosphere models become a good approximation (see SDF00 for more details in this comparison). Finally, it should be pointed out that for VLMS, $\Delta\mathrm{T}_{\mathrm{eff}}$ can be as large as 500K !

4.2. Differences in the isochrones

Comparisons between the different isochrones is presented in Fig 4. We see that the slope of the BCAH isochrones is steeper, their VLMS are less luminous while their low-mass stars are more luminous. These tracks will consequently give younger ages for VLMS compared to what would be found using other sets of tracks. The discrepancies vanish when the stars reach the ZAMS. The DM97 isochrones are very similar to the SDF00 ones in the low mass end but for $\mathrm{M} > 0.5\,\mathrm{M}_\odot$ the DM97 isochrones are systematically less luminous. The Geneva models are systematically hotter (due in part to their use of grey atmosphere models) by $\sim 200\,\mathrm{K}$. Their 10 Myr isochrones would appear as old as 20 Myr with our tracks. Dealing with SDF00, their isochrones are intermediate between the DM97 and BCAH ones and the morphology is very similar to the Geneva isochrones. We also observe very good agreements between the isochrones below $\sim 0.4\,\mathrm{M}_\odot$ for $t > 10^7\,\mathrm{yr}$.

5. Effects of mass accretion

Accretion can significantly modify the morphology of PMS tracks depending mostly on the mass accretion rate and on the energetic associated with this process (Siess, Forestini, & Bertout 1997, 1999). Schematically, the evolution of an accreting PMS stars is depicted in Fig. 5 and proceeds as follows : The stars initially too cold ($\mathrm{T} < 10^6$ K) to allow deuterium burning contracts but due to the continuous mass deposition the evolutionary path is shifted towards higher effective temperatures. When the central temperature reaches 10^6 K, deuterium ignites in the center. The release of nuclear burning combined with the mass increase produce an expansion of the star and the track moves back up in the HRD, presenting a first "kink". When the total (initial + accreted) deuterium is ultimately depleted, contraction resumes. The star then follows an "homologous tracks" between successive mass tracks. Finally, at the end of the accretion process, the star relaxes but it will keep the memory of its accretion history for at least a Kelvin-Helmholtz timescale. Figure 5 also shows that during its radiative path, the accreting star is usually more luminous than in the standard case and from our previous study, it will appear younger than it is in reality.

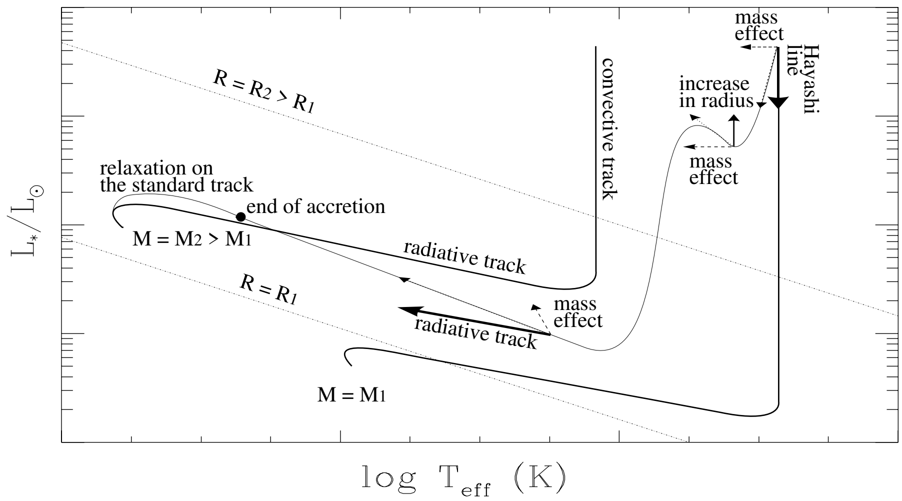


Figure 5. Schematic evolution of an accreting star in the HR diagram (see text for explanations)

In a previous study of the effect of mass accretion on the evolution of PMS stars, Siess et al. (1999) showed that the mass determination of accreting stars is slightly affected by this process with $\Delta M/M_0 \lesssim 5\,\%$. Concerning the age determination, different works (Siess et al. 1997, 2000; Hartmann, Cassen, & Kenyon 1997; Tout, Livio, & Bonnell et al. 2000) indicate that on the Hayashi region, accreting stars appear to be older than they are from standard computations while their age are underestimated in the Henyey region. However, the spread in the age estimates depends on the initial state of the star and of the accretion history (Tout et al. 2000). Nevertheless these determinations will always remain very uncertain before a few million years.

6. Conclusion

Both on the theoretical and observational side, errors are introduced in the determination of effective temperature and luminosity. These uncertainties can significantly affect the mass and age determination of PMS stars. In particular, we showed that an uncertainty $\Delta T_{\rm eff} = \pm\, 100$K and $\Delta \log L = \pm 0.1\, L_\odot$ makes the age determination of YSO very uncertain, with age estimates varying by a factor of 2 to 4 below 1-2 Myr. Our study also indicates that hotter or less luminous models underestimate stellar ages. The determination of stellar mass is less uncertain with typical error of the order of $\Delta M/M_0 \lesssim 10 - 20\,\%$ and the general trend is that hotter tracks underestimate the mass of convective stars while overluminous models give smaller masses for radiative stars.

Improving the determination of stellar parameters requires a better treatment of the constitutive physics of a stellar evolution code. Convection is probably the most critical aspect of stellar modeling since it affects both the interior and the atmosphere of cool stars. As mentioned in the introduction, a time-dependent, non-local and multi-dimensional theory is still lacking and efforts should concentrate on this issue. Rotation has also a potential impact on the location of the tracks but a realistic treatment of this process requires 2D simulations which are not yet available. Additionally, this modeling required a good knowledge of the evolution of the transport and loss of the angular momentum. Models including accretion have revealed to strongly modify stellar evolution and further progress in this field is also dependent on 2D computations. Finally, let us mention that a better knowledge of the initial conditions is crucial. As presented by G. Wuchterl in this volume, following the evolution of a star from its protostellar phase significantly changes its position in the HRD. In particular, the "collapse" tracks are cooler than classical ones by a few hundred Kelvin, deuterium is mostly burnt during the main accretion phase and the stellar structure is subject to slight changes.

On the observational side, more accurate conversion tables between colors and $T_{\rm eff}$ and a good estimate of the star's metallicity would also reduce the uncertainties on the mass and age determination. Although observations introduce some uncertainties, they will however allow us to bring strong constraints on PMS models and the determination of stellar masses from binary systems is very promising in this respect.

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