New pre-MS evolutionary tracks and planet formation

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Abstract.

I present the first study of early stellar evolution that starts with 'cloud'-conditions and uses a system of equations that contain a solar model solution. All previous studies of protostellar collapse either make numerous assumptions, specifically tailored for different parts of the flow and different parts of the evolution or they do not reach the pre-main sequence phase. I will show how critical, isothermal equilibrium 'Bonnor-Ebert' spheres of 0.05 to 10 solar masses appear on the pre-main sequence. Based on a new proposal for the definition of stellar zero age I will discuss the resulting star formation times, mean mass accretion-rates and median luminosities and their time-dependence. Properties of young brown-dwarfs and proto giant planets are determined from in-situ formation theories. By utilizing the new age-concept luminosities of these substeller objects are compared to those of the theoretical young stellar population.

1. Introduction

Present stellar evolution theory mostly deals with stars that are in hydrostatic equilibrium, where gas pressure balances gravity. The motion and inertia of stellar gas are usually neglected. The starting point of stellar evolution calculations is the early pre-main sequence phase. One important aim of star formation theory being still an unsolved problem is to provide the initial conditions for stellar evolution, i.e., the masses, radii and the internal structure of young stars as soon as they can be considered to be in hydrostatic equilibrium for the first time. The calculation of appropriate starting conditions for stellar evolution is complicated by the fact that, in general, young stars still accrete mass. Therefore, the hydrostatic parts of young stars and their photospheres are more or less directly connected to circumstellar material, being in motion due to mass-inflow and/or outflow. Both moving circumstellar matter and the accretion process are by nature non-hydrostatic. Flows that contain both the hydrostatic protostellar core and the hydrodynamic accretion flow must be calculated by using at least the equations of radiation hydrodynamics including convection and cause a wealth of technical difficulties.

Modelers of early stellar evolution and the pre-main sequence phase have therefore relied on simplified concepts to make the problem tractable. Originally, Hayashi et al. (1962) argued that the cloud collapse should be so fast that the fragment would evolve adiabatically to stellar conditions and the hydrostatic young star would appear as an isentropic sphere radiating at high luminosities, thus causing a fully convective structure, close to the top of the Hayashi-track. Larson (1969) showed that radiative losses during collapse are substantial and early collapse would proceed isothermally. The following detailed direct calculations of protostellar collapse faced a number of technical difficulties and could not predict PMS stellar properties. An alternative was to use simplified, sometimes semi-analytical concepts to characterize the collapse and accretion flow with key parameters (mass of stellar embryo, mass accretion rate) chosen after careful consideration of empirical and theoretical results. Once the mass is chosen, the initial entropy and radial entropy structure has to be specified before the initial model can be constructed. The choice of entropy essentially results in a value for the stellar radius. To be sure that the details of the star formation process, or more precisely, the specific initial conditions do not influence such studies, the initial luminosities are chosen to be very high. If they are sufficiently high, the later evolution rapidly becomes independent of the earlier evolution.

Thus the theoretical knowledge about protostellar collapse and the pre-main sequence remained separated. On the one hand, modeling based on classical stellar structure theory was able to produce pre-main sequence tracks that could be related to observations if the question about the initial entropy distribution was put aside. On the other hand, models of the protostellar collapse revealed the entropy structure to be a signature of the accretion history, but were unable to provide pre-main sequence observables needed to be confronted with observations.

Recent advances, both in computational techniques and in the modeling of time-dependent convection, now make it possible to calculate the pre-main sequence evolution directly from cloud initial conditions by monitoring the protostellar collapse until mass accretion fades and the stellar photosphere becomes visible. I present the results of such calculations for cloud fragments of masses ranging from 0.05 to 10 $M_\odot$ and discuss the consequences for the hydrostatic stellar evolution on the pre-main sequence. A more detailed discussion of the results presented here might be found in Wuchterl and Tscharnuter (2000).

My apologies to the reader, that due to the space limitations I cannot address the planetary issues, as in the conference talk.

1.1. Model equations

I use the equations of radiation hydrodynamics (RHD) in the grey Eddington approximation and with spherical symmetry in their integral form. Convective energy transfer and mixing is included by using a new, time-dependent convection model (Wuchterl and Feuchtinger 1998) derived from the model of Kuhfuß (1987). It closely approximates standard mixing length theory in a local, static limit and has been successfully tested in calculations of the Sun and RR Lyrae pulsations (Wuchterl and Feuchtinger 1998). The convection model is used with the standard parameters given in Wuchterl and Feuchtinger (1998). Where the mixing length parameter α_{ML} is changed it is explicitely noted.

Detailed equations of state (Wuchterl 1989, 1990) and opacities for a (proto) solar composition are used (Yorke 1979, 1980a), Alexander and Ferguson (1994), Weiss et al. (1990); compilation by Götz 1993, X = 0.77, Y = 0.213, Z = 0.017,

$X_D = 3.85\,10^{-5}$). Convective mixing of Deuterium and Deuterium burning (with reaction rates from Caughlan and Fowler 1988) are included.

The equations are solved with a 'protostellar' version of the VIP-code (Dorfi and Feuchtinger 1995), where convection is added as outlined by Wuchterl (1995a).

2. Collapse of Bonnor-Ebert spheres

In this section I discuss the results for the collapse of critical Bonnor-Ebert spheres with a temperature of 10 K and masses of 0.05 to 10 $M_\odot$ within a constant volume, as obtained by the methods described above.

The results described below are quantities derived from the flows which are obtained as the solution for the Bonnor-Ebert collapses. Since there is no a priori hydrostatic part and no a priori photospheric model in the model (they result as special properties of the solutions of the flow equations) I briefly describe how the stellar parameters age, effective temperature, radii and masses are obtained from the radiation hydrodynamical flows. I restrict the discussion mostly to these basic parameters to give an overview over the collapse solutions. I start the discussion with a proposal for the definition of zero stellar age, because as it turns out, most definitions of stellar parameters will only be valid after this instant of time.

2.1. Stellar zero age

To compare the luminosities of objects of various masses at a given age a general definition of zero age is necessary. As the thermally controlled Kelvin-Helmholtz contraction is the dominating evolutionary process in young gas spheres, whether they are giant planets, brown dwarfs or stars, I propose, to use the instant of time, when the interior of the gas spheres is thermally enclosed for the first time, as age zero. The enclosure means that photons cannot escape from the entire object directly but are radiated from a photosphere. Energy transfer to the photospheric bottleneck then delays the cooling and determines how the thermal reservoir in the interior is emptied. The cooling history can then be used to define an age since the heat reservoir was formed. As a practical definition for age zero I propose to use the instant of time when the Rosseland mean optical depth of a gaseous object equals 2/3, i.e.,

$$\mathrm{Age} = 0 : \tau_{\mathrm{Ross}}(t) = \int_{r'}^{R} \kappa_{\mathrm{Ross}} \varrho \, dr = \frac{2}{3} \,. \tag{1}$$

I use 2/3 here because of the advantage for, e.g., the T_{eff} definition in the comparison to D'Antona and Mazzitelli (1994) but recommend to use Age = 0 at $\tau_{\mathrm{Ross}}(t) = 1$, in general. For a protostar this instant of time is practically at the end of the isothermal phase of the collapse. Furthermore, with definition (1) the luminosities of the protoplanets can be compared to stars and brown dwarfs of similar age. We can now study the luminosity emitted by the cloud volume as a function of age. In the beginning the luminosity comes from the still almost isothermal cloud fragment, in the end from the pre-main sequence star that has formed in the centre.

2.2. Luminosity and effective temperature

The optical depth radius, R_τ, is determined by searching for the radius r' at which the Rosseland-mean optical depth is 2/3. With the luminosity at the outer boundary and R_τ, I determine an effective temperature, by

$$L = 4\pi R_\tau^2 \sigma T_{\mathrm{eff}}^4 \,. \tag{2}$$

These are the T_{eff}-values plotted in the Hertzsprung Russell diagram. To give an estimate for the uncertainty involved when placing a protostar into the diagram I additionally plot two alternative temperature definitions in Fig. 1: (1) a temperature $T(R_T)$based on the temperature radius, R_T, that is governed by

$$r = R_T : L(r) = 4\pi r^2 \sigma T(r)^4 \,, \tag{3}$$

cf. Baschek et al. (1991). This is the temperature at a distinct point in the flow where the luminosity corresponds to the value that would be obtained by a blackbody radiating at the local flow matter-temperature. (2) a photospheric temperature defined by

$$T_{\mathrm{phot}} = T(R_\tau) \,, \tag{4}$$

i.e., the local flow temperature at the optical depth radius. It is a measure of the temperature at the location from which the photons typically escape towards an observer.

2.3. Collapse of a solar mass

The resulting theoretical Hertzsprung-Russell diagram for the collapse of a 1 $\mathrm{M}_\odot$ Bonnor-Ebert sphere is shown in Fig. 1. In this case the mixing length parameter α_{ML} is chosen to be 1.4 to facilitate the comparison with the fully hydrostatic pre-main sequence calculation. The thick line shows the evolutionary track in the Hertzsprung-Russell diagram by using the effective temperature based on the optical depth radius R_τ. The track starts at the instant of zero age, indicated by the diamond symbol. Temperatures given before zero age (dash-dotted part) are central temperatures of the still transparent, almost isothermal cloud. With the onset of accretion onto the core the luminosity rises sharply with a moderate increase in T_{eff}. The 'mouse-head' is the hall mark of the formation of the second (inner) atomic hydrogen core that forms after the (second) collapse of the dissociating molecular hydrogen core. At the cusp after the first luminosity maximum the final accretion phase is entered. As the luminosity rises towards the second maximum, the first core is accreted onto the second one and the Mach numbers of the flow increase above ten. The small luminosity decrease after the second maximum accompanies the adjustment of the accretion flow and the mass accretion rate onto the final core to the substantial luminosity now radiated from the accretion shock.

When the luminosity starts rising again the quasi-steady main-accretion phase commences. Shortly after the flat top part of the track is reached the luminosity, due to D burning, becomes significant and reaches a maximum of 60% at the global luminosity maximum. When the volume is significantly depleted by the accretion process the luminosity starts decreasing and T_{eff} rises as parts of the flow closer to the young star become visible. When the dust cocoon becomes transparent the optical depth radius 'jumps' into the 'stellar' photosphere

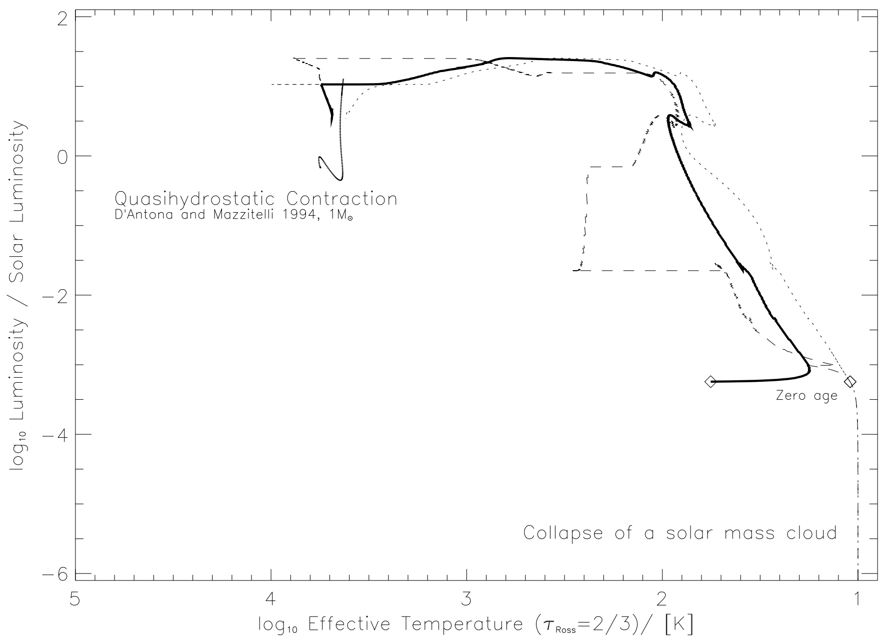

Figure 1. Early stellar evolution in the Hertzsprung-Russell diagram: Comparison of results for the collapse of a $1\,\mathrm{M}_{\odot}$, 'Bonnor-Ebert' sphere (thick line) and a classical pre-main sequence track (*thin line*). Both are for mixing length convection, with $\alpha_{\mathrm{ML}} = 1.4$. The classical PMS-track (thin line on the left) is the $1\,\mathrm{M}_{\odot}$, 'MLT Alexander', case after D'Antona and Mazzitelli 1994. The *thick line* for the cloud collapse uses T_{eff}. Alternative temperatures are given for the cloud collapse results: The *dashed line* is the temperature based on the *temperature radius* as discussed by Baschek et al. (1991). The *dotted line* gives $T = T_{\mathrm{phot}}$. The two diamonds indicate zero age. See text for details.

the effective temperature sharply increases, crosses the classical PMS-track, the Hayashi line and finally reaches the 'corner' of the collapse track, at maximum T_{eff}. From this point on T_{eff} coincides with the temperature definition based on the temperature radius (thick and dashed line overlap).

Hence the radiation hydrodynamical results for temperature based on R_T and R_τ converge to the equality valid in classical, hydrostatic photospheres. The photospheric temperature (dotted) at $\tau = 2/3$, passes the shock at this instant and produces a sharp spike to the left as $\tau = 2/3$ is at the peak temperature just downstream from the accretion shock, and still upstream from the radiative relaxation layer. As the accretion luminosity becomes negligibly small and after 'D burnout' the collapse track turns almost parallel to the classical track, slightly pointing towards the ZAMS location of the Sun on the classical track. The photospheric temperature remains different from the other two temperatures, and slightly cooler than the T_{eff} value of the fully hydrostatic classical track. Note that the photosphere of the collapse calculation is convective all along the Hayashi-part of the track and $T_{\mathrm{phot}} = T_{\mathrm{eff}}$, valid for a compact, hydrostatic, radiative photosphere in Eddington approximation is not guaranteed under these conditions.

2.4. Collapse PMS-tracks and isochrones

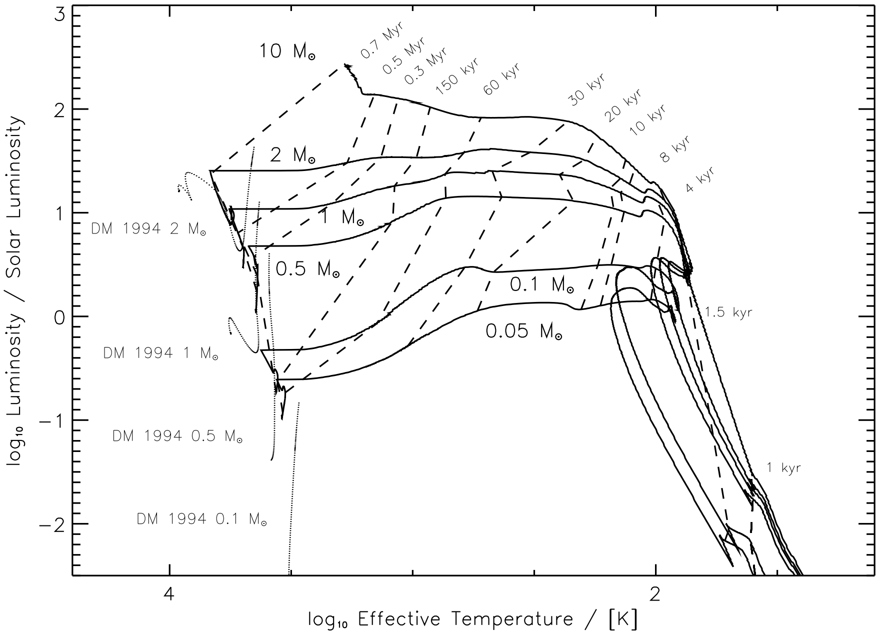

Figure 2. Evolutionary tracks in the Hertzsprung-Russell diagram for the collapse and early pre-main sequence evolution of 0.05, 0.1, 0.5, 1, 2 and $10\,\mathrm{M}_{\odot}$ cloud fragments (*full lines*). The *dashed lines* indicate isochrones for the collapse tracks, labeled with the respective ages. Zero age is defined here as the moment when the respective cloud fragment becomes optically thick and the interior is thermally locked as the first photosphere forms (Rosseland mean optical depth reaches 2/3). Quasi-hydrostatic tracks for $0.1, 0.5, 1$ and $2\,\mathrm{M}_{\odot}$ from D'Antona and Mazzitelli (1994), 'Alexander MLT'-case, $\alpha_{\mathrm{ML}} = 1.4$ (*dotted lines*) are plotted for comparison.

In Fig. 2 an overview over the collapse and PMS evolution of Bonnor-Ebert-sphere cloud fragments with masses of 0.05, 0.1, 0.5, 1, 2 and $10\,\mathrm{M}_{\odot}$ is given. They are compared to classical, non accreting, fully hydrostatic tracks for 0.1, 0.5, 1, and $2\,\mathrm{M}_{\odot}$ after D'Antona and Mazzitelli (1994). For the comparison an electronic version of their 'Alexander, MLT'-tracks for $\alpha_{\mathrm{ML}} = 1.4$ was used.

The early evolution dominated by the initial cloud collapse is very similar for all masses. At an age of 1000 yr the first hydrostatic cores form, with an age spread of a few hundred years. All fragments enter the main accretion phase at an age slightly above 8 kyr. All tracks remain below effective temperatures of 2000 K up to 30 kyr. The protostars still remain in their dust cocoons and radiate from dust photospheres. The luminosity decline has already started at this age for the lowest mass fragment. At 60 kyr the first object has arrived on the pre-main sequence, close to the Hayashi track. It has formed from the lowest mass cloud fragment of $0.05\,M_{\odot}$ and is a young brown dwarf. The higher mass fragments follow until the $2\mathrm{M}_{\odot}$ fragment arrives on its PMS-track at 0.5 Myr. The $10\,\mathrm{M}_{\odot}$ fragment is still accreting at 0.7 Myr, with a hydrostatic central stellar embryo of $4.5\,\mathrm{M}_{\odot}$.

A detailed comparison with the classical tracks (dotted line) during the later phases can be made using the magnification in Fig. 3. The displayed part of

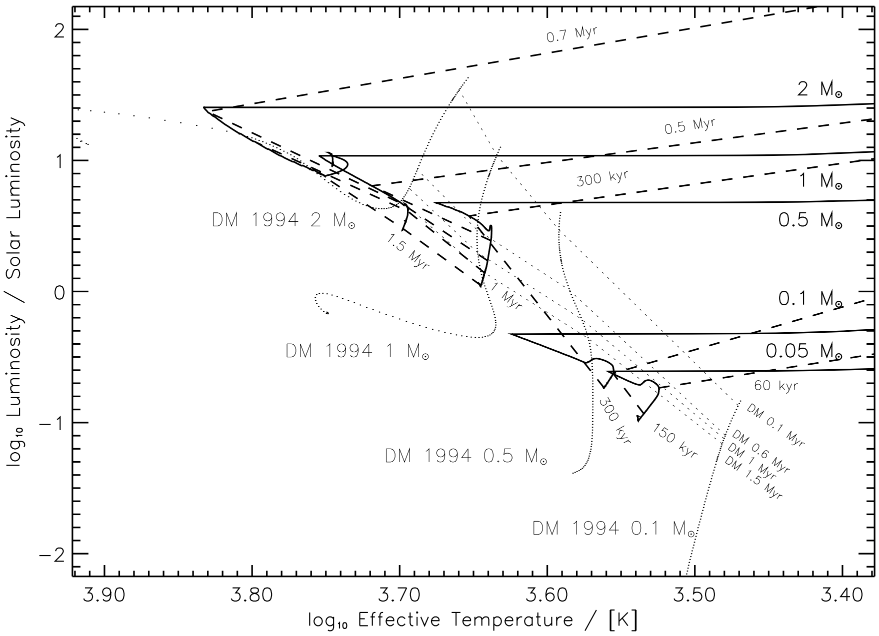

Figure 3. Hertzsprung-Russell diagram for the early pre-main sequence evolution of $0.05, 0.1, 0.5, 1$ and $2\,\mathrm{M}_{\odot}$ cloud fragments (*full lines*), detail of Fig 2. The *dashed* lines are isochrones for the collapse tracks, labelled with the respective ages. Zero age is defined here as the moment when the respective cloud fragment becomes optically thick and the interior thermally locked as the first photosphere forms (Rosseland mean optical depth reaches 2/3). Quasi-hydrostatic tracks for $0.1, 0.5, 1$ and $2\mathrm{M}_{\odot}$, (*dotted tracks*) and the corresponding isochrones for $0.1, 0.6, 1$ and $1.5\,\mathrm{Myr}$, (*dotted lines labelled with ages*) (D'Antona and Mazzitelli 1994, 'Alexander + MLT'-case, $\alpha_{\mathrm{ML}} = 1.4$) are shown for comparison. Note that, e.g., $0.5\,\mathrm{M}_{\odot}$ at $1\,\mathrm{Myr}$ (collapse) corresponds to $1\,\mathrm{M}_{\odot}$ at $1.5\,\mathrm{Myr}$ (classical).

the HRD essentially covers the evolutionary phases after the final stellar photospheres become visible. The horizontal parts of the collapse tracks are due to the sharp rise in effective temperature when the dust cocoon becomes optically thin and the photons start to escape directly from the stellar photosphere below the fading accretion shock. In general the collapse tracks appear about 0.05 to 0.09 dex hotter on the pre-main sequence than the classical tracks. The differences are not due to differences in opacities, the convection theory or the treatment of frequency dependent radiation transfer. This is assured by careful selection of the hydrostatic comparison-tracks. The accretion luminosity produced by the shock does not contribute significantly to this difference once the tracks are nearly vertical. I think that the primary reason for the increased T_{eff}, at given luminosity is the different thermal structure with an off-centre peak-temperature, that results in more compact objects.

The early PMS evolution of the collapsed cloud fragments shows a relation to the classical tracks that changes with mass. The $2\,\mathrm{M}_{\odot}$ fragment arrives close to the radiative, Henyey part of the corresponding classical track. The $1\,\mathrm{M}_{\odot}$ and the $0.5\,\mathrm{M}_{\odot}$ case arrive on the PMS with a luminosity corresponding to about half way down on the convective, Hayashi parts of the classical tracks. The $0.1\,\mathrm{M}_{\odot}$ fragment arrives with a luminosity corresponding to the top of the classical track. The $0.05\,\mathrm{M}_{\odot}$ fragment (a proto brown dwarf) is shown to give an indication of the further mass dependence of the relation to the $0.1\,\mathrm{M}_{\odot}$ classical track. For the two lowest masses the age difference can be attributed to an offset in zero age. The results of the collapse calculations indicate substantial corrections in PMS stellar properties for masses of $0.5\,\mathrm{M}_{\odot}$ and higher. PMS objects of these masses already are half-way in the direction of the Henyey-track when they become visible.

3. Conclusions

A study with spherical symmetry can certainly not address all aspects of the star formation process, as magnetic fields and angular momentum are ingnored, but it has the advantage that the process can be studied by keeping close to basic physical principles—at least as close as stellar evolution theory, with the notorious problem of the convection model.

The results can be summarized as follows:

- the star formation processes, i.e., the protostellar collapse translates initial cloud conditions into initial stellar thermal structure,
- pre-main sequence evolution depends qualitatively and quantitatively on the collapse flows;
- D burning ignites and mostly occurs during the accretion phase for cloud fragments of 0.5, 1, 2, and $10\,\mathrm{M}_{\odot}$;
- I confirm that protostars and PMS objects have an outer convective shell and a central radiative zone;
- the radiative core lasts at least to a (new) age of 1.5 Myr for cloud fragments of 0.5, 1, and $2\,\mathrm{M}_{\odot}$ and I expect off-centre ignition of hydrogen burning;
- collapse pre-main sequence tracks are initially cooler than classical tracks. Later they *cross* the Hayashi line rapidly and start their quasi-classical

decent along a mixed radiative/convective contraction track. After the final stellar photosphere becomes visible they appear to the left of the Hayashi lines. Typically at 0.05 dex hotter effective temperatures than the corresponding classical, fully hydrostatic pre-main sequence model;

- collapse ages below 2 Myr are up to a Myr larger than classical ages for the same luminosity.

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