DID THE INFANT R136 AND NGC 3603 CLUSTERS UNDERGO RESIDUAL GAS EXPULSION?

SAMBARAN BANERJEE AND PAVEL KROUPA

Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121, Bonn, Germany; sambaran@astro.uni-bonn.de, pavel@astro.uni-bonn.de

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ABSTRACT

Based on kinematic data observed for very young, massive clusters that appear to be in dynamical equilibrium, it has recently been argued that such young systems are examples of where the early residual gas expulsion did not happen or had no dynamical effect. The intriguing scenario of a star cluster forming through a single starburst has thereby been challenged. Choosing the case of the R136 cluster of the Large Magellanic Cloud, the most cited one in this context, we perform direct N-body computations that mimic the early evolution of this cluster including the gas-removal phase (on a thermal timescale). Our calculations show that under plausible initial conditions which are consistent with observational data, a large fraction (>60%) of a gas-expelled, expanding R136-like cluster is bound to regain dynamical equilibrium by its current age. Therefore, the recent measurements of velocity dispersion in the inner regions of R136, which indicate that the cluster is in dynamical equilibrium, are consistent with an earlier substantial gas expulsion of R136 followed by a rapid re-virialization (in \(\approx 1\) Myr). Additionally, we find that the less massive Galactic NGC 3603 Young Cluster (NYC), with a substantially longer re-virialization time, is likely to be found to have deviated from dynamical equilibrium at its present age (\(\approx 1\) Myr). The recently obtained stellar proper motions in the central part of the NYC indeed suggest this and are consistent with the computed models. This work significantly extends previous models of the Orion Nebula Cluster which already demonstrated that the re-virialization time of young post-gas-expulsion clusters decreases with increasing pre-expulsion density.

Key words: galaxies: individual (LMC) – galaxies: star clusters: general – open clusters and associations: individual (R136, NGC 3603) – stars: kinematics and dynamics

1. INTRODUCTION

The question of how a young star cluster is formed has been debated for decades. According to the classic scenario, a cluster forms essentially through a single starburst event. The individual proto-stellar cores within the parent or proto-cluster gas cloud approach their hydrogen-burning main sequences (MSs) to form an infant star cluster which still remains embedded within the residual gas that did not collapse to stars. This residual gas receives kinetic energy and radiation pressure from the radiation of the massive MS and pre-main-sequence (PMS) stars until it becomes unbound from the system and then escapes. This gas-removal process can be expected to be very rapid—typically faster than or similar to the dynamical crossing time of the embedded cluster (Lada & Lada 2003). The remaining gas-free cluster must expand due to the corresponding dilution of the gravitational potential well. For the hypothetical case of instantaneous gas removal, the resultant cluster should become unbound if the total mass lost as gas is equal to or more than the mass remaining in the stars (i.e., star formation efficiency (SFE) \(\epsilon \lesssim 50\%\)), as is true for any gravitationally self-bound system. For slower gas removal, the survivability of the gas-deprived cluster as a bound system, for \(\epsilon \lesssim 50\%\), increases (Kroupa 2008). Two-body relaxation, which evolves the cluster toward a higher central concentration until the beginning of gas expulsion, also enhances survival.

The above scenario, applicable to the formation of Galactic and extragalactic young star clusters, was first depicted by, e.g., Hills (1980), Elmegreen (1983), and Mathieu (1983), either analytically or by small \(N\) direct \(N\)-body studies (Lada et al. 1984). These milestone works were later elaborated on by Kroupa et al. (2001), Geyer & Burkert (2001), and Baumgardt & Kroupa (2007) by extensive direct \(N\)-body calculations of gas-expelling model infant clusters. Such theoretical studies, along with observations of young embedded systems (Lada 1999; Elmegreen et al. 2000), suggest a minimal SFE of \(\epsilon \approx 1/3\) for forming a bound, gas-free cluster, applicable to embedded systems initially in dynamical (or virial) equilibrium. A piece of observational evidence of the residual gas-expulsion process can be the \(<2.5\) Myr old Orion Nebula Cluster (ONC), whose measured velocity dispersion implies that it must be expanding (Jones & Walker 1988). While the ONC was widely considered to end-up in an unbound OB association (e.g., Zinnecker et al. 1993), the detailed modeling by Kroupa et al. (2001) implies that it is instead destined to become a bound cluster very similar to the Pleiades by 100 Myr. Recent proper motion measurements of the Galactic \(\approx 1\) Myr old NGC 3603 Young Cluster (NYC) by Rochau et al. (2010) also suggest that its stars might be away from energy-equipartition. Notably, a demonstration of the expansion of clusters younger than a few Myr as they age is presented by Brandner (2008).

The key properties of the stellar initial mass function (IMF; Kroupa et al. 2013), in particular its observed universality, are also supported by a monolithic cluster formation scenario that involves competitive gas accretion by the most massive proto-stellar cores. For example, detailed three-dimensional, adaptive-mesh FLASH calculations including radiation feedback by Peters et al. (2010, 2011) well reproduce not only the general form of the universal IMF, but also the relation between the total mass (in stars) of an embedded cluster and the mass of its most massive stellar member (Weidner & Kroupa 2004). Recently, Liu et al. (2012) find observational signatures of competitive accretion in the proto-cluster G10.6-0.4.

Very recently however, questions have been raised against the clustered mode of star formation, preferring instead a hierarchical or continuous star formation (e.g., Bressert et al. 2010; Gutermuth et al. 2011). The latter is inferred from the stellar density distribution in young, star forming regions over a “global” scale. Notably, Pfalzner et al. (2012) showed that unless the density contrast among the individual clusters is very high, any such conclusions based on surface density profiles can be highly ambiguous and are useful only when...
sufficiently deep and complete data are available. Furthermore, from the kinematics of several very young clusters indicating their dynamical equilibrium, in particular that of the R136 cluster in the Large Magellanic Cloud (LMC), it has been argued that they must have avoided any substantial residual gas-expulsion phase (i.e., effectively have had 100% SFE, also see Goodwin 2009 in this context); otherwise, they would have been found to be expanding at such a young age. This has been particularly emphasized very recently by Hénault-Brunet et al. (2012). A key ingredient that might be missing in such arguments is the consideration of the re-virialization of the expanding gas-expelled cluster, i.e., the quick formation of a bound system after a fraction of the expanding cluster reverses back on a free-fall timescale.

The possible fate of the expanding ONC as Pleiades-like bound system has been shown by Kroupa et al. (2001), whose models already demonstrate that the re-virialization time decreases with increasing initial cluster density (Figure 1 of Kroupa et al. 2001). The survivability as a bound cluster after gas removal was later studied in detail by, e.g., Baumgardt & Kroupa (2007). In this work, we find it crucial to study this issue again with particular focus on the case of R136. This becomes essential because of the current interpretations of the kinematic data of young, massive clusters such as R136, which seem to contradict the classical picture of monolithic cluster formation and the associated residual gas expulsion event. We show that under plausible conditions, the re-virialization of an R136-like massive cluster, after gas removal, is prompt enough to cause it to be found in virial equilibrium despite its young age. The recently obtained low (line-of-sight) velocity dispersion of single O-stars in R136 (Hénault-Brunet et al. 2012) is also found to be consistent with a re-virialized system. We also find that the much lighter NYC, on the other hand, is unlikely to be virialized at its current age of ≈1 Myr (Stolte et al. 2004, 2006), as indicated by Rochau et al. (2010).

2. MODEL COMPUTATIONS

2.1. Gas Removal

A thorough modeling of gas removal from embedded clusters is complicated by radiation hydrodynamical processes, which are extremely complex and involve uncertain physical mechanisms. For simplicity, we therefore mimic the essential dynamical effects of the gas-expulsion process by applying a diluting, spherically-symmetric external gravitational potential to a model cluster as in Kroupa et al. (2001). Specifically, we use the potential of the spherically-symmetric, time(t)-varying mass distribution

\[ M_g(t) = M_g(0) \quad t < \tau_d, \]
\[ M_g(t) = M_g(0) \exp \left( -\frac{(t - \tau_d)}{\tau_g} \right) \quad t > \tau_d. \]  

Here, \( M_g(t) \) is the total mass in gas that is spatially distributed with the same initial Plummer density distribution (Kroupa 2008; see below) as the stars and starts depleting with timescale \( \tau_g \) after a delay of \( \tau_d \). The Plummer radius of the gas distribution is kept time-invariant (Kroupa et al. 2001). Such an analytic approach is partially justified by Geyer & Burkert (2001) who perform comparison computations treating the gas with the SPH method.

The exact values of the essential parameters quantifying the gas-expulsion timescale, viz., \( \tau_g \) and \( \tau_d \), depend on gas-physics. For simplicity, we use an average gas velocity of \( v_g \approx 10 \text{ km s}^{-1} \), which is the typical sound speed in an H\textsc{ii} (ionized hydrogen) region. This gives

\[ \tau_g = \frac{r_g(0)}{v_g}, \]

where \( r_g(0) \) is the initial half-mass radius of the stellar cluster/gas. The coupling of stellar radiation with the ionized residual proto-cluster gas substantially overpressures the latter and can even make it radiation-pressure-dominated (RPD) for massive clusters in the initial phase of the expansion of the gas. During the RPD phase, the gas is driven out at speeds considerably exceeding the sound speed of the ionized medium (Krumholz & Matzner 2009). Once the expanding gas becomes gas-pressure-dominated (GPD), it then continues to flow out with the sound speed of an H\textsc{ii} region (Hills 1980). Hence, the above \( \tau_g \) from \( v_g \approx 10 \text{ km s}^{-1} \), represents its upper limit; it can be shorter depending on the duration of the RPD state (also see Section 4). Notably, the initial RPD phase is crucial to launching the gas from very massive systems whose escape speed exceeds the sound speed in H\textsc{ii} gas (Krumholz & Matzner 2009).

As for the delay-time, we select the representative value of \( \tau_d \approx 0.6 \text{ Myr} \) (Kroupa et al. 2001). The correct value of \( \tau_d \) is again complicated by radiative gas-physics. An idea of \( \tau_d \) can be obtained from the lifetimes of the ultracompact H\textsc{ii} (UCHII) regions, which can be up to \( \approx 10^7 \text{ yr} \) (0.1 Myr; Churchwell 2002). The very compact pre-gas-expulsion clusters (Section 2.2) have sizes \( r_g(0) \) only a factor of \( \approx 3-4 \) larger than the typical size of a UCHII region (\( \approx 0.1 \text{ pc} \)). If one applies a similar Strömgren sphere expansion scenario (Churchwell 2002 and references therein) to the compact embedded cluster, then the estimated delay-time, \( \tau_d \), before a sphere of radius \( r_g(0) \) becomes ionized would also be larger by a similar factor, and hence close to the above representative value. Once the gas is ionized, it couples strongly with the radiation from the O/B stars and launches immediately (see above). High-velocity jet outflows from protostars (Patel et al. 2005) also facilitate the gas removal.

For super-massive clusters (\( >10^6 \text{ M}_\odot \)), however, a “stagnation radius” can form within the embedded cluster, inside which the radiation cooling becomes sufficiently efficient to possibly form second-generation stars (Wünsch et al. 2011). Also, as discussed above, the gas-outflow can initially be supersonic, which generates shock-fronts. Although shocked, it is unlikely that star formation will occur in such an RPD gas. Later, during the GPD outflow, the flow can still be supersonic in the rarer outer parts of the embedded cluster where the average sound speed might be lower than that typical for H\textsc{ii} gas. However, it is not clear whether the cooling in the shocked outer regions would be efficient enough to form stars.

Admittedly, the above arguments do not include complications such as unusual morphologies of UCHIIIs and a possibly non-spherical ionization front, among others, and only provide basic estimates of the gas-removal timescales. Observationally, Galactic \( \approx1 \text{ Myr} \) old gas-free young clusters such as the ONC and the NYC imply that the embedded phase is \( \tau_d < 1 \text{ Myr} \). The above widely-used gas-expulsion model does realize the essential dynamical effects on the star cluster. In particular, such simplification has practically no effect on the remaining cloud after the gas is expelled, e.g., on it’s re-virialization, which is the focus of this work.

2.2. Initial Configuration, Stellar Dynamics, and Evolution

The initial model embedded stellar clusters are Plummer spheres (Kroupa 2008) which the gas follows as well. This
is a reasonable approximation since dense interstellar medium (ISM) filaments appear to have Plummer-like sections (Malinen et al. 2012; see also below). The $r_2(0)$ of embedded clusters are substantially smaller than the typical sizes of exposed young clusters, as found in the semi-analytic calculations by Marks & Kroupa (2012). These calculations constrain the birth density of a large number of observed clusters by their observed population of binary stars, leading to a remarkable overlap with the densities of star-forming molecular clumps (Figure 6 in Marks & Kroupa 2012). Our initial clusters thus follow the empirical relation between $r_2(0)$ and the embedded cluster mass (only the stars) $M_{\text{ele}}(0)$ by Marks & Kroupa (2012), i.e.,

$$\frac{r_2(0)}{\text{pc}} = 0.10^{0.07} \times \left( \frac{M_{\text{ele}}(0)}{M_\odot} \right)^{0.13\pm0.04}, \tag{2}$$

which is a rather weak dependence. This independently obtained result is in excellent agreement with the observed results from Herschel (André et al. 2011, Figure 6.3). The SFE is taken to be $\epsilon = 1/3$, i.e., $M_*(0) = 2M_{\text{ele}}(0)$ (see Section 4 for a discussion).

Notably, André et al. (2011) and Malinen et al. (2012) refer to the shape and the compactness of ISM filamentation. The star forming spherical/spheroidal proto-clusters form within the ISM filaments and at their intersections (Schneider et al. 2012); a part of the filament that collapses under self-gravity to form an embedded cluster would become spherical/spheroidal. Recent Herschel observations of ridges in molecular clouds and of the associated filaments support this (Hennemann et al. 2012; Schneider et al. 2010; Hill et al. 2011). The compact sizes ($\approx 0.1$ pc) of these ISM filaments (André et al. 2011) then dictate the high compactness of the initial embedded systems. There are, of course, the competing viewpoints of whether all the stars form within one cloud (the standard scenario) or the final cluster can be formed hierarchically (see Section 1). Currently, the possibility of forming massive stars within the filaments but outside any cluster has also been suggested (e.g., Bressert et al. 2012). So far as our computations in this paper are concerned, we adopt the standard scenario and investigate whether the observed kinematics of the young clusters like R136 and NYC (to start with) can be reasonably explained within such a context. In that case, our chosen initial conditions well reflect the sizes and the shapes of the observed filaments.

The IMF's of the clusters are chosen to be canonical (Kroupa 2001) with the most massive star following the $m_{\text{max}} = M_{\text{ele}}(0)$ relation of Weidner & Kroupa (2004). To that end, an “optimized sampling” algorithm (Kroupa et al. 2013) is used instead of randomly sampling the IMF. All of the computed models are fully mass-segregated using the method of Baumgardt et al. (2008), as observed in young clusters (Littlefair et al. 2003; Chen et al. 2007; Portegies Zwart et al. 2010). For computational ease, we assume all of the members of the initial cluster to be single stars. Since the O-stars in young clusters are typically found in binaries (Sana & Evans 2011; Sana et al. 2012), our initial stellar population, admittedly, does not completely represent that of a young cluster. However, binarity is unlikely to substantially influence the expansion of a cluster during gas expulsion and re-collapse, and virialization thereafter, which is the focus of this work. Although the initial segregated state is detected for several Galactic young clusters, it is yet to be confirmed for young clusters in general (see Portegies Zwart et al. 2010 for a discussion). Therefore, for comparison purposes, we compute identical models without any initial mass segregation. We find that mass segregation does not influence the conclusions (Section 3.1).

The dynamical evolution of the model clusters is computed using the state-of-the-art NBODY6 code (Aarseth 2003). In addition to integrating the particle orbits using the highly accurate fourth-order Hermite scheme and dealing with the diverging gravitational forces in close encounters through regularizations, NBODY6 also employs the well-tested analytical stellar and binary evolution recipes of Hurley et al. (2000, 2002), i.e., the SSE and the BSE schemes. NBODY6 also includes the time-variable Plummer gas potential as described above.

The initial masses of the computed model embedded clusters are chosen to be $M_{\text{ele}}(0) \approx 10^5 M_\odot$, which represents an upper mass limit of R136 (Crowther et al. 2010). Their Plummer radii are chosen from Equation (2). We also consider an embedded cluster of $M_{\text{ele}}(0) = 1.3 \times 10^4 M_\odot$ to mimic the gas removal from a Galactic NYC-like cluster (Stolte et al. 2004, 2006; Rochau et al. 2010). The metallicities of the former models are taken to be $Z = 0.5 Z_\odot$, as appropriate for the LMC, and that for the NYC model is $Z = Z_\odot$. Our computed models are summarized in Table 1, where those in Kroupa et al. (2001) are also added for comparison. For both of our computed models, the $\tau_{g,S}$ are similar to the initial crossing times $\tau_{c}(0)$; $\tau_{g} \approx 2$ and 1 time(s) $\tau_{c}(0)$ for the R136 and the NYC model, respectively. Since $\tau_{g} < \tau_{c}(0)$ for the Kroupa et al. (2001) models, our gas expulsions are less “prompt” owing to higher initial concentrations. The $\text{MCLUSTER}$ program (Küpper et al. 2011) is used to set the initial configurations. As it is difficult to model the weak tidal field of the LMC, the clusters are evolved in the absence of any galactic potential.

### 3. RESULTS

#### 3.1. Gas Expulsion from an R136-Like Cluster

Figure 1 shows the evolution of the Lagrange radii, $R_f$, in our computed R136 model clusters (Table 1) with $\tau_d = 0.6$ (top panel) and 0 (bottom) Myr. The $\tau_d = 0$ case is computed as a test case only to compare with that of the more realistic delay $\tau_d = 0.6$ Myr. From the beginning of the gas expulsion, the cluster expands rapidly with timescale $\tau_c$. At least 60% of the cluster, by mass, then collapses back to a steady size, i.e., regains

| Cluster | $M_{\text{ele}}(0)/M_\odot$ | $M_\odot(0)/M_\odot$ | $r_2(0)/\text{pc}$ | $Z/Z_\odot$ | $\tau_g/\text{Myr}$ | $\tau_c(0)/\text{Myr}$ | $\tau_d/\text{Myr}$ | BSE | $\tau_{\text{vir}}/\text{Myr}$ |
|---------|-----------------|-----------------|-----------------|------------|-----------------|-----------------|-----------------|-----|-----------------|
| R136    | $1.0 \times 10^7$ | $2.0 \times 10^7$ | 0.45            | 0.5        | 0.045           | 0.021           | 0.0, 0.6        | Yes | 0.9            |
| NYC     | $1.3 \times 10^4$ | $2.6 \times 10^4$ | 0.34            | 1.0        | 0.034           | 0.038           | 0.0, 0.6        | Yes | 2.2            |
| ONC-A   | $3.7 \times 10^3$ | $7.4 \times 10^3$ | 0.45            | 1.0        | 0.045           | 0.23            | 0.6            | Yes | $> 10$         |
| ONC-B   | $4.2 \times 10^3$ | $8.4 \times 10^3$ | 0.21            | 1.0        | 0.021           | 0.066           | 0.6            | Yes | $\approx 3$    |

Notes. The ONC-A/B computations are from Kroupa et al. (2001) and included for comparison. The quoted $\tau_{\text{vir}}$s correspond to the re-virialization times of 30% of the initial cluster mass (in stars) after the delay time $\tau_d$. The “BSE” column indicates the presence of stellar evolution.
virialization in $\tau_{\text{vir}} \approx 1$ Myr (beyond $\tau_d$). The inner regions virialize even earlier. Given that the bulk of the R136 cluster is $\approx 3$ Myr old (Andersen et al. 2009), it ought to be currently in dynamical equilibrium as a whole even if it has undergone a substantial gas-expulsion phase in the past. We discuss this further in Section 4. The gas-free cluster is expanded by a factor of $\approx 3$ in terms of its half-mass radius, $r_h$, after reverting to dynamical equilibrium. Notably, the re-virialization happened in spite of the wind mass-loss from the massive stars that was operating during these computations. A comparison of the two panels in Figure 1 makes it apparent that a finite $\tau_d$ (with $\tau_g$ unchanged) keeps the form of the cluster’s expansion and re-virialization identical—it merely applies a time-translation to the overall evolution.

Figure 2 shows the $R_f$-evolution for identical R136 models but without initial mass-segregation. It demonstrates that the cluster evolutions are identical throughout to the previous cases with primordial mass segregation, in particular during the expanding phase and the re-collapse to virialization. In other words, primordial mass-segregation has no effect on the re-virialization of a cluster.

Very recently, Hénault-Brunet et al. (2012) measured radial/line-of-sight velocities (RV) of single O-stars within 1 pc $\lesssim R \lesssim$ 5 pc projected distance from R136’s center$^1$ with data obtained from the VLT-FLAMES Tarantula Survey (VFTS; Evans et al. 2011). They conclude that the RV dispersion, $V_r$, of the single O-stars within this region is $4 \text{ km s}^{-1} \lesssim V_r \lesssim 5 \text{ km s}^{-1}$, agreeing with R136 being in virial equilibrium.

Figure 3 shows the evolution of $V_r$ corresponding to the R136 computations in Figure 1 for the 1 pc $\lesssim R \lesssim$ 5 pc projection from the density center and stellar masses $M > 16 M_\odot$, i.e., those of the O-stars. It demonstrates that after re-virialization, the O-stars indeed have $V_r$ remarkably similar to that measured by Hénault-Brunet et al. (2012). The initial large fluctuations in $V_r$ in the upper panel of Figure 3 ($\tau_d = 0.6$ Myr) are due to the initial mass-segregated condition, which results in only a few O-stars within 1 pc $\lesssim R \lesssim$ 5 pc initially. The measured RV data is therefore consistent with R136 going through a gas-expulsion phase and now being in a re-virialized state, unlike what is claimed by Hénault-Brunet et al. (2012).

3.2. The Case of the NGC 3603 Young Cluster

Figure 4 (top) shows the Lagrangian radii of our computed NYC cluster (Table 1). The mass of NYC (Stolte et al. 2004, 2006)
Figure 3. Evolution of the radial velocity (RV) dispersion, $V_r$, of the O-stars ($M > 16.0 \, M_\odot$), within the projected distances $1 \, \text{pc} < R < 5 \, \text{pc}$ from the cluster center, for the computed R136 models. The top and the bottom panels correspond to the computations with $\tau_d = 0.6$ and $0 \, \text{Myr}$, respectively.

The computed $V_{1d}$ at $t = 1 \, \text{Myr}$ is somewhat less than the measured $V_{1d} \approx 4.5 \pm 0.8 \, \text{km s}^{-1}$ and the observed system must currently be super-virial, unlike the computed sub-virial state at $t = 1 \, \text{Myr}$, as the inferred dynamical mass $^3$ exceeds the photometric mass (Rochau et al. 2010). These can be easily accounted for by a plausible $0.6 < \tau_d < 0.8 \, \text{Myr}$ delay in the gas removal (see Figure 4), which would then result in agreement with the observed $V_{1d}$ and the super-virial state of NYC. Furthermore, NYC’s mass is uncertain by a factor of $\approx 2$ (Rochau et al. 2010).

Figure 5 replots Figure 4 with a $\tau_d \approx 0.6 \, \text{Myr}$ delay which, in turn, corresponds to the results of a computation with this delay in gas expulsion (see Section 3.1). This makes the cluster super-virial at its $\approx 1 \, \text{Myr}$ current age. The corresponding $V_{1d}$ is still somewhat smaller than the observed value but is within $3\sigma$ limits. Notably, NYC might, in fact, be somewhat $^2$ The $V_{1d}$ is obtained from proper motion measurements and is therefore “binary-corrected.” $^3$ The dynamical $1.7 \times 10^4 \, M_\odot$, does not represent an upper limit as quoted by Rochau et al. (2010), but is only an individual estimate.
1.5
2.5
3
2.5
2
3.5
(see Section 3.1). They show that NYC would be super-virial at its current ≈τd an initial gas-expulsion time-delay of

younger (see Figure 4 of Stolte et al. 2004), and dispersion (bottom) of the same computed NYC models as in Figure 4 where

Figure 5. Evolutions of the Lagrange radii (top) and one-dimensional velocity dispersion (bottom) of the same computed NYC models as in Figure 4 where an initial gas-expulsion time-delay of τd = 0.6 Myr is applied while plotting. Hence, the plots are essentially the same as in Figure 4 except that they begin at t = 0.6 Myr and correspond to those from a computation with τd = 0.6 Myr (see Section 3.1). They show that NYC would be super-virial at its current ≈1 Myr age, as observed.

younger (see Figure 4 of Stolte et al. 2004), and V1d also depends on the exact initial mass and size, which are subject to uncertainties. Moreover, NYC’s V1d and age are susceptible to its distance uncertainties. Notably, Cottaar et al. (2012) also find the Westerlund I cluster to be sub-virial.

4. CONCLUSIONS AND OUTLOOK

The key message from our above computations and analyses is a reminder that an observed dynamical equilibrium state of a very young stellar cluster does not necessarily dictate that the cluster has not undergone a gas-expulsion phase. The non-occurrence of gas removal has been highlighted, particularly by putting forward the case of R136, by recent authors, e.g., Hénault-Brunet et al. (2012). This is why we focus on R136 in this study. We also demonstrate, choosing the example of NGC 3606, that lower-mass clusters take much longer to re-virialize (see Table 1), so that it is also appropriate to find non-equilibrium signatures in them. This has been shown to be true also for the ONC by Kroupa et al. (2001, see Table 1). The above must be remembered while interpreting the kinematics of any young cluster.

Notably, R136 exhibits an age-spread; its massive stellar population can be younger, i.e., ≲2 Myr old (Massey & Hunter 1998). If the gas expulsion is assumed to commence only after the formation of the most massive stars, then a current state of equilibrium is still plausible given the τvir ≈ 1 Myr re-virialization time. It should, however, be remembered that age-estimates of massive stars are highly uncertain. There is no concrete evidence that invalidates the scenario involving the formation of R136’s entire stellar population all at once ≈3 Myr (Andersen et al. 2009) ago and the most massive single stars forming later via dynamically induced binary mergers (Banerjee et al. 2012b) or appearing younger due to mass transfer in close O-star binaries.

Although the present study does not cover a general range of the parameters τd, τg, rh(0) and ϵ, these computations can still provide a fair idea of the effects of varying these parameters over their plausible ranges. By applying time-shifts to the point of expansion of the clusters in Figures 1 and 2, it can be concluded that τd ≲ 2 Myr required R136 to be virialized at t = 3 Myr, since τvir ≈ 1 Myr. Although an unambiguous τd requires radiation hydrodynamic calculations, this upper limit is perhaps too large a value for τd in light of the discussions in Section 2.1. The currently chosen values of τd are upper limits based on the typical H ii-gas sound speed of ≈10 km s⁻¹ (Section 2.1).

As discussed in Section 2.1, the outflow speed can initially be significantly higher than the sound speed, driven mainly by radiation pressure, resulting in smaller τg’s than those assumed. This would make the gas expulsion more prompt, keeping τvir practically unchanged.

As for the SFE, the chosen ϵ ≈ 1/3 is in the range of the observationally estimated SFEs by Lada & Lada (2003, see their Table 2). Recent theoretical modeling of star formation with high-resolution resistive magnetohydrodynamics (Machida & Matsumoto 2012) also suggest ϵ ≈ 33%. In any case, a larger ϵ would also result in a bound system and shorter τvir as the re-virializing mass would be larger. As for rh(0)s, their increasing values would increase τg’s, so our conclusions depend on our adopted initial high compactness. However, this condition is plausible because such compact star-forming environments (a factor of ≈10 smaller than typical young clusters, i.e., rh(0) ≈ 0.3–0.4 pc) are inferred observationally by André et al. (2011) and also from the semi-analytic study by Marks & Kroupa (2012) independently (the re-virialization time depends on the above typical compactness but, of course, not on the specific Equation (2)). In other words, plausible variations of the model parameters are unlikely to alter our above primary conclusions since none imply a substantial lengthening of τd, τg or τvir.

An immediate improvement over the present study would be to introduce an appropriate binary population, as in Banerjee et al. (2012a, 2012b). In light of the present and upcoming observations of Galactic and extragalactic young clusters, an important pending task is to systematically and quantitatively study the effect of gas expulsion over their entire mass range with varying parameters such as τd, τg, rh(0) and ϵ, including realistic stellar populations. Such a model bank would be extremely valuable to interpret the ever-enriching kinematic data of young stellar clusters.

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