

Pre-Main Sequence Models for Low-Mass Stars and Brown Dwarfs

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Abstract. We present evolutionary models for young low mass stars ($m \leq 1M_{\odot}$) based on recent improvement of the theory: equation of state, atmosphere models, etc. We concentrate on early evolutionary phases from the initial deuterium burning phase to the zero-age Main Sequence. Evolutionary models for young brown dwarfs are also presented. We discuss the uncertainties of the present models. We analyse the difficulties arising when comparing models with observations for very young objects, in particular concerning the problem of reddening.

1. Introduction

Within the past years, important efforts have been devoted to the observation and the theory of very-low-mass stars (VLMS) and substellar objects (brown dwarfs BD and giant planets GP). The main theoretical improvements involve the description of the interior of these cool and dense objects (equation of state for dense plasmas, screening factors, etc...; see the review by Chabrier and Baraffe 2000) and the model atmosphere (molecular opacity, formation of dust, etc...; see the review by Allard et al. 1997). A major advance in the field is the development of a new generation of consistent models based on the coupling of interior and atmosphere models, providing direct comparison of evolutionary models with observations in colour-colour and colour-magnitude diagrams (CMD). Several observational tests, mainly provided by relatively old objects (age $\gtrsim 100$ Myr), now assess the validity of this theory devoted to stellar and substellar objects with masses $\leq 1M_{\odot}$. General agreement is found with (i) the mass - radius relationship of observed eclipsing binaries, (ii) mass - magnitude relationships in *VJHK* provided by binary systems, (iii) mass - spectral type

relationships for M-dwarfs, (iv) colour - magnitude relationships for intermediate age open clusters (Pleiades, Hyades, etc...), field disk M- and L-dwarfs, halo stars, and globular cluster Main Sequences and (v) spectra of M-dwarfs. Details and references for such confrontations of models with observations can be found in Chabrier and Baraffe (2000). Although some discrepancies between models and observations remain (see §2), uncertainties due to the input physics are now significantly reduced.

Numerous surveys devoted to the search for substellar objects have been conducted in young clusters with ages spanning from ~ 1 -10 Myrs, providing a wealth of data for pre-Main Sequence (PMS) objects. The reliability of the present theory for VLMS and BD allows now a thorough analysis for such PMS objects. Unlike older Main Sequence stars and BDs, comparison between observations and models for very young objects presents 3 major difficulties: (i) extinction due to the surrounding dust modifies both the intrinsic magnitude and the colours of the object, (ii) gravity affects both the spectrum and the evolution, (iii) the evolution and spectrum of very young objects ($t \lesssim 1$ Myrs) may still be affected by the presence of an accretion disk or circumstellar material remaining from the protostellar stage.

This paper is devoted to PMS models for VLMS and BDs and completes the work of Baraffe et al. (1998, BCAH98) which was essentially devoted to the comparison of models with observations of older objects ($t \gtrsim 100$ Myrs). We discuss the remaining uncertainties of the models (§2) and analyse their confrontation with available observations (§3).

2. Pre-Main Sequence Models

2.1. Evolutionary Tracks

The present models are based on the input physics described in Baraffe et al. (1998, and references therein). The robustness of these models is anchored in two areas: the microphysics determining the equation of state (EOS) in the stellar interior, and the outer boundary condition and synthetic spectra based on non-grey atmosphere models (Hauschildt, Allard & Baron 1999). Figure 1 shows evolutionary tracks from $0.02 M_{\odot}$ to $1 M_{\odot}$. The stellar/substellar transition is located at $\sim 0.075 M_{\odot}$, below which objects become partially degenerate and never reach thermal equilibrium characterising the Main Sequence. Evolutionary models start at the beginning of the initial deuterium burning phase. The deuterium burning minimum mass is $0.013 M_{\odot}$ (Saumon et al. 1996; Chabrier & Baraffe 2000). The D burning phase lasts less than 1 Myr for $m \gtrsim 0.2 M_{\odot}$, between 1 and 5 Myr for $0.05 \lesssim m \lesssim 0.2 M_{\odot}$ and almost 20 Myr for a $0.02 M_{\odot}$ brown dwarf. At such young ages, evolution is characterised by a rapid contraction of the object once central D is significantly depleted. Consequently, there is a significant variation of the surface gravity from $\log g \sim 3$ to ~ 4.5 from 1 Myr to 50 Myr, for the masses displayed in Fig. 1. Since the present atmosphere models (Hauschildt et al. 1999) assume the plan parallel approximation, we have checked its validity even for these low gravities. A comparison of these models with atmosphere models including effects of spherical geometry shows that the latter are important only for surface gravities $\log g \lesssim 2$ (Hauschildt,

Allard, Ferguson, et al. 1999). This is well below the range of gravities involved in the evolution of the present objects.

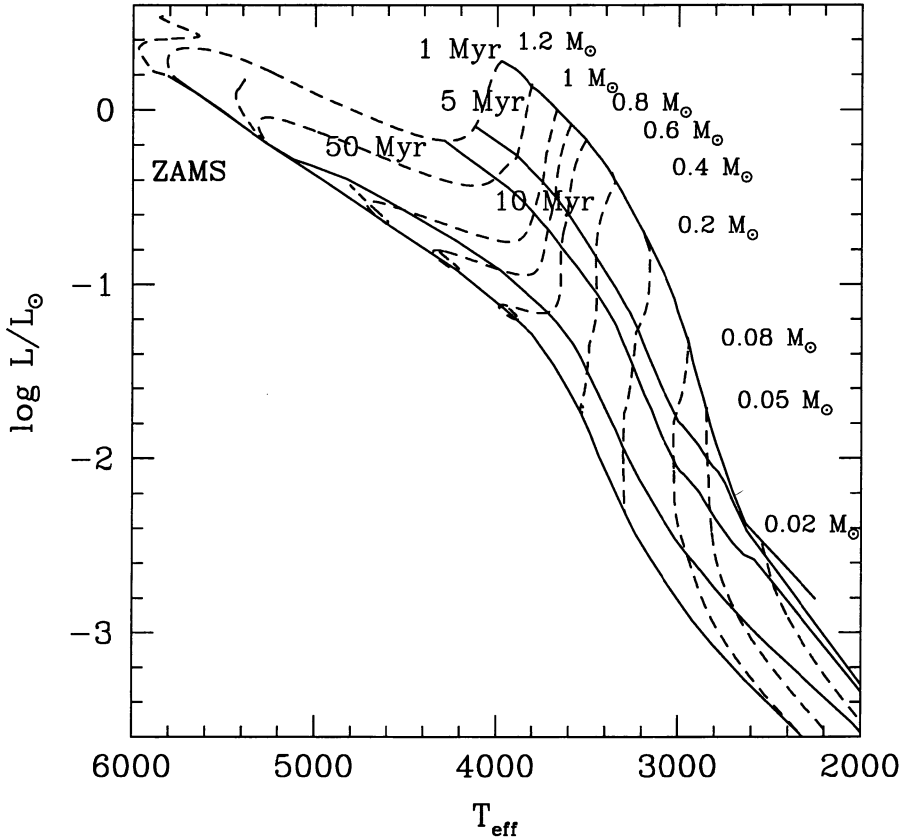


Figure 1. Evolutionary tracks in the Hertzsprung-Russell diagram for masses from $1.2 M_{\odot}$ to $0.02 M_{\odot}$ (dashed lines) and ages spanning from 1 Myr to the ZAMS (for stars). Several Isochrones for 1, 5, 10 and 50 Myr are indicated by solid lines from right to left. The location of the ZAMS, for stars down to $0.075 M_{\odot}$, is also indicated (left solid line).

2.2. Improvement and Uncertainties

As already mentioned, one of the main improvement in the modeling of VLMS and BDS is the use of outer boundary conditions based on realistic non-grey atmosphere models. As demonstrated by Chabrier & Baraffe (1997; and references therein) the use of radiative $T(\tau)$ relationships and/or grey atmosphere models is unvalid when molecules form near the photosphere, below $T_{\text{eff}} \sim 4000\text{K}$. Outer

boundary conditions based on the latter approximations yield hotter models for a given mass, as illustrated in Fig. 2a. Interestingly enough, masses up to $1 M_{\odot}$ are affected by the choice of the outer boundary condition, since at young ages evolution proceeds at significantly lower T_{eff} than on the MS for $m > 0.5 M_{\odot}$ (see Fig. 1). The use of an inappropriate outer boundary condition, such as the Eddington approximation, yields an overestimation of T_{eff} for a given m up to 300 K (see Fig. 2a).

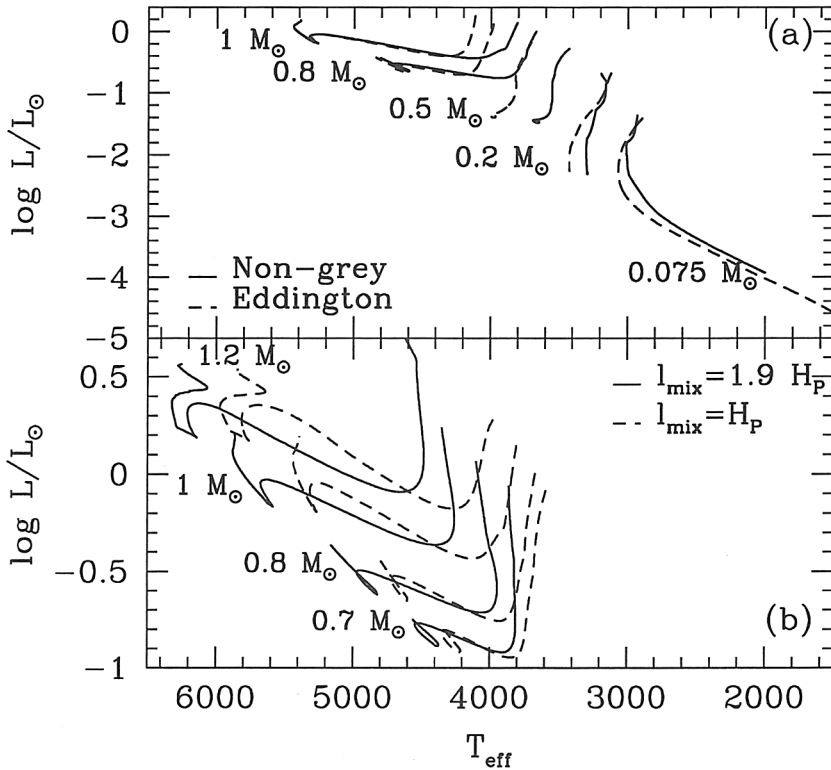


Figure 2. (a) Effect of the outer boundary condition on evolutionary tracks. (b) Effect of a variation of the mixing length l_{mix} .

One of the main uncertainty for masses $m \geq 0.7 M_{\odot}$ is due to convection. These stars show relatively extended superadiabatic outer layers, which are extremely sensitive to the treatment of convection. In the framework of the mixing length formalism, this translates into a sensitivity to the mixing length $l_{\text{mix}} \propto H_P$, with H_P the pressure scaleheight. Figure 2b illustrates the effect of a variation of l_{mix} on PMS tracks. For the present models, $l_{\text{mix}} = 1.9 H_P$ is

the value required to fit the Sun at its present age. Recently, Ludwig, Freytag & Steffen (1999) calibrated the mixing length parameter $\alpha = l_{\text{mix}}/H_{\text{P}}$ with 2D hydrodynamical models performed in the parameter space $4300 \text{ K} \leq T_{\text{eff}} \leq 7100 \text{ K}$ and gravities $2.54 \leq \log g \leq 4.74$. They found a moderate variation of the mixing length parameter around typically 1.5. Fig. 2b shows that a variation of α from 1 to 1.9 yields an increase of T_{eff} up to 500K for the highest masses during their PMS evolution. For masses $m \lesssim 0.7M_{\odot}$, the size of the superadiabatic layers reduces and the transition from the convective to the radiative outer layers is characterised by an abrupt transition from a fully adiabatic to a radiative structure. The sensitivity of the models to l_{mix} is thus small, in the framework of the mixing length formalism. To confirm this low sensitivity, however, multi-dimensional simulations as done by Ludwig et al. (1999) must clearly be extended below $T_{\text{eff}} \leq 4300 \text{ K}$.

Finally, although huge improvement was done in the field of molecular opacities (see Allard et al. 1997), reducing considerably the uncertainties of non-grey atmosphere models and synthetic spectra, some shortcomings still remain. As mentioned in BCAH98, the present models still show a ~ 0.5 mag discrepancy with observations in optical *VRI* colour - magnitude diagrams. This problem was partly identified as a shortcoming in the TiO line list, one of the main absorber in the optical. A new TiO line list recently computed by Schwenke (1998) improves indeed the situation (see Fig. 3a), although some discrepancies with observations in $(V - I)$ (see Fig. 3a) and $(R - I)$ colours still remain (see Chabrier et al. 2000). The effect of the new TiO line list is illustrated in Fig. 3a, where disk field objects of Monet et al. (1992) and Dahn et al. (1995) are also displayed. Although the new TiO line list reduces significantly the discrepancy with observations (cf. Fig. 3a), the fit of the models to the data is not perfect yet for objects fainter than $M_{\text{V}} \sim 10$. Moreover, as illustrated in Fig. 3b in near-IR colours, the use of this new TiO line list affects the spectrum in the near-IR, and worsens the excellent agreement with observational data from the Pleiades in $(I - K) - M_{\text{I}}$ obtained previously with the BCAH98 models. Another uncertainty appears in the water molecular linelist. BCAH98 uses the list of Miller et al. (1994) which is known to be incomplete for high energy transitions. Although a more complete linelist was recently computed by Partridge & Schwenke (1997), it still presents shortcomings and yields large discrepancies with photometric observations in the near-IR above $T_{\text{eff}} \gtrsim 2300\text{K}$, as illustrated in Fig. 3b (dash-dotted line).

Given the problems with the current linelists, improvement of the present evolutionary models have to await the computation of more reliable H_2O , and to a lesser extend TiO, linelists. Although the different molecular linelists mentioned above affect significantly the spectra and colours, they hardly affect the deeper atmospheric layers, and therefore the outer boundary condition to the interior. Thus, their effect on evolutionary models in terms of T_{eff} and L is small. The use of the new TiO and/or water linelist does not affect evolutionary models by more than 100 K in T_{eff} and 10% in L at a given age. This illustrates the remaining (small) uncertainty of the models from the evolution viewpoint due to molecular opacities. Below $T_{\text{eff}} \lesssim 2300\text{K}$, grain formation starts to affect both the spectrum and the evolution, and must be taken into account (cf. Chabrier et al. 2000). This is out the scope of the present paper, which is based

on dust-free models. Only substellar objects with $m \lesssim 0.01M_{\odot}$ and older than 1 Myr are affected by dust formation.

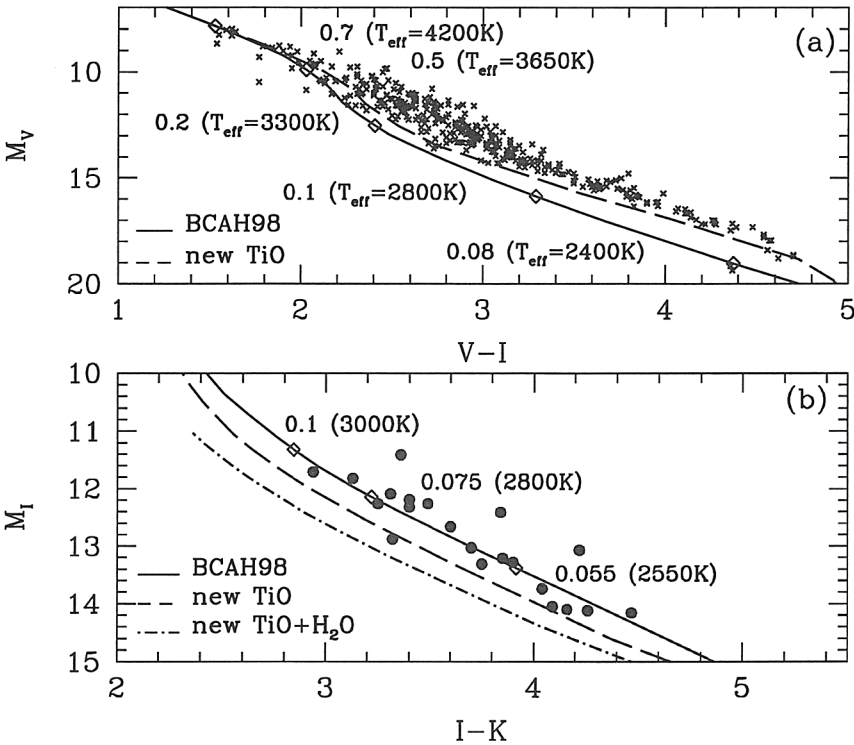


Figure 3. (a) Effect of the TiO line list on models in a $(V - I) - M_V$ diagram. The solid line corresponds to an isochrone of 1 Gyr based on the present models (BCAH98). The dashed line correspond to models computed with the new TiO line list, for the same age. Observations (crosses) are disk field stars from Monet et al. (1992) and Dahn et al. (1995). Masses (in M_{\odot}) and T_{eff} are indicated and correspond to the open diamonds on the solid line. (b) Effect of TiO and H_2O line lists on models in a $(I - K) - M_I$ diagram. The solid and dashed lines are the same models as in (a) for an age of 120 Myr. The dash-dotted line corresponds to models with new TiO and H_2O linelists, for 120 Myr. Observational data (full circles) belong to the Pleiades, corresponding to an age of 120 Myr (Martín et al. 2000).

3. Comparison with Observations

The previous section describes uncertainties inherent to the input physics of VLMS and BDs models. For PMS models specifically, another important source of uncertainty comes from the choice of initial models. The present models are

based on extremely simplified assumptions, starting shortly before the deuterium burning phase in an initially fully convective configuration, and neglecting the protostellar accretion phase. These assumptions are standard (see also Siess et al. 2000). Some attempts exist to use more sophisticated initial conditions based on protostar models (see Palla & Stahler 1999; and references therein). Given however the complexity of star formation processes and protostellar collapse calculations (see Masunaga, Miyama & Inutsuka 1998; Masunaga & Inutsuka 2000; and references therein; Wuchterl, this conference), many problems are to date unsolved and the link between the dynamical phase of collapse and the quasi-static phase of evolution is still very obscure.

Testing different initial conditions, we find out that after a few Myr they become inconsequential and models converge toward the same track. However, these tests are still based on relatively simple assumptions. The comparison of PMS tracks with observations of very young objects can improve our understanding of the protostellar collapse phase and can tell us at which stage initial conditions become important.

Because of the problem of large reddening in young clusters, direct comparison of observations with models in colour - magnitude diagrams are extremely uncertain. There are only a few exceptions, such as σ Orionis which exhibits low extinction. Recently, Béjar et al. (1999) and Zapatero et al. (1999) obtained optical and near-IR photometry for low mass objects in this cluster. The data are well reproduced by a 5 Myr isochrone based on the BCAH98 models in a $(I - J) - M_I$ CMD (see Fig. 1 of Zapatero et al. 1999), down to $0.015 M_{\odot}$. Such observations are extremely important, since they provide the best opportunity to determine the Initial Mass Function (IMF) down to the substellar regime (see Béjar et al. 2000). Indeed, for such young clusters, no significant dynamical evolution is expected and their mass function should be close to the true IMF.

Young multiple systems provide also excellent tests for PMS models at young ages, because of the expected coevality of their different components. In addition, another strong constraint is supplied by the estimate of dynamical masses based on the orbital motion of circumstellar/circumbinary disks (Simon, Dutrey & Guilloteau 2000; Simon, this conference). One of the best example is provided by the quadruple system GG TAU (White et al. 1999; White, this conference), with components covering the whole mass-range of VLMS and BDs from $1 M_{\odot}$ to $\sim 0.02 M_{\odot}$. Orbital velocity measurements of the circumbinary disk surrounding the two most massive components imply a constraint on their combined stellar mass (Dutrey, Guilloteau & Simon 1994; Guilloteau, Dutrey & Simon 1999). This mass constraint and the hypothesis of coevality provide a stringent test for PMS models. Models based on non-grey atmospheres (BCAH98) are the only ones consistent with these observations (for details see White et al. 1999; Luhman 1999).

Two major difficulties remain however when comparing the models with such data: (i) the spectral type classification and (ii) its transformation to T_{eff} based on a T_{eff} - scale. Young objects are expected to show spectral features between that of giants and dwarfs, and a better representation of their spectral properties may require a new classification more appropriate to these intermediate surface gravities. The transformation of the inferred spectral type to T_{eff} is even more difficult, because of the lack of reliable T_{eff} - scales for such young

T Tauri like objects. Significant efforts were devoted within the past years to the elaboration of improved T_{eff} - scales for M-dwarfs (Leggett et al. 1996) and M-giants (Perrin et al. 1998; van Belle et al. 1999). However, work remains to be done for T Tauri like objects. Recently, Luhman (1999) defined a T_{eff} - scale intermediate between giants and dwarfs and based on the isochrone of the BCAH98 models which passes through the 4 components of GG Tau. Interestingly enough, applying this T_{eff} - scale to young clusters such as IC348 (Luhman 1999) and star forming regions (Chamaeleon I, Comerón, Neuhäuser & Kaas 2000), the cluster members show a small scatter in age and no apparent trend of a correlation between age and mass. As mentioned by Comerón et al. (2000), this suggests an almost coeval population in Chamaeleon I which formed within less than 1 Myr. Confirmation of this property in other young clusters is urgently required to improve our understanding of the starformation timescale in young stellar associations.

4. Conclusion

The good agreement of models based on improved physics with observations for relatively old ($t \gtrsim 100$ Myr) VLMS and BDs now yields good confidence in the theory of these objects. Such evolutionary models can now be confronted to the complex realm of very young objects, thus providing important informations on star formation processes and initial conditions for PMS models. Although based on extremely simple initial conditions (no accretion phase, no account of protostellar collapse phase and timescale), these models are the most consistent with present observations of very young objects (estimate of dynamical masses, tests of coevality in multiple systems, CMD, etc.). Such consistency must be confirmed with more observational tests and the elaboration of a reliable T_{eff} -scale, in order to guide protostar collapse models, which at some age must converge toward the PMS tracks.

Note: Tracks from $0.02 M_{\odot}$ to $1.2 M_{\odot}$ and $t \geq 1$ Myr are available by anonymous ftp:

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ftp ftp.ens-lyon.fr
username: anonymous
ftp > cd /pub/users/CRAL/ibaraffe
ftp > get README
ftp > get BCAH98_models.*
ftp > quit
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