THE FIRST MILLION YEARS OF THE SUN: A CALCULATION OF FORMATION AND EARLY EVOLUTION OF A SOLAR-MASS STAR

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Accepted for publication in ApJ Letters

ABSTRACT

We present the first coherent dynamical study of the cloud fragmentation-phase, collapse and early stellar evolution of a solar mass star. We determine young star properties as the consequence of the parent cloud evolution. Mass, luminosity and effective temperature in the first million years of the proto-Sun result from gravitational fragmentation of a molecular cloud region that produces a cluster of prestellar clumps. We calculate the global dynamical behavior of the cloud using isothermal 3D hydrodynamics and follow the evolution of individual protostars in detail using a 1D radiation-fluid-dynamic system of equations that comprises a correct standard solar model solution, as a limiting case. We calculate the pre-main sequence (PMS) evolutionary tracks of a solar mass star in a dense stellar cluster environment and compare it to one that forms in isolation. Up to an age of 950 000 years differences in the accretion history lead to significantly different temperature and luminosity evolution. As accretion fades and the stars approach their final masses the two dynamic PMS tracks converge. After that the contraction of the quasi-hydrostatic stellar interiors dominate the overall stellar properties and proceed in very similar ways. Hence the position of a star in the Hertzsprung-Russell diagram becomes a function of age and mass only. However, our quantitative description of cloud fragmentation, star formation and early stellar evolution predicts substantial corrections to the classical, i.e. hydrostatic and initially fully convective models: At an age of 1 million years the proto-Sun is twice as bright and 500 Kelvin hotter than according to calculations that neglect the star formation process.

Subject headings: Hertzsprung-Russel diagram – hydrodynamics – stars: evolution – stars: formation – stars: pre-main sequence – Sun: evolution

1. INTRODUCTION

Stars are born in interstellar clouds of molecular hydrogen. Very often supersonic turbulence is observed in those clouds and then the mass growth of young stars are intimately coupled to the dynamical cloud environment. Stars form by gravitational collapse of shock-compressed density fluctuations(e.g. Elmegreen 1993, Padoan 1995, Klessen, Heitsch, & Mac Low 2000, Heitsch, Mac Low, & Klessen 2001, Padoan & Nordlund 2001). But other clouds are known, that are quiet and closely resemble isothermal, hydrostatic 'Bonnor-Ebert'-spheres (Alves et al. 2001).

Once a gas clump becomes gravitationally unstable, it begins to collapse giving birth to a protostar. While the structure of molecular clouds is well studied observationally, our knowledge about intrinsic properties of these youngest stars relies almost entirely on theoretical stellar models. These models give ages, masses and radii when brightness, distance and effective temperature are known. The so determined ages constitute the only practical 'clock' for tracing the history of star-formation regions and for studying the evolution of circumstellar disks and planet formation. They constitute the basis of our empirical understanding of the evolution of the young Sun and the origin of solar systems.

Until recently (Wuchterl & Tscharnuter 2001, hereafter WT) it was necessary to *assume* a set of initial conditions for the stars at very young ages (typically at a few 10^5 years) in order to calculate the properties at larger ages. Usually the internal thermal structure of the star is estimated at a moment when the dynamical infall motions from the cloud are thought to have faded and the stellar contraction is sufficiently slow, so that pressure forces balance gravity. Then hydrostatic equilibrium is a good approximation. Young star properties are therefore usually calculated without considering gravitational cloud collapse and protostellar accretion in detail. See, however, Winkler & Newman (1980a,b), but also Hartmann, Cassen & Kenyon (1997) for a discussion of the possible effects of accretion. Altogether, classical PMS calculations typically assume fully convective initial conditions as argued for by Hayashi (1961).

However, it can be shown that the assumption of fully convective stellar structure *does not* result from the collapse of isolated, marginally gravitationally unstable, isothermal, hydrostatic equilibrium, so called 'Bonnor-Ebert' spheres (WT). Hence, early stellar evolution theory has to be reconsidered. Our novel approach here is to determine the structure and evolution of young stars following from a quantitative description of the cloud fragmentation process (§2). We present the first calculation of the properties of the new born star as being a member of a cluster of protostars forming from the fragmentation of a highly-structured molecular cloud, and follow in detail the collapse of a one solar mass fragment until it becomes observable in the visible light (§3). We demonstrate that the newly born star shows the trace of the fragmentation and collapse process during its main accretion phase and the early hydrostatic PMS contraction. At an age of a million years, however, its properties are almost identical for quiet and turbulent cloud conditions (§4).

2. TOWARDS A CONSISTENT DESCRIPTION OF STAR FORMATION

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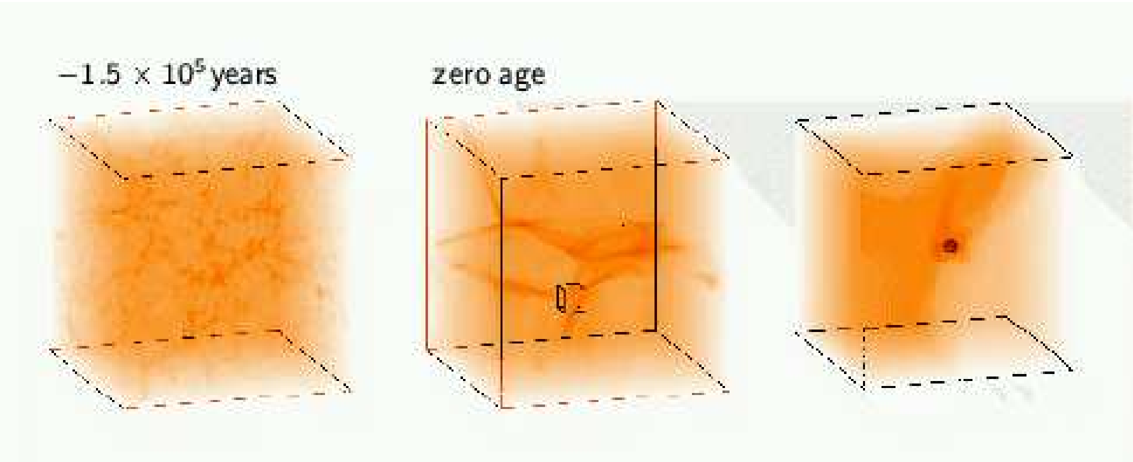

FIG. 1.— The 3D density distribution of the dynamical molecular cloud fragmentation calculation at two different times (model $\mathcal{I}$ of KB00, KB01). As we cannot treat the whole cloud, we focus on a sub-volume of mass $196\,M_\odot$ and size $(0.32\,\mathrm{pc})^3$. The left image depicts the initial random Gaussian fluctuation field, and the central image shows the system when the young proto-Sun reaches stellar zero age (i.e. when the cloud core for the first time becomes optically thick). During this 1.5×10^5 year period local collapse occurs and a cluster of deeply embedded and heavily accreting pre- and protostellar condensations begins to build up (i.e. objects without and with central hydrostatic core). The region where the proto-solar condensation forms is shown enlarged on the right-hand side. The volume considered in the 1D-RHD simulation is indicated by the circle.

Molecular cloud complexes have diameters up to several 10 pc and masses in the range 10^3 to $10^6\,M_\odot$. They are characterized by the presence of strongly supersonic turbulent gas motions, as indicated by large observed line widths. Without constant energy input, interstellar turbulence dissipates rapidly on a free-fall time-scale (Mac Low et al. 1998, Stone, Ostriker, & Gammie 1998, Mac Low 1999). Hence, the observed cloud structure is very transient. In the current calculation we consider a molecular cloud region where turbulence is decayed and has left behind density fluctuations characterized by a Gaussian random field which follows a power spectrum $P(k)\propto 1/k^2$ (Klessen, Burkert, & Bate 1998, and in detail Klessen & Burkert 2000, 2001, hereafter KB00 and KB01, respectively).

The equation of hydrodynamics are solved using a particle based method (SPH — smoothed particle hydrodynamics, see Benz 1990, or Monaghan 1992) in combination with the special-purpose hardware device GRAPE (GRavity Pipe, see Sugimoto et al. 1990, Ebisuzaki et al. 1993). As we cannot treat molecular clouds as a whole with sufficient numerical resolution, we focus on a sub-region of the cloud with mass $196\,M_\odot$ and size $(0.32\,\mathrm{pc})^3$ and adopt periodic boundary conditions (Klessen 1997). With a mean density of $n(H_2) = 10^5\,\mathrm{cm}^{-3}$ and temperature $T = 10\,\mathrm{K}$, the simulated volume contains 222 thermal Jeans masses. To be able to continue the calculation beyond the formation of the first collapsing object, compact cores are replaced by 'sink' particles (Bate, Bonnell, & Price 1995) once they exceed a density of $n(H_2) = 10^9\,\mathrm{cm}^{-3}$, where we keep track of the mass accretion, and the linear and angular momenta. The 'sink' particle size defines the volume of the 1D-RHD calculation. The fragmentation calculation covers a time-range from -1.5×10^5 years to 3.7×10^7 years. The system is gravitationally unstable and begins to form a cluster of 56 protostellar cores (as illustration see Figure 1), corresponding to the 'clustered' mode of star formation (Klessen 2001b).

Besides that specific choice of the initial molecular cloud conditions, the only free parameters that remain in our dynamical star formation model are introduced by the time-dependent convection-model, needed to describe stellar structure in a 'realistic' way. These parameters are determined as usual in stellar structure theory by demanding agreement between the model-solution and the actual solar convection zone as measured by helioseismology.

We aim to describe the birth and the first million years of a solar mass star. Therefore we select from the 3D cloud simulation that protostellar core with final mass closest to $1\,M_\odot$ and use its mass accretion history (Klessen 2001a, hereafter K01a) to determine the mass flow into a spherical control volume centered on the star. For the stellar mass range considered here feedback effects are not strong enough to halt or delay accretion into this protostellar 'feeding zone'. Thus, the core accretion rates are good estimates for the actual stellar accretion rates. Deviations may be expected only if the protostellar cores form a binary star, where the infalling mass must be distributed between two stars, or if very high-angular momentum material is accreted, where a certain mass fraction may end up in a circumbinary disk and not accrete onto a star at all. For single stars matter accreting onto a protostellar disk may be temporarily 'stored' in the disk before getting transported onto the star. The flow *within* the control volume is calculated by solving the equations of radiation hydrodynamics (RHD) in the grey Eddington approximation and with spherical symmetry (Castor 1972, Mihalas & Mihalas 1984), in their integral form (Winkler & Norman 1986). At any time we require that the total mass in the volume agrees with the 3D fragmentation calculation. Convective energy transfer and mixing is treated by using a new, time-dependent convection scheme (Wuchterl & Feuchtinger 1998) derived from the model of Kuhfuß (1987). We include detailed equations of state and opacities (WT), and compute deuterium burning processes with standard reaction rates (Caughlan & Fowler 1988) and convective mixing. The 1D-RHD calculation covers a spherical volume of radius $R = 160\,\mathrm{AU} = 2.46\times10^{15}\,\mathrm{cm}$ and contains a mass $0.028\,M_\odot$ at $t = 0$. The calculation started 1.5×10^5 years before the moment of stellar zero age, with a mass $2\times10^{-5}\,M_\odot$. The final mass of the star is $0.971\,M_\odot$.

3. THE FORMATION OF A $1\,M_\odot$-STAR

The fragment we have chosen is highlighted in the 3D cloud structure in Figure 1 at the moment when it becomes optically thick and departs from isothermality, as determined by the 1D solution. We use this instant to define the stellar zero age (WT). The mass accretion rates obtained for the selected fragment are strongly time varying and peak around $1.5\times10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ (K01a).

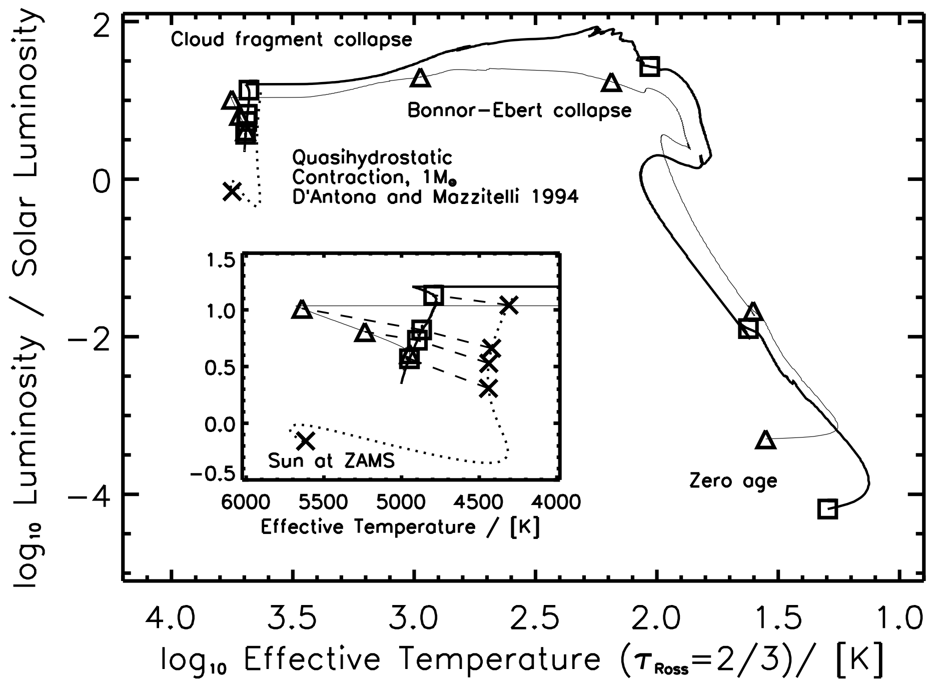

FIG. 2.— Early stellar evolution in the Hertzsprung-Russell diagram. Three evolutionary effective-temperature-luminosity relations (tracks) relevant to the young Sun are compared. The dotted line is a classical stellar structure, hydrostatic-equilibrium PMS track for $1\,M_{\odot}$, for an initially fully convective gas sphere ('MLT Alexander' model of DM94). The two other lines are obtained by describing the formation of the star as a result of the collapse of an interstellar cloud. The *thin line* is for a cloud fragment in initial equilibrium (a so called 'Bonnor-Ebert' sphere of a solar mass, see WT for details). The (thick line) is for a cloud fragment that results from the dynamical fragmentation of a molecular cloud (KB00, KB01). The two diamonds, in the lower right, indicate zero age for the two collapse-results. Triangles (WT, Bonnor-Ebert), squares (this work) and crosses (DM94) along the respective evolutionary tracks mark ages of 1, 10, 100, 350 kyr, 0.5 and 1 Myr. The cross at the end of the hydrostatic track denotes the moment when energy generation by nuclear reactions in the stellar interior, for the first time in stellar live *fully* compensates the energy losses due to radiation from the stellar photosphere, i.e. the zero age main sequence (ZAMS). Corresponding age-marks for 0.1, 0.35, 0.5 and 1 Myr are connected by dashed lines in the insert.

Before reaching zero age, the temperature is close to the initial cloud value of 10 K and densities are still low enough so that the heat produced by the collapse is easily radiated away from the transparent cloud. Once the envelope becomes optically thick, the temperature increases rapidly as the accretion luminosity rises. We determine the effective temperature at the radius where the optical depth $\tau_{\rm Ross} = 2/3$ (see Baschek Scholz, & Wehrse 1991 for a careful discussion). Luminosity and temperature for the non-isothermal phase obtained from the 1D-RHD calculation are shown in Figure 2. The zero age is marked by a diamond, close to the beginning of the thick line in the lower right of Figure 2. For comparison the results of a Bonnor-Ebert-collapse (WT) and a classical hydrostatic stellar evolution calculation (D'Antona & Mazzitelli 1994, hereafter DM94) are shown as well. The equations used in the latter study correspond to the hydrostatic limit of the current dynamical model (WT), all physical parameters (opacities, etc.) are identical or match closely (see WT).

The non-isothermal phase can be divided into three parts: (1) There is a first luminosity increase up to $20\,L_{\odot}$ with the temperature staying below about 100 K. The central density of the fragment rises until a hydrostatic core forms and the accretion flow onto that core is accelerated until quasi-steady state is established. (2) The subsequent main accretion phase leads to an increase in temperature to 2000 K while the luminosity shows a broad maximum at $\sim 100\,L_{\odot}$. Compared to the isolated 'Bonnor-Ebert case' the violent accretion in the cluster-environment produces a considerably higher luminosity, and the oscillations around maximum reflect the variable rates at which mass is supplied to the accreting protostar as it travels through the dynamical environment of the proto-cluster. (3) Once accretion fades, the star approaches its final mass. The stellar photosphere becomes visible and the luminosity decreases at roughly constant temperature. This is the classical pre-main sequence (PMS) contraction phase, shown as a blow up in Figure 2. The luminosity decreases at almost constant temperature and the evolutionary tracks are nearly vertical being approximately parallel to the classical 'hydrostatic' track.

4. DISCUSSION

Our dynamical model allows us to address the question of whether a trace of the initial fragmentation and collapse process can be found once the young star arrives at its final mass and becomes optically visible. Indeed, the star that forms in a dynamical cloud environment is brighter when it reaches the PMS phase compared to the isolated Bonnor-Ebert case. This is due to the higher accretion in the dynamically evolving cluster environment (see also K01a).

As the mass accretion rates of evolving protostars in dense clusters are influenced by mutual stochastic interactions and differ significantly from isolated ones, the positions of stars in the main accretion phase in the HR diagram are not functions of mass and age alone, but also depend on the statistical properties of the protostellar environment. This affects attempts to infer age and mass at this very early phase using bolometric temperatures and luminosities of protostellar cores (see e.g. Myers & Ladd 1993, Myers et al. 1998). It is only possible as the statistical average over many different theoretical accretion histories for different cluster environments or for an observational sample of protostars with similar cloud conditions.

As the accretion flow fades away, however, the evolutionary tracks of protostars *converge*, and the memory of environmental and initial conditions is largely lost in the sense that one (final) mass corresponds to one track. For given mass and elemental composition the stellar properties then depend on age only. For our one solar mass stars this happens at 0.95×10^6 years where the effective temperatures become equal and remain within 20 K until the end of the 1D-RHD calculation at 2×10^6 years. However, substantial *differences* remain compared to the classical hydrostatic calculations. The temperature obtained from collapse models is consistently higher by about 500 K compared to classical hydrostatic computations at corresponding luminosities.[5]

This deviation is the result of a *qualitatively* different stellar structure (WT). Most notable, the solar mass stars resulting from collapse are *not* fully convective as is assumed in the hydrostatic calculations, instead they do have a radiative core of similar relative size as the present Sun. Convection is confined to a shell in the outer third of the stellar radius. Stellar structure along the new dynamical evolutionary tracks can be viewed as homologous to the present Sun rather than to a fully convective structure. Consequently, the proto-Sun does not evolve along the classical Hayashi track for a solar mass star, but roughly parallel to that. It has a higher effective temperature corresponding to the smaller radius of a partially radiative object of the same luminosity as a fully convective one.

As the dynamical PMS tracks converge for the two most extreme assumptions about the stellar environment (dense stellar clusters vs. isolated stars) we predict that a solar mass star at an age of 10^6 years will have a luminosity of $4 \pm 0.4\,L_\odot$ and an effective temperature of 4950 ± 20 K. The uncertainties reflect the fading traces of the adopted two highly disparate initial and environmental cloud conditions. For identical assumptions made about convection theory and stellar opacities (DM94), the classical values are $2.0\,L_\odot$ and 4440 K, respectively.

Our predictions rely most critically on the correctness of the following parts used in our argument: (1) The structure of young stars can be calculated in spherical symmetry, (2) our prescription of convection is sufficiently accurate outside the regime where it has been tested, i.e. the present-day Sun, and (3) our radiative transfer treatment and especially the present sources of stellar opacity are sufficiently complete. However, it needs to be pointed out that *all* those assumptions are also made for the classical calculations that we have used for reference.

We thank our second referee for comments and discussion. This work was supported by the *Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)*. GW was partly supported by the *Fonds zur Förderung der wissenschaftlichen Forschung (FWF)* under project numbers S7305–AST and S7307–AST and the *Deutsche Forschungsgemeinschaft (DFG)*, SFB 359 (key research project of the German national science foundation on 'Reactive flows, diffusion and transport'). RSK acknowledges support by a Otto-Hahn-Stipendium of the Max-Planck-Gesellschaft and subsidies from a NASA astrophysics theory program supporting the joint Center for Star Formation Studies at NASA-Ames Research Center, UC Berkeley, and UC Santa Cruz. We thank the MPI für Astronomie, Heidelberg for use of their GRAPE-System and E. Dorfi, Univ. Vienna for providing substantial amounts of computational resources on his VAX-cluster where the 1D computations were performed.

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[5] To indicate the consequences for stellar mass determinations, we point out that during the second million years the temperature of our one solar mass star corresponds to stars with $2\,M_\odot$ on the classical hydrostatic tracks. The differences in temperature and luminosity equivalently imply corrections for the inferred ages: the 'classical' luminosity at 10^6 years is $6.2\,L_\odot$, while the corresponding 'collapse' values are smaller, $3.8\,L_\odot$ and $4.2\,L_\odot$, respectively. At 2×10^6 years, the new calculations give luminosities of twice the solar value. The 'classical' age for equivalent luminosities is 0.8×10^6 years.