EQUILIBRIUM STAR CLUSTER FORMATION

JONATHAN C. TAN

Department of Astronomy, University of Florida, Gainesville, FL 32611-2055; and Institute of Astronomy, Department of Physics,
ETH Hönggerberg, CH-8093 Zurich, Switzerland

MARK R. KRUMHOLZ[1]

Department of Astrophysical Sciences, Princeton University, Peyton Hall, Ivy Lane, Princeton, NJ 08544-1001

AND

CHRISTOPHER F. MCKEE

Departments of Physics and Astronomy, University of California, Berkeley, 366 Le Conte Hall,
Berkeley, CA 94720-7300

ABSTRACT

We argue that rich star clusters take at least several local dynamical times to form and so are quasi-equilibrium structures during their assembly. Observations supporting this conclusion include morphologies of star-forming clumps, momentum flux of protostellar outflows from forming clusters, age spreads of stars in the Orion Nebula cluster (ONC) and other clusters, and the age of a dynamical ejection event from the ONC. We show that these long formation timescales are consistent with the expected star formation rate in turbulent gas, as recently evaluated by Krumholz & McKee. Finally, we discuss the implications of these timescales for star formation efficiencies, the disruption of gas by stellar feedback, mass segregation of stars, and the longevity of turbulence in molecular clumps.

Subject headings: stars: formation — stars: kinematics — stars: winds, outflows

1. INTRODUCTION

Star clusters are born from the densest gas clumps in giant molecular clouds and are likely to be responsible for the majority of stars ever formed (Lada & Lada 2003). The timescale over which a clump transforms into a cluster is a basic constraint for theoretical models. If formation takes only ~1 dynamical time, then star formation is the result of a global collapse of the clump that internal sources of feedback are insufficient to impede. If it takes several dynamical times, then the clump gas must reach an approximate equilibrium, with self-gravity resisted by internal sources of pressure. In this case, star formation is a local process within the protocluster. Runaway gravitational instability occurs on scales much smaller than the overall cluster, involving only a small fraction of the mass at any given time. The cluster formation timescale also determines how much dynamical mass segregation occurs in the gas-rich phase, which may account for the observed central concentration of massive stars in young clusters (Hillenbrand & Hartmann 1998).

Elmegreen (2000) has argued that, over a wide range of scales, star formation occurs in ~1 crossing time. For star clusters the observational evidence cited for short formation times is the age spread of stars and substructure in their spatial distributions. We examine these arguments in detail in § 2 and show that the evidence for rich clusters in fact points to a considerably slower formation process. Hartmann et al. (2001) have argued for star formation in 1 crossing time for low-mass, distributed star-forming regions such as Taurus. Tassis & Mouschovias (2004) have presented counterarguments. However, neither of these analyses applies to individual rich star clusters, on which we focus.

We define here the important timescales for a protocluster gas clump of mass M, radius R, one-dimensional velocity dispersion σ, density ρ, and column density Σ. The free-fall time is $t_{ff} = [3\pi/(32G\rho)]^{1/2}$, and the dynamical, or crossing, time is $t_{dyn} = R/\sigma$. The virial parameter, $\alpha_{vir} \equiv 5\sigma^2 R/(GM)$ (Bertoldi & McKee 1992), defines the relationship of these two; for $\alpha_{vir} \sim 1$, we have $t_{ff} \approx 0.5 t_{dyn}$. Clumps are centrally concentrated (Mueller et al. 2002), so the free-fall and dynamical times vary by location within them. We therefore define t_{ff} and t_{dyn} as mass-weighted averages over the region containing 90% of the mass, although in practice this may be difficult to determine because of confusion on the outskirts of clusters. Finally, we define the formation time t_{form} as the time over which 90% of the stars in a cluster form. Note that this is 2.3 times the exponentiation time t_0 in the accelerating star formation model of Palla & Stahler (2000).

In § 2, we discuss observational evidence that rich clusters take at least several dynamical times to form, drawing on various stages of the formation process. In § 3, we use a theoretical estimate of the star formation rate to show that long formation times are to be expected. Finally, we discuss the implications of this result in § 4.

2. OBSERVATIONAL EVIDENCE FOR SLOW FORMATION

2.1. *Morphologies of Gas Clumps*

Shirley et al. (2003) observed CS ($J = 5 \rightarrow 4$) emission from about 60 dense gas clumps containing high-mass star formation. Their surface densities and masses are very similar to more revealed rich, young star clusters, so they are likely to be similar objects at an early stage of formation. Shirley et al. determined clump aspect ratios, defined as the ratio of major and minor axes of the 20%-of-peak contour, which is well detected and resolved. The distribution of aspect ratios peaks at 1.26 ± 0.22, consistent with most clumps' being circularly symmetric. This morphology contrasts with simulations of rapid cluster formation in which one or two gas filaments tend to dominate (e.g., Bate et al. 2003). Nonperiodic simulations with stellar feedback that run for longer times need to be performed to see

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[1] Hubble Fellow.

how long it takes to establish spherical morphologies. From the CS data it is not possible to tell if the clumps of gas relaxed before star formation started or after. Studies of earlier stages of star cluster formation, as traced by the infrared dark clouds (Egan et al. 1998), can address this.

2.2. *Morphologies of Embedded Stars*

Since molecular clumps are turbulent, stars should form in substructures, which will dissolve as the stars orbit. Thus, the amount of substructure can constrain the formation time. The dissipation time of a substructure depends on whether it is bound (Scally & Clarke 2002) and the nature of its velocity dispersion (Goodwin & Whitworth 2004). If unbound, it dissipates in a time $\sim t_{\rm dyn}$. Assuming all stars form in substructures at constant rate implies $t_{\rm form} \sim (M/M_{\rm sub})t_{\rm dyn}$, where $M_{\rm sub}$ is the mass in substructures. If a subcluster is bound, then rather than dissolving it will sink to the cluster center as a result of dynamical friction. The sinking time from radius $r_{\rm form}$ is $t_{\rm sink} = 0.68(r_{\rm form}/R)^2(\Lambda/\ln\Lambda)t_{\rm dyn}$ (Binney & Tremaine 1987), where Λ is the ratio of cluster to most-massive subcluster mass. This assumes that the cluster density varies as r^{-2}, but a different exponent would not substantially change the result. Assuming a constant star formation rate, so the last subcluster formed at least a time $t_{\rm form}/\Lambda$ ago, that all stars form in subclusters, and that on average subclusters form at $r_{\rm form} = R/2$, the formation time and the mass of the largest visible subcluster are related by $t_{\rm form} \leq 0.17(2r_{\rm form}/R)^2(\Lambda^2/\ln\Lambda)t_{\rm dyn}$. To improve upon these approximate analytic estimates requires global numerical simulations of stars forming from turbulent gas (e.g., Schmeja & Klessen 2006).

Comparing with observations, we find, contrary to Elmegreen (2000), that they are consistent with long formation times. The Orion Nebula cluster (ONC) has quite smooth contours of projected stellar surface density with no significant substructure (Hillenbrand & Hartmann 1998), giving no limit on $t_{\rm form}$ (see also Scally & Clarke 2002). In IC 348, there are eight small subclusters, but these contain only $\sim$10–20 stars each, roughly 20% of the total 345 stars in the cluster (Lada & Lada 1995), giving $t_{\rm form} \sim 5t_{\rm dyn}$ even if all subclusters are unbound. The largest subcluster has 18 members, so $\Lambda \approx 19$ and $t_{\rm form} \leq 21t_{\rm dyn}$ if subclusters are bound. Note that we have neglected the artificial enhancement of apparent substructure by patchy extinction. If this effect is significant, the true ages may be even larger. In no case do we find rich clusters with all or most of their mass in substructures, which would imply $t_{\rm form} \approx t_{\rm dyn}$.

2.3. *Momentum Flux of Protostellar Outflows*

Tan & McKee (2002) estimated the star formation rate in eight clusters using the observed momentum flux of protostellar outflows. Outflows are magnetocentrifugally driven from the star and inner accretion disk (see, e.g., Shu et al. 2000), expelling a fraction f_w of the mass flux $\dot{m}_*$ reaching the star. Outflow models find that the ratio $f_p \equiv f_w v_w/v_{\rm K}$ is constant to within $\sim$30% (Najita & Shu 1994), where v_w is the outflow velocity and $v_{\rm K}$ is the Keplerian velocity at the equatorial radius of the star. Thus, the total momentum flux $\dot{p}_w = f_p \dot{m}_* v_{\rm K}$ is determined by the star formation rate and the evolution of protostellar radii, with only a weak dependence on the latter. Tan & McKee (2002) find that for clusters with a Salpeter initial mass function (IMF) from 0.1 to 120 $M_\odot$, $\dot{p}_w/\dot{M}_* \simeq 87$ km s^{-1}, where $\dot{M}_*$ is the total star formation rate. Loss of momentum in outflow-outflow interactions would lower this estimate, but this effect is probably small, as outflow jets are well collimated. Thus, observations of $\dot{p}_w$ give a measurement of $\dot{M}_*$ and hence the cluster formation timescale. The measurement of $\dot{p}_w$ is quite uncertain, but the data suggest that it would take $\sim$3–5 dynamical times to transform $\sim$30% of the mass into stars (Tan & McKee 2002). Although this is currently one of the more uncertain methods of estimating $t_{\rm form}$, its accuracy should improve as models and observations of individual protostellar outflows are refined.

2.4. *Age Spreads of Pre–Main-Sequence Stars*

The age spread of stars in a cluster is a direct measure of the formation time. Ages can be difficult to determine because they require fitting observed luminosities and temperatures to pre–main-sequence models, which have quite large systematic uncertainties, particularly for low (subsolar-) mass stars. The models also depend on uncertain parameters such as the deuterium abundance, the accretion rate, and accretion geometry (Stahler 1988; Palla & Stahler 1999, hereafter PS99; Hartmann 2003), which influence the position of the "birth line," where stars first appear on the H-R diagram. Fortunately, the initial stellar contraction is quite rapid, so the birth-line position mostly affects ages $\lesssim$1 Myr. Patchy extinction also introduces systematic errors into age estimates, as do unresolved binaries, although for these one may make approximate statistical corrections (PS99). Photometric variability is another potential source of error, but recent observations by Burningham et al. (2005) find that variability cannot mimic age spreads of several million years. In summary, age estimates for intermediate-mass ($M \sim 1\ M_\odot$), older (age $\gtrsim$1 Myr) stars are reasonably robust.

For the ONC, PS99 estimated ages of 258 stars with masses $0.4\ M_\odot < m_* < 6.0\ M_\odot$ from the sample of Hillenbrand (1997). PS99 found 82 stars aged 0–1 Myr, 57 aged 1–2 Myr, 34 aged 2–3 Myr, 17 aged 3–4 Myr, eight aged 4–5 Myr, eight aged 5–6 Myr, eight aged 6–7 Myr, and six aged 7–10 Myr. Hartmann (2003) has argued that the oldest ages ($\sim$10 Myr) may be due to a problem of foreground contamination. We conclude that a significant fraction of the stars are 3 Myr old. This is a lower limit to $t_{\rm form}$, since star formation is still continuing in the cluster, and because the sample is potentially incomplete for the oldest low-mass stars. This result is broadly consistent with ONC age determinations based on lithium abundances in pre–main-sequence stars (Palla et al. 2005), a few of which imply ages as large as $\sim$10 Myr. Elmegreen (2000) estimates a density of $n_{\rm H} = 1.2 \times 10^5$ cm^{-3} for the gas clump from which the ONC formed, giving a dynamical time of 2.5×10^5 yr and an age $\geq$12 crossing times. Note that Elmegreen argued star formation was rapid in the ONC, adopting an age spread of only 1 Myr.

Elmegreen's dynamical time is probably somewhat low; a better estimate is $t_{\rm dyn} = 0.95(\alpha_{\rm vir}G)^{-1/2}(M/\Sigma^3)^{1/4}$. We use this rather than relying on a measured velocity dispersion because, for star clusters, this is often hard to determine as a consequence of incompleteness, confusion, and variation in the velocity dispersion with location in the cluster. The mass and surface density are easier to measure. For gas systems, the typical virial parameter is $\alpha_{\rm vir} \approx 1.3$ (McKee & Tan 2003). For stellar systems we adopt a King model, which implies $\alpha_{\rm vir} \geq 2.0$ if we take σ to be the dispersion of the Maxwellian velocity distribution. For the ONC, Hillenbrand & Hartmann (1998) find $M = 4600\ M_\odot$ and $\Sigma = 0.12$ g cm^{-2}, giving $t_{\rm dyn} = 7 \times 10^5$ yr and an implied cluster age of 4 dynamical times.

In addition to the ONC, which has the best observational data, we can make estimates of the formation and dynamical

times for only a few other rich, forming star clusters. Palla & Stahler (2000) find age spreads of $t_{\text{form}} \approx 2.3$ Myr for both ρ Ophiuchi and IC 348. For ρ Oph, the central cluster is embedded in the L1688 dark cloud. The cluster has a radius of ≈ 1 pc, and the gas mass within this radius (which dominates the total mass) is roughly 1500 $M_\odot$ (Loren 1989). The inferred dynamical time is 7.6×10^5 yr, implying a formation time of 3 dynamical times—in a system that is still gas-dominated. The central cluster in IC 348, which contains roughly half the stars and for which Palla & Stahler make their age estimate, has a radius of 0.5 pc and contains ≈ 200 $M_\odot$ of stars (Lada & Lada 1995). Stars probably dominate the mass (Herbig 1998), so we infer a dynamical time of 6×10^5 yr, giving a formation time of 4 dynamical times.

It is more difficult to determine both formation and dynamical times for other systems, so, contrary to Elmegreen (2000), few conclusions can be drawn. For example, Forbes (1996) did not find evidence for an age spread in NGC 6531, but the analysis was insensitive to timescales shorter than $\gtrsim 3$ Myr. Hodapp & Deane (1993) determined ages up to 6 Myr for stars in L1641 but studied only 12 objects, did not correct for binarity, and used relatively old pre–main-sequence tracks. Palla & Stahler (2000) found formation times for Taurus-Auriga, Lupus, Chamaeleon, Upper Scorpius, and NGC 2264 that are $\gtrsim 3$ Myr, but the first three of these are not rich clusters, Upper Sco has undergone too much dynamical spreading to reliably estimate its dynamical time at formation, and NGC 2264 is too distant for a complete census to reliably determine its mass and column density and, thus, its dynamical time. In NGC 3603, Eisenhauer et al. (1998) find both young stars ($\lesssim 0.5$ Myr) and Wolf-Rayet stars 2–3 Myr old, but as with NGC 2264, it is too distant to reliably determine a dynamical time. Elmegreen (2000) comments that star clusters with age spreads of ~ 10 Myr, for example, NGC 1850, NGC 2004, NGC 4755, NGC 6611, and the Pleiades, could be the result of "multiple and independent star formation events," which then form a single cluster by merging or only appear to be a single cluster because of projection. We would argue that in the former case, the age spread is a true indication of the cluster formation time, although, as Elmegreen points out, the relevant dynamical timescale may need to be evaluated over a larger region that hosted the initial subclusters. However, in all these systems, there is no evidence to favor merging of independent subclusters over continuous formation in situ.

2.5. *Age of a Dynamical Ejection Event in Orion*

Dynamical ejection events provide another method of age estimation. One such event involving four massive stars (a binary and two singles) that appear to have come from the ONC has been dated to ~ 2.5 Myr ago (Hoogerwerf et al. 2001). The central value of the time since this ejection event is 2.3 $\pm$ 0.2 Myr in Hoogerwerf et al.'s analysis; however, if the cluster's distance of about 450 pc is adopted, then the best estimate is 2.5 Myr. The identification with the ONC is based on the extrapolation of the motion of the center of mass of the four stars from the ejection event to the present day, leading to a predicted position coincident with the ONC (uncertainties are a couple of parsecs). This result implies that 2.5 Myr ago the ONC was already a rich cluster containing at least four stars of spectral type earlier than O9/B0. Before this the stars had to form and have enough time to find and eject each other in a close interaction. Thus, the estimate of 2.5 Myr is again a lower limit to t_{form} for the ONC, so that $t_{\text{form}} \geq 4t_{\text{dyn}}$.

3. THEORETICAL FORMATION TIMESCALE

Krumholz & McKee (2005, hereafter KM05) estimate the star formation rate in supersonically turbulent gas, and we use this result to compute how long star formation in a clump must continue to reach $\sim 30\%$ efficiency. Consider a clump with density and pressure profiles $\rho \propto r^{-k_\rho}$ and $P \propto r^{-k_P}$. Hydrostatic equilibrium requires that its mass, radius, and effective sound speed $c \equiv (P/\rho)^{1/2}$ be related by $M = k_P c^2 R/G$. The effective sound speed is related to the one-dimensional velocity dispersion σ_{cl} by $c = \phi_B^{1/2} \sigma_{\text{cl}}$, where ϕ_B is a factor accounting for magnetic support. The clump velocity dispersion in terms of clump mass and surface density is thus

$$\sigma_{\text{cl}} = \left(\frac{G^2 \pi M \Sigma}{k_P^2 \phi_B^2} \right)^{1/4} \rightarrow 2.4 M_3^{1/4} \Sigma_0^{1/4} \text{ km s}^{-1}, \quad (1)$$

where M_3 is the clump mass in units of 10^3 $M_\odot$, Σ_0 is the column density in grams per square centimeter, and the numerical evaluation is for the fiducial parameters of McKee & Tan (2003; $k_P = 1$, $\phi_B = 2.8$, and $\alpha_{\text{vir}} = 1.3$). Based on analysis of the structure of turbulent media and comparison with numerical simulations, KM05 find that the fraction of the mass forming stars every free-fall time is $\text{SFR}_{\text{ff}} \approx 0.073 \alpha_{\text{vir}}^{-0.68} \mathcal{M}^{-0.32}$, where $\mathcal{M} \equiv \sigma_{\text{cl}}/c_s$ is the Mach number and c_s is the thermal sound speed. For our clump, this gives $\text{SFR}_{\text{ff-cl}} \approx 0.027 T_1^{0.16} (M_3 \Sigma_0)^{-0.08}$, where T_1 is temperature in units of 10 K. At this rate, turning 30% of the gas into stars takes 5–6 dynamical times for a 1000 $M_\odot$ clump, with a very weak dependence on temperature, mass, or surface density.

KM05 modeled clouds that were not centrally concentrated, so we can improve this estimate by considering density variation. In turbulent media that are not centrally condensed, the velocity dispersion increases with length scale l as $\sigma \propto l^{1/2}$ regardless of position in the medium, but the tidal field of a clump may introduce a dependence on the distance r from the clump center as well. The expected variation is $\sigma \propto r^{1-k_\rho/2}$, and observations show $k_\rho \simeq 1.5$ (Mueller et al. 2002). On length scales $l \ll r$, the tidal field of the clump is negligible and we should find $\sigma \propto l^{1/2}$, as for a uniform medium, while for $l \gg r$ the tidal field will dominate. Since the size scale of a star-forming core is much less than r over the vast majority of a star-forming clump, we can approximate this behavior by $\sigma \approx \sigma_{\text{cl}} r^{(1-k_\rho)/2} R^{k_\rho/2-1} l^{1/2}$ for $l \ll r$. Thus, the star formation rate varies within the clump as $\text{SFR}_{\text{ff}} = \text{SFR}_{\text{ff-cl}} r^{0.32(k_\rho/2-1)} R^{0.32(1-k_\rho/2)}$. Similarly, the free-fall time as a function of distance from the clump center is $t_{\text{ff}} = t_{\text{ff-cl}} [3/(3-k_\rho)]^{1/2} (r/R_{\text{cl}})^{k_\rho/2}$. Integrating over radial shells, the total star formation rate is

$$\dot{M}_* = \int_0^R 4\pi r^2 \rho \frac{\text{SFR}_{\text{ff}}}{t_{\text{ff}}} dr = \frac{(3-k_\rho)^{3/2}}{2.3(2-k_\rho)} M \frac{\text{SFR}_{\text{ff-cl}}}{t_{\text{ff-cl}}}. \quad (2)$$

Thus, central condensation increases the star formation rate by a factor of $(3-k_\rho)^{3/2}/[2.3(2-k_\rho)]$ relative to a uniform medium. For our fiducial $k_\rho = 1.5$, this means that the time required to reach 30% star formation efficiency is reduced by a factor of 1.6 relative to our previous estimate, giving 3–4 dynamical times.

4. DISCUSSION

We have presented observational and theoretical evidence that rich star clusters require at least several dynamical timescales to form. This is significant, because it implies that star

clusters cannot form by a process of freely decaying turbulence leading to global collapse, which could not possibly take so long. Instead, something must impede or entirely prevent global collapse, so that rich star clusters are in approximate equilibrium during their assembly. For the ONC, ρ Oph, and IC 348, where we can reasonably estimate both formation and dynamical times, formation typically requires $\gtrsim$3–4 dynamical times, consistent with theoretical predictions for the time required to turn ~30% of the gas into stars. The central regions have much smaller dynamical times than the cluster average, so we predict that in the center, a larger fraction of the gas will form stars.

Another implication of this work is that massive-star feedback may not be as effective as once assumed in dispersing gas in young clusters. This is consistent with observations that massive stars are not always the last to form in their clusters (e.g., Eisenhauer et al. 1998; Hoogerwerf et al. 2001) and theoretical work showing that clumpiness greatly inhibits gas dispersal (Tan & McKee 2004; Dale et al. 2005). Tan & McKee (2004) find that in a clump like the proto-ONC, if ~3% of the mass forms stars per dynamical time, feedback requires ~2 Myr (about $3t_{\mathrm{dyn}}$) to disperse the gas. Dynamical ejection of massive stars, as observed in the ONC (Hoogerwerf et al. 2001; Tan 2004), would increase this time.

Long formation times are also important for mass segregation. For example, a 3 Myr formation time for the ONC corresponds to about 8 diameter crossing times at the half-mass radius of 0.5 pc, which is the unit of time used in the study of Bonnell & Davies (1998). If the 30 most massive stars are born at the half-mass radius, then after 3 Myr the median location of the six most massive stars migrates to only 0.075 pc, suggesting that some of the observed mass segregation (Hil-

lenbrand & Hartmann 1998) could be dynamical rather than primordial. Gas drag will likely enhance the segregation beyond the purely N-body effects explored by Bonnell & Davies.

Although undriven supersonic turbulence decays in ~1 dynamical time (Stone et al. 1998), the observed turbulence in molecular clumps does not damp so quickly. Driving by protostellar feedback is a possible explanation. A virialized clump that radiates away half its kinetic energy per dynamical time has a luminosity $L_{\mathrm{diss}} \approx 4M_3^{5/4}\Sigma_0^{5/4}\ L_{\odot}$, but the IMF-averaged energy release associated with accretion is $L_{\mathrm{acc}} \approx 2000M_3\Sigma_0^{3/4}(\eta/10)^{-1}\ L_{\odot}$, where η is the number of dynamical times required to transform 50% of the gas into stars. Outflows should eject about half this energy back into the clump (Shu et al. 2000), so even if only ~1% of this goes into driving turbulence, that is sufficient to offset the decay. Recent observations that find that outflows inject enough energy to maintain turbulence (Williams et al. 2003; Quillen et al. 2005) support this idea, as do the numerical simulations by Li & Nakamura (2006). However, this work is preliminary and has not yet shown that feedback can maintain turbulence over the cluster lifetime of $4t_{\mathrm{dyn}}$ that observations seem to require.

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