1. INTRODUCTION

Star formation is a complex process. In the standard theory of star formation, stars build up from the “inside-out” collapse of singular isothermal spheres, which are generally assumed to result from the quasi-static contraction of magnetically supported cloud cores due to ambipolar diffusion (Shu 1977; Shu, Adams, & Lizano 1987). This picture is able to reproduce many observed features of protostars; however, it has always been challenged by more dynamical points of view (see, e.g., Whitworth et al. 1996 for a critical discussion). An alternative approach takes interstellar turbulence into account, where supersonic random motions in molecular clouds lead to transient shock-generated density fluctuations. Some may exceed the threshold of gravitational stability and collapse to form stars (e.g., Elmegreen 1993; Padoan 1995; Padoan & Nordlund 1999). The location, timescale, and efficiency of star formation hereby intimately depend on the stochastic properties of the underlying turbulent velocity field (Klessen, Heitsch, & Mac Low 2000, hereafter KHM; Heitsch, Mac Low, & Klessen 2001, hereafter HMK; see also Klessen 2000). The majority of stars form in a clustered environment (see the review by Clarke, Bonnell, & Hillenbrand 2000 and Elmegreen et al. 2000). For massive clusters, the mutual interaction of collapsing protostellar cores in the dense central region and their competition for accretion from a common gas reservoir are important processes that determine stellar mass growth (Bonnell et al. 1997; Klessen & Burkert 2000, 2001, hereafter KB1 and KB2, respectively). It is this star-forming environment that is considered in the present Letter.

A gravitationally unstable, collapsing gas clump follows an observationally well-determined sequence. Prior to the formation of a hydrostatic nucleus, an observed prestellar condensation exhibits a density structure that has a flat inner part, then decreases outward roughly as $\rho \propto r^{-2}$, and is truncated at some finite radius (e.g., Bacmann et al. 2000). Once the central young stellar object (YSO) builds up, the class 0 phase is reached and the density follows $\rho \propto r^{-2}$ down to the observational resolution limit. As larger and larger portions of the infalling envelope get accreted, the protostar is identified as a class I object, and when accretion fades away it enters the T Tauri phase (e.g., André, Ward-Thompson, & Barsony 2000). IR and submillimeter observations suggest that the accretion rate $\dot{M}$ varies strongly and declines with time. Accretion is largest in the class 0 phase and drops significantly in the subsequent evolution (e.g., André & Montmerle 1994; Bontemps et al. 1996; Henriksen, André, & Bontemps 1999, hereafter HAB). The estimated lifetimes are a few times $10^3$ yr for the class 0 phase and a few times $10^4$ yr for the class I phase.

These observational findings favor the dynamical picture of star formation (e.g., Larson 1969; Penston 1969; Hunter 1977; HAB; Basu 1997) but could in principle be reconciled with an inside-out collapse model when adopting initial conditions different from the classical quasi-static singular isothermal sphere. All analytical studies and most numerical work of protostellar core collapse (e.g., Foster & Chevalier 1993; Tomisaka 1996; Ogino, Tomisaka, & Nakamura 1999; Wuchterl & Tscharnuter 2001, hereafter WT) concentrate on isolated objects. It is thus the aim of the present study to illustrate the effect of a dense cluster environment on protostellar mass accretion rates.

2. NUMERICAL MODELS OF CLUSTERED STAR FORMATION

In the approach adopted here, molecular clouds form clusters of stars in regions where interstellar turbulence becomes too weak to supply sufficient support against gravitational collapse, either because the region is compressed by a large-scale shock (KHM; HMK) or because interstellar turbulence is not replenished and decays on short timescales (Mac Low et al. 1998; Stone, Ostriker, & Gammie 1998; Mac Low 1999). The latter scenario is investigated by Klessen, Burkert, & Bate (1998), KB1, and KB2 using smoothed particle hydrodynamics simulations of the evolution and fragmentation of molecular cloud regions where decaying turbulence is assumed to have left behind random Gaussian density fluctuations. The complete lack of turbulent support leads to rapid star formation in a...
Fig. 1.—Examples of time-varying mass accretion rates for protostellar cores forming in a dense cluster environment. The left panel shows accretion rate $\dot{M}$ versus time after formation $t - t_{\text{form}}$ for 49 randomly selected protostellar cores in the high-resolution model of KB1. The time of core formation $t_{\text{form}}$ is identified by the occurrence of the first hydrostatic stellar object. Accretion rates at times $t - t_{\text{form}} < 0$ indicate the mass flow into the control volume prior to that (the gas clump is still in the prestellar phase). To link individual accretion histories to the overall cluster evolution, $t_{\text{form}}$ is indicated in the upper right corner of each plot and measures the elapsed time since the start of the simulation. The free-fall timescale of the considered molecular region is $t_{ff} = 10^5$ yr. High-mass stars tend to form early in the dynamical evolution and are able to maintain high accretion rates throughout the entire simulation. On the contrary, low-mass stars tend to form later in the cluster evolution, and $\dot{M}$ declines strongly after the short initial peak accretion phase. Altogether, the accretion histories of cores (even of those with similar masses) differ dramatically from each other due to the stochastic influence of the cluster environment, as clumps merge and protostellar cores compete for accretion from a common gaseous environment. The right panel plots are the same cores $\dot{M}$ as a function of the accreted mass $M$ with respect to the final mass $M_{\text{end}}$, which is indicated in the center of each plot. Note that the mass range spans 2 orders of magnitude. [See the electronic edition of the Journal for a color version of this figure.]
strongly clustered mode. The interplay between self-gravity and isothermal gas pressure considered in the models reproduces the basic features of young star clusters remarkably well, e.g., the mass distribution of protostars is well fitted by a lognormal with width and peak comparable to observational estimates of the initial mass function (KB1; KB2). The current analysis is based on the high-resolution simulation discussed in KB1.

The considered molecular cloud region has a mean density of \( n(\text{H}_2) = 10^5 \text{ cm}^{-3} \) and a temperature of 10 K. Its initial Gaussian density field follows a power spectrum \( P(k) \propto k^{-2} \) in a volume of (0.32 pc)\(^3\) containing roughly 200 \( M_\odot \). As the system contracts gravitationally, a cluster of 56 protostellar cores builds up. As no feedback is included, the common cluster gas reservoir from which these cores feed is exhausted after roughly \( \sim 10^5 \text{ yr} \), corresponding to \( \sim 3 \) global free-fall timescales.

Once the nucleus of a collapsing gas clump in the model exceeds a density \( n(\text{H}_2) \approx 10^9 \text{ cm}^{-3} \), it is identified as protostellar core and replaced by a “sink” particle, which has the ability to accrete matter while keeping track of mass and linear and angular momentum (Bate, Bonnell, & Price 1995). Matter that accretes through the boundary of the sink volume would continue to fall and reach the central hydrostatic YSO within less than \( \sim 1000 \text{ yr} \) (WT). The diameter of the accretion volume is 320 AU, roughly equivalent to the Jeans scale at the threshold density. For the stellar mass range considered here, feedback effects are not strong enough to halt or delay accretion onto the stellar photosphere (Wuchterl & Klessen 2001, hereafter WK). Thus, the core accretion rates derived here are good estimates for the actual stellar accretion rates. Deviations are expected only for very high mass stars, which will at some stage begin to emit UV photons, or for protostellar cores forming binary stars, 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.

3. TIME-VARYING PROTO StellaR ACCREtion RATES

The following conclusions about the mass accretion rate in dense clusters can be derived.

1. Protostellar accretion rates in a dense cluster environment are strongly time variable. This is illustrated in Figure 1 for 49 randomly selected cores.

2. The typical density profiles of gas clumps that give birth to protostars exhibit a flat inner core, followed by a density falloff \( \rho \propto r^{-2} \), and are truncated at some finite radius (in the dense centers of clusters often due to tidal interaction with neighboring cores). Figure 12 in KB1 presents examples. As a result, a short-lived initial phase of strong accretion occurs when the flat inner part of the prestellar clump collapses. This corresponds to the class 0 phase of protostellar evolution. If these cores were to remain isolated and unperturbed, the mass growth rate would gradually decline in time as the outer envelope accretes onto the center. This is the class I phase. Once the truncation radius is reached, accretion fades and the object enters the class II phase. This behavior is expected from analytical models (e.g., HAB) and agrees with other numerical studies (e.g., Foster & Chevalier 1993; WT). However, collapse does not start from rest for the density fluctuations considered here, and the accretion rates exceed the theoretically predicted values even for the most isolated objects in the simulation.

3. The mass accretion rates of cores in a dense cluster deviate strongly from the rates of isolated cores. This is a direct result of the mutual dynamical interaction and competition between protostellar cores. While gas clumps collapse to build up protostars, they may merge as they follow the flow pattern toward
the cluster potential minimum. The timescales for both processes are comparable. The density and velocity structure of merged gas clumps generally differs significantly from their progenitor clumps, and the predictions for isolated cores are no longer valid. More importantly, these new larger clumps contain multiple protostellar cores, which subsequently compete with each other for the accretion from a common gas reservoir. The most massive core in a clump is hereby able to accrete more matter than its competitors (Bonnell et al. 1997; KB1). Its accretion rate is enhanced through the clump merger, whereas the accretion rate of low-mass cores typically decreases. Temporary accretion peaks in the wake of clump mergers are visible in abundance in Figure 1. Furthermore, the small aggregates of cores that build up are dynamically unstable, and low-mass cores may be ejected. As they leave the high-density environment, accretion terminates and their final mass is reached.

4. The most massive protostars begin to form first and continue to accrete at high rate throughout the entire cluster evolution. As the most massive gas clumps tend to have the largest density contrast, they are the first to collapse and constitute the center of the nascent cluster. These protostellar cores are fed at a high rate and gain mass very quickly. As their parental clumps merge with others, more gas is fed into their “sphere of influence.” They are able to maintain or even increase the accretion rate when competing with lower mass cores (e.g., cores 1 and 8 in Fig. 1). Low-mass stars, on average, tend to form somewhat later in the dynamical evolution of the system (as indicated by the absolute formation times in Fig. 1; also Fig. 8 in KB1) and typically have only short periods of high accretion.

5. Individual cores in a cluster environment form and evolve through a sequence of highly probabilistic events; therefore, their accretion histories differ even if they accumulate the same final mass. Accretion rates for protostars of certain mass can be determined only in a statistical sense. For the investigated cluster, I define four mass bins, each containing 14 cores, and calculate the average accretion rate \( \langle M \rangle \) and its mean absolute deviation. The result is shown in Figure 2, with the considered mass range indicated at the top of each plot. An exponential decline with a cutoff at \( t_{\text{end}} \) offers a reasonable approximation to \( \langle M \rangle \),

\[
\log \langle M \rangle (M_\odot \text{ yr}^{-1}) = A - \frac{t - t_{\text{form}}}{\tau} \quad \text{for } 0 \leq t - t_{\text{form}} \leq t_{\text{end}},
\]

with normalization \( A \) and decline time \( \tau \) obtained from fitting \( \langle M \rangle \) over 80% of the average accretion duration. There is an implicit upper mass limit \( M_\ast = 10^{3.5} \text{M}_\odot \) when \( t_{\text{end}} \rightarrow \infty \). The integration of \( \langle M \rangle \) yields \( \langle M_{\text{end}} \rangle < M_\ast \). The values \( A, \tau, \langle M_{\text{end}} \rangle \), and \( M_\ast \) are listed in Table 1. Note that as individual accretion rates deviate considerably from the cluster average, when constructing cluster accretion rates from the fit formula a time-dependent random component with roughly 50% deviation should be superposed onto the mean.

6. As \( M \) and \( M_{\text{end}} \) of evolving protostars in dense clusters are influenced by mutual stochastic interactions, the bolometric luminosity \( L_{\text{bol}} \) and temperature \( T_{\text{bol}} \) are not functions of mass and age alone (Myers et al. 1998; WT) but also depend on the statistical properties of the parental cluster (WK). For protostars in the main accretion phase, mass and age determination from comparison with theoretical tracks, either in the \( \log L_{\text{bol}} - \log T_{\text{bol}} \) or the Hertzsprung-Russell diagram, is possible only in an approximated way—as the average over many different theoretical accretion histories for different cluster environments. This may still affect protostars when they enter the pre–main-sequence contraction phase and accretion fades off. A quantitative analysis of the expected errors for different cluster environments will be the subject of a subsequent investigation.

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