From Darkness to Light
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Protostellar collapse and the evolution towards and on the pre-main sequence

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Abstract. I discuss star formation based on calculating the cloud collapse. The pre-main sequence evolution of a young star is followed concurrently with a determination of the accretion flow. Both, star and accretion flow, are obtained simultaneously by solving the equations of radiation hydrodynamics for various cloud fragments. Hence mass and accretion-rate are a result of the calculations rather than being an assumption that enters the model.

The resulting properties of young stars during the embedded and pre-main sequence phases are discussed for cloud fragments that are assumed to be marginally gravitationally unstable, isothermal, equilibrium, 'Bonnor-Ebert' spheres.

The resulting protostars of 2 $M_\odot$ appear close to the location of the Henyey part of the respective classical evolutionary track and at substantially larger ages for given luminosities than inferred from previous calculations. 1 $M_\odot$ stars appear at lower luminosities, to the left of the Hayashi-tracks and are about 1 Ma older than on a classical track at the same luminosity. They burn most of their Deuterium during the main accretion phase before mass accretion halts and they become visible. They do not become fully convective during the entire evolution calculated, i.e., up to 1.5 Ma.

1. From darkness to light

Star formation is a transition from darkness to light. The conditions in a molecular cloud are of very low density and the clouds are transparent for the radiation at the frequencies that carry most of the energy. Hence the built-up of large thermal reservoirs and high luminosities is counteracted by efficient cooling. Stable clouds remain isothermal and at low luminosity. Stars have roughly the density of water and are very opaque for light of all wavelengths. Hence heat generated in their interiors is trapped and can only escape once it has been transferred to the photosphere. To perform this energy transfer, substantial temperature gradients are built up. The stellar interiors therefore become hot for any significant energy source, gravitational compression being the dominant one for the youngest stars. Their interiors contain an amount of energy that takes of the order of million years to be radiated away at typical stellar luminosities. Star formation may therefore be viewed as transition from transparent isothermal 'cloud' states at low temperature to dense, opaque hot 'stellar' states. The pre-main sequence evolution is the transition of the 'optically trapped', opaque thermal structure produced by the protostellar collapse to the thermal structure on the main sequence that is produced by the balance between stellar surface radiation losses and nuclear energy generation. Naturally the question arises of how much this transition from collapse generated thermal structure to main sequence 'thermal equilibrium' depends on the cloud collapse and the accretion phases, i.e. how and when the thermal energy is enclosed in an optically thick stellar embryo. The usual answer is, that independent of the star-formation details the stellar structure sufficiently early on is fully convective and the detailed history to this stage is quickly forgotten (the latest discussion of this issue, that argues for a fully convective structure may be found in Stahler 1988). If the assumption of fully convective initial stellar structure holds in general, it certainly should hold in spherical symmetry.

To check this assumption and hence to address the question of whether stellar collapse determines early stellar evolution in any significant way, I will discuss the pre-main sequence evolution of stars that results as the consequence of the collapse of specific cloud fragments. These fragments are initially assumed to be Bonnor-Ebert spheres, at the verge of being gravitationally unstable. Hence assumptions are only made about the earliest cloud structure. The initial *stellar* structure (thermal and mechanical) is determined from the collapse- and accretion flow that builds up the hydrostatic part of the protostar and subsequently the pre-main sequence object. This allows a discussion of early stellar evolution without assumptions about initial stellar structure (usually fully convective or following a simple polytropic pressure-density relation), that had to be made in almost all earlier studies of the pre-main sequence phases, with Winkler & Newman (1980a,b) being a notable exception. The primary aim here is not to provide new pre-main sequence tracks but to check the validness of a key assumption that goes into all existing calculations of stellar evolution before the zero age main sequence is reached.

2. Stellar evolution calculations before the main sequence

The calculation of stellar models after the zero age main sequence (ZAMS) is greatly facilitated by two key properties of main sequence stars that relate to the slowness of the change of main-sequence stellar structure driven by nuclear reactions. Because hydrogen burning is proceeding on a Ga time-scale, hydrodynamical phenomena, occuring on the dynamical, stellar sound crossing time-scale, which is on the order of hours, can be ignored because there is always enough time to approach the hydrostatic equilibrium. Secondly the thermal- or Kelvin-Helmholtz time-scale (typically a few Ma) is also much smaller than the evolutionary time-scale, and hence stellar thermal relaxation phenomena — gravitational contraction or expansion — can be neglected. Any evolutionary change in stellar structure will occur under such conditions after energy transfer processes had sufficient time to redistribute heat and provide temperature gradients that assure the thermal equilibrium between energy generation in the interior and photospheric energy losses. From a chemically homogenous, ZAMS model, the stellar parameters for a given mass can be obtained once the elemental composition (X, Y, Z, say) is specified. No input of a thermal structure is necessary, as it results from the fact that a main-sequence star is in thermal equilibrium.

Stellar models before the ZAMS do usually also neglect dynamical effects and rely on the assumption of hydrostatic equilibrium. That is a useful simplification because the essential dynamical effect for protostars and young stars is accretion. Collapse and accretion happen on the free-fall time-scale, or a viscous disk accretion time-scale if applicable. But the separation of the dynamical time-scale and the evolutionary time-scale is much less clear and especially for masses larger than the solar value, mass-changes of the stars are modelled by mass-accretion prescriptions to account for some of the accretion effects (see e.g. Palla, this volume).

The theoretical problem of the correct initial stellar structure is much severer for the thermal issues. The pre-main sequence evolution is altogether a gravothermal relaxation process. The evolutionary time-scale on the pre-main sequence is the Kelvin-Helmholtz time-scale of gravitational contraction. It is not separated from the evolutionary time-scale like on the main sequence because thermal evolution is the overall evolution. In other words the relaxation of the initial thermal structure to the main sequence thermal structure is the key factor in determining the evolution of the stellar properties. Energy generation by nuclear burning of light elements and the accompanying small overall compositional changes are but small corrections of the dominating gravitational contraction. This does not change until hydrogen burning finally starts to contribute significant fractions of the stellar luminosity, close to the ZAMS.

The evolution on the pre-main sequence starts at a stage close to the end of accretion, with a thermal structure that is substantially different from the ZAMS structure. If the thermal structure would initially differ only a little the star could well start close to the ZAMS and the PMS-phase would be very short. It is a property of the star formation process that it apparently produces a thermal structure that greatly differs from the ZAMS and as a consequence young stars appear well above the main sequence. Hence arguments for the initial thermal structure to start the pre-main sequence evolution must come from star-formation studies.

But the reference to star formation theory to obtain the initial stellar structure is adding difficulty because in the earliest phases dynamical effects govern the evolution and instead of obtaining an easy solution for an initial thermal structure we are faced with discussing the even earlier phases of cloud collapse and accretion. Hence the common approach is to use thermal structures that come from simplified treatments of star formation. The earliest discussion are Hayashis arguments, based on homologous gas spheres that lead him to conclude that young stars would have a fully convective structure and hence for given mass appear along a line in the Hertzsprung-Russel diagram that is defined by isentropic stellar interiors (Hayashi 1961, Hayashi et al. 1962). Since then a number of steps have been taken to refine the star-formation description that was used to derive the initial thermal structure, but always the initial thermal structure at least of some fraction of the final stellar mass had to be assumed and accretion had to be described in very approximate ways. Hayashi's conclusions, that young stars must be fully convective remained the guiding principle for constructing the initial stellar structure.

Once an initial stellar structure has been adopted and a stellar evolution program is at hand, the pre-main sequence modeling proceeds as follows: (1) the elemental composition X, Y, Z has to be chosen, and (2) the convection model has to be specified. The composition in a star formation region can in principle be determined observationally, but in practice the active photospheres of young stars present many difficulties. The convection model is a notorious issue in astrophysics because unlike for the rest of stellar structure theory there is no conclusive derivation from basic physical principles at hand. The usual way out is to use mixing length theory, a prescription obtaining its accuracy from fitting its free parameters to the Sun. The most prominent parameter is the ratio of the mixing length to the local hydrostatic pressure scale height, but other choices relating to the radiative losses of the convective elements when they are not very optically thick have to be made. Alternative convection theories partly avoid this step but decisions about approximations during the derivation of the theories result in choices comparable to the choice of the mixing length parameter.

Some, but not all pre-main sequence studies therefore calculate a variety of solar-mass pre-main sequence evolutions and carry them to the solar age. They then decide about the convection assumptions by a detailed comparison to the Sun (e.g. D'Antona and Mazzitelli 1994, for different convection theories). With the convection theory calibrated by the solar case, the pre-main sequence evolution of stars with other masses are calculated, for the same assumptions about the initial thermal structure.

The fitting of the Sun in principle is still done based on the assumption of the initial thermal structure. But the results relating to the calibration of the convection model should be independent of it because at the age of the Sun, when the fitting is made, a few hundred Kelvin-Helmholtz time-scales have elapsed and any thermal memory has been lost.

3. Protostellar collapse to the pre-main sequence

The obvious way to remove the necessity of assuming an initial thermal structure for the pre-main sequence evolution is to calculate the cloud collapse and follow it sufficiently long. This has been already attempted by Hayashi (1966) but is complicated by many technical problems.

Recently Wuchterl and Tscharnuter (2000), see Wuchterl 2000, for a brief overview, have given the pre-main sequence evolution obtained from the collapse of simple cloud fragments, Bonnor-Ebert spheres. The assumption about the initial thermal structure thus could be eliminated, by the specification of the parent cloud structure and the determination of the collapse and accretion flow. A primordial 'solar' elemental composition was chosen and convection was calibrated at the Sun (see Wuchterl and Feuchtinger 1999).

Wuchterl and Tscharnuter (2000) solved the equations of grey radiation hydrodynamics in spherical symmetry with convection and deuterium burning included. Apart from the calibration of convection at the Sun and selecting the Bonnor-Ebert spheres as cloud initial conditions, no assumptions were made or added as the calculations proceeded through cloud collapse, hydrostatic core formation, main accretion phase and finally to the pre-main sequence.

For the first time[1] the 'initial' thermal structure of the stars on their pre-main sequence tracks was determined from the flow equations rather then being assumed.

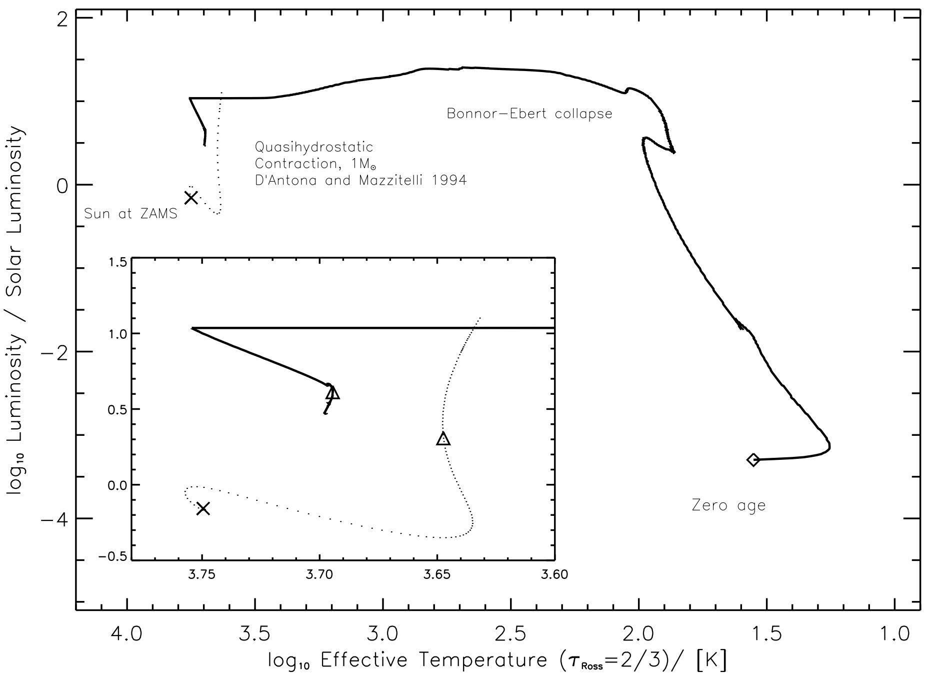

Figure 1. Comparison of the collapse of a solar mass Bonnor-Ebert sphere (full line, Wuchterl and Tscharnuter 2000) and a D'Antona and Mazzitelli (1994) track (dotted). Triangles mark ages of 1 Ma

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To compare the results of the pre-main sequence tracks obtained from the collapse-calculations to the classical hydrostatic tracks, in the Hertzsprung-Russel diagram, the study of D'Antona and Mazzitelli (1994) was selected as the reference. The reason being that the system of a equations used in the D'Antona and Mazzitelli studies is set up and calibrated to the Sun in a very clear way and the atmospheric radiative transfer is comparatively simple. That allows to assure that the hydrostatic system of equations used for the D'Antona and Mazzitelli (1994), 'MLT, Alexander' case — in which mixing length convection is used and opacities and equations of state agree with Wuchterl and Tscharnuter's (2000) — is a limiting case of the system of radiation-hydrodynamical equations used by Wuchterl and Tscharnuter. The limit being recovered for vanishing,

[1]Winler and Newman (1980a,b) determined the thermal structure neglecting convection and deuterium burning

i.e. very subsonic gas-motion and when only the time-derivatives in the matter energy equation but not in the radiation energy equation remain non-zero (quasi-hydrostatic conditions). Hence any difference in the results should be due to the fact, that D'Antona and Mazzitelli use a fully convective initial stellar structure, but Wuchterl and Tscharnuter calculate the thermal structure from the cloud collapse. Any difference to other pre-main sequence tracks should be considered to add up 'on top' of the difference of the 'collapse' tracks to the D'Antona and Mazzitelli (1994), 'MLT, Alexander'-tracks[2].

As an example the results of the Bonnor-Ebert collapse (Wuchterl and Tscharnuter 2000) and the D'Antona and Mazzitelli (1994),'MLT, Alexander'-case are compared for the solar mass case in the Hertzsprung-Russel diagram, see Fig. 1. Note the large range in effective temperature, that is due to the fact that the collapse calculation (full line) starts at cloud conditions and the temperature remains close to 10K throughout the cloud during the isothermal phase. As the cloud becomes optically thick, a hydrostatic protostellar core forms — the effective temperature slowly increases to 100 K with luminosity rising above the solar value. The main accretion phase corresponds to the flat top part of the hydrodynamical evolutionary track. The slight bump at $\lg T_{\rm eff} = 2.85$ is due to deuterium burning, that is almost fully completed during the main accretion phase, i.e. when the stellar embryo is still embedded in the accretion envelope. After that the luminosity decreases because accretion fades as most of the mass of the cloud fragment is collected in the hydrostatic star at the center. When the envelope becomes transparent for the photons emitted from the stellar photosphere, the effective temperature increases sharply and the upper left 'corner' of the collapse track is reached. From this moment on photons escape directly from the final stellar photosphere, that subsequently remains visible through the remnant protostellar envelope. The envelope is transparent but accretion still significantly contributes to the total luminosity. An observer would note this enhanced effective temperature as 'veiling' of the spectral lines. As accretion onto the photosphere becomes negligible for the star's energy budget, the accretion luminosity, stops to significantly contribute to the total luminosity, and hence there is no significant effect on the effective temperature beyond this point. The 'collapse'-track turns almost to the vertical at this point, after the star has gravothermally adjusted to the new conditions, i.e. to a situation without significant mass, momentum and energy input due to the still ongoing but rapidly fading accretion flow. Ram-pressure and energy deposition caused by the inflow become negligible for the overall stellar structure, most prominently the radius, at this point. This phase is better viewed in the insert, in Fig. 1, that magnifies the pre-main sequence part of the evolution. In the insert this point is close to the triangle that marks an age of 1 Ma on both, the 'collapse' and the hydrostatic D'Antona and Mazzitelli track (dotted line).

At this point, at the triangle, the collapse result can be compared to the 'hydrostatic' tracks for the first time, because 'dynamic' accretion effects do not affect anymore most of the mass, that is already hydrostatic. Hence the triangle

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[2]For a comprehensive discussion of the uncertainties in hydrostatic pre-main sequence tracks see, Siess (this volume) and for a discussion of the effects of more detailed microphysics and frequency-dependent photospheric radiative transfer, see Baraffe (this volume).

roughly marks the position were the thermal structure has been 'delivered' by the star formation process, which is quantitatively described here as the spherical collapse of a solar mass, critical Bonnor-Ebert sphere.

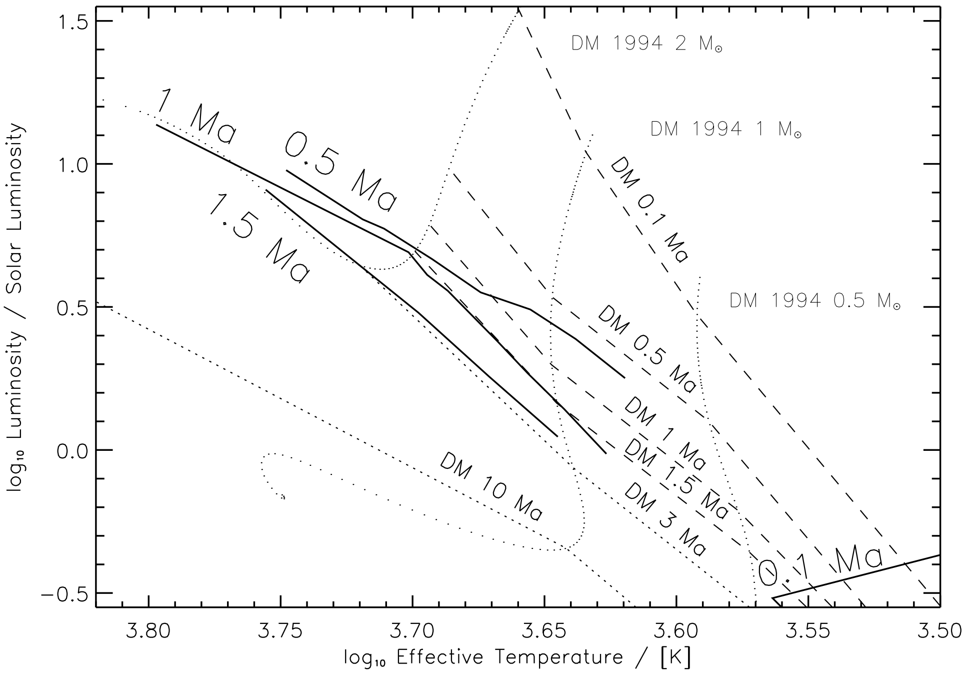

Figure 2. Isochrones obtained from the collapse of Bonner-Ebert spheres of various masses, full lines (Wuchterl and Tscharnuter 2000), and isochrones (dashed lines) and evolutionary tracks (dotted lines) from fully hydrostatic calculations (D'Antona and Mazzitelli 1994,'MLT, Alexander'-case). Isochrones are labelled with ages in units of 10^6 years.

Two differences between 'collapse' and 'hydrostatic' tracks are noted immediately when luminosities and effective temperatures are compared at an age of 1 Ma, i.e. at the positions marked by the triangles. (1) 'collapse' luminosities are about a factor of two larger than the classical values, and (2) 'collapse' effective temperatures are about 500 K higher. These differences reflect the differences in internal structure. The D'Antona and Mazzitelli star is fully convective and hence on the Hayashi track at this moment. The star obtained from the Bonnor-Ebert collapse, has an off-center temperature maximum (as found already by Winkler and Newman 1980 a,b) and has an inner radiative core that extends to two thirds of the stellar radius and contains about half of the mass. The 'Bonnor Ebert' star furthermore has already burnt most of its deuterium during the accretion phase and D-burning cannot significantly contribute to the energy budget of the star, or the luminosity at that point or at any later time. In one sentence: the young star from the collapse has a radial structure, that is similar (homologous) to the Sun, while the D'Antona and Mazzitelli star is still fully convective.

4. Isochrones — classical vs. collapse

What would be the consequences of the new pre-main sequence tracks for the ages of young stars and clusters? Two illustrate that, isochrones obtained from the collapse of Bonner-Ebert spheres of various masses (Wuchterl and Tscharnuter 2000) are compared to the D'Antona and Mazzitelli (1994),'MLT, Alexander' isochrones in Fig. 2. The higher luminosities and effective temperatures of the collapse tracks result in isochrones, that give younger ages for given $(L, T_{\rm eff})$. A useful reference is the 1.5 Ma 'collapse'-isochrone, that runs close to the 3 Ma D'Antona and Mazzitelli isochrone. The full line labelled 0.1 Ma marks an estimate for location in the HRD below which Bonnor-Ebert spheres arrive on the pre-main sequence with ages less than 10^5 a. These are low mass objects that do not have a significant accretion phase inside an envelope and hence become 'visible' immediately after there hydrostatic cores have formed.

5. New theoretical observables for Bonnor-Ebert-collapse

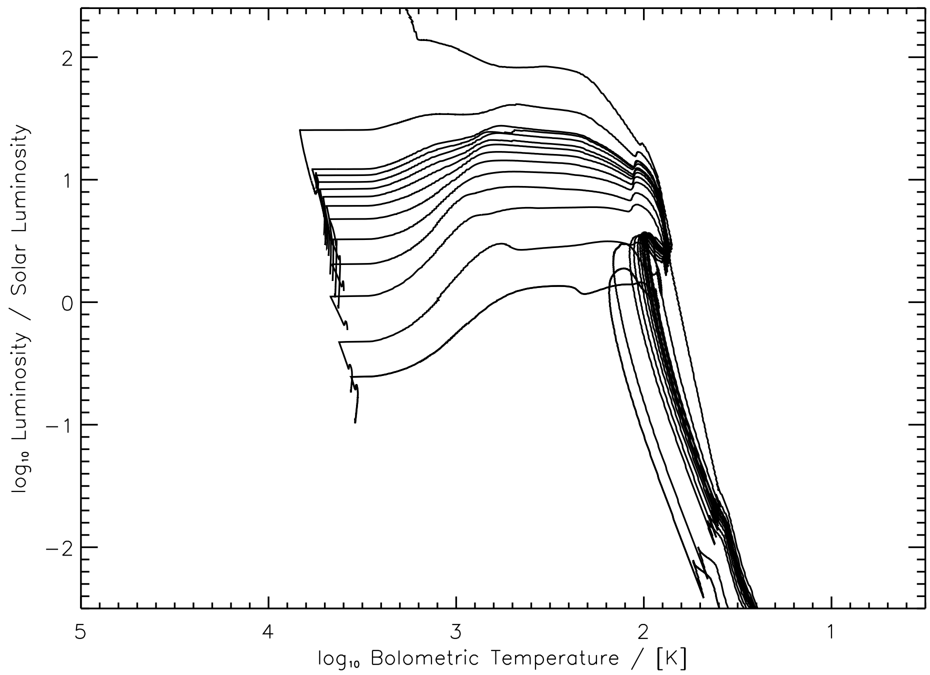

Figure 3. Theoretical bolometric luminosity vs. bolometric temperature diagram for the collapse of Bonnor-Ebert spheres with masses of 0.05 to $10\,\mathrm{M}_\odot$.

Calculating the pre-main sequence evolution from the cloud collapse does not only provide a solution for the problem of the initial thermal structure of stars, but also provides valuable information about the embedded phases of star formation. Because the stars and their properties are obtained together with a solution for the accretion flow, additional quantities are self-consistently determined they allow the theoretical calculation of observables that cannot be predicted by the classical stellar-evolution type, hydrostatic pre-main sequence calculations.

A couple of observables, that are useful in the early phases of star formation are discussed by André et al. (2000). I present such observables as they result from the collapse of critical 10 K Bonnor-Ebert spheres of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 2 and 10 $M_\odot$, after chosing the mixing length to correctly represent the Sun (from the calculations by Wuchterl and Tscharnuter 2000). The scaling is chosen to facilitate comparison with the Figs given by André et al. (2000).

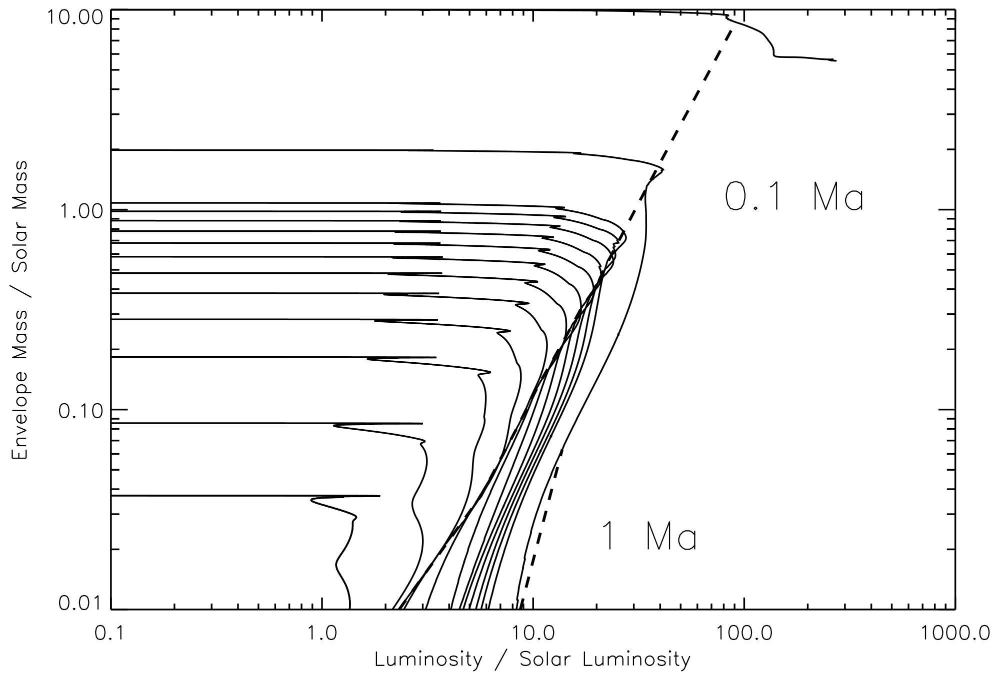

Figure 4. Theoretical envelope mass vs. bolometric temperature diagram for the collapse of Bonnor-Ebert spheres with masses of 0.05 to 10 $M_\odot$. Isochrones for ages of 10^5 and 10^6 years are indicated by dashed lines.

The theoretical bolometric luminosity, bolometric temperature diagram is shown in Fig. 3. At low luminosity and low temperature and up to $\log_{10} L = 0.5$ at $\log_{10} T = 1.9$ most of the evolutionary tracks follow a similar path in the diagram. That is a consequence of the fact that the first optically thick protostellar core that forms and approaches hydrostatic equilibrium is of similar mass, independent of the cloud fragment's mass. Only at the smallest masses, 0.05 and $0.1\,\mathrm{M}_\odot$ departures are visible due to the fact that the respective optically thick parts are significant fractions of the total mass from the beginning and hence there are no cool envelopes that can hide the hotter parts. As the opacity limit of fragmentation is approached at even smaller masses the fragments are heated even before they are able to collapse.

As the tracks for the various masses fan out above 100 K the main accretion phases are visible as flat luminosity maxima. At the end of the flat parts, around $\log_{10} T = 2.9$ bumps in the luminosity are visible for the masses that burn deuterium. From about 0.5 to $2\,\mathrm{M}_\odot$ deuterium burning causes a luminosity maximum there. For those masses deuterium is almost completely burnt before the stellar photospheres become visible. After those maxima, above $\log_{10} T =$ 3.0 luminosities start to decrease towards their pre-main sequence values as the envelopes are emptied and accretion rates start do decline significantly. Arrival at the pre-main sequence, i.e. visibility of the final stellar photospheres occurs at the high-temperature 'corners' of the tracks.

The theoretical envelope mass, bolometric luminosity diagram is shown in Fig. 4. The lowest mass fragments rapidly accrete to the final stellar masses, a fact reflected by their envelopes diminished at ages less than 0.1 Ma. Only the $2\,\mathrm{M}_\odot$ case reaches a Ma in the range shown. The 1 Ma isochrone points towards the solar mass track, that reaches a Ma with a very small envelope mass ($M_{\mathrm{env}} = 0.001\,\mathrm{M}_\odot$ at 0.5 Ma). The $10\,\mathrm{M}_\odot$ fragment is calculated to a stellar mass of $4.4\,\mathrm{M}_\odot$ and hence the lower limit for the M_{env} evolution.

I would like to emphasize that all quantities involved in the construction of the figures here result from the solution of the radiation-hydrodynamics with the various Bonnor-Ebert spheres as initial conditions. No values for stellar masses, envelope masses, mass accretion rates etc. have been assumed. The entire suite of observables is the consequence of a solution of the cloud collapse problem together with a convection theory. The free parameters of this convection theory (Wuchterl and Feuchtinger 1999) are left fixed once the solar convection zone has been described correctly.

6. Conclusion

Calculations of the spherical collapse of Bonnor-Ebert spheres provide pre-main sequence properties for stars without relying on special assumptions about 'initial stellar structure'. Unlike to what has been assumed the collapse of a solar mass cloud fragments results in young star interiors that are more similar to our present Sun, than to fully convective structures. Collapse tracks predict significant corrections for young star properties and are also able to simultaneously provide theoretical values for observables of the embedded phases of star formation. In the future pre-main sequence tracks will not only be quantitatively linked to the Sun but also to the observations of the early phases of star formation. Because the pre-main sequence objects contain a memory of star formation they will shed more light on the darkness the come from.

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